WATER & ENVIRONMENT NEWSLETTER

A newsletter of the
Isotope Hydrology Section
International Atomic Energy Agency
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Sunset at Dead Sea (see inside for an article, credit: K.Kulkarni/IAEA)

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From the Section Head...

Dear Colleagues,

This issue of Water and Environment Newsletter is being released on the occasion of the 3rd World Water Forum in Kyoto, Japan from 16-23 March 2003. The Isotope Hydrology Section is contributing to the Forum through various theme sessions, in particular those related to groundwater and partnerships with other organizations. The Forum aims to increase political commitments for concrete action to improve water availability and sustainable resource management worldwide. A successful Forum will go a long way in improving the present and future water availability on a global scale.

The Kyoto Forum will build on the outcomes of the recent World Summit on Sustainable Development (WSSD) held in Johannesburg, South Africa. The Agency participated in the WSSD and its side events, and announced a partnership initiative with UNESCO and others on improved capacity building and technology applications for water resource and coastal zone management. The WSSD implementation plan recognizes the following four actions for the sustainable development and management of water resources:

- "Develop integrated water resources management and water efficiency plans by 2005, with support to developing countries, through actions at all levels to develop and implement national/regional strategies, plans and programmes with regard to integrated river basin, watershed and groundwater management, …"

- "Support developing countries and countries with economies in transition in their efforts to monitor and assess the quantity and quality of water resources,…"

- "Improve water resource management and scientific understanding of the water cycle through cooperation in joint observation and research,…."

- "Promote effective coordination among the various international and intergovernmental bodies and processes working on water-related issues, both within the United Nations system and between the United Nations and international financial institutions,.."

Through recent re-alignments in the Agency's water resources program, we are already addressing the above issues. Besides the large efforts in capacity building and water quality and quantity assessments in the developing countries through the Technical Cooperation programme, we have several initiatives that address the other points of the WSSD plan.

A new coordinated research project (CRP) on isotope tracing of hydrological processes in large river basins was launched in March 2002. The project aims to develop a methodology and monitoring network for isotopes to understand hydrological processes in large river basins. The research project involves 17 research groups worldwide.

Characterization of moisture sources in local precipitation is an important component of our improved understanding of the hydrological cycle and the potential impact of climate change on water resources. The role of global precipitation isotope data was highlighted at a meeting of the Global Energy and Water Experiment (GEWEX) project which focuses on a better understanding of the earth's energy and water cycles. A joint project is being formulated under the Agency's leadership that would attempt to use isotope data from GNIP for improved modelling of moisture sources in precipitation.

Installation of a tritium-helium isotope measurement facility for age dating of young groundwater is now well underway at our laboratory in Vienna. Tritium-helium dating of groundwater has been shown to be an effective and powerful tool for obtaining groundwater ages of the order of 1 to 50 years and a new project has been planned for the years 2004-2005 to develop a global database of groundwater ages in river baseflow and shallow aquifers. This database is expected to vastly improve our ability to characterize groundwater recharge and river hydrological processes.

The coming year, International Year of Freshwater, also promises to be quite busy and important for integrating isotopes in hydrologic sciences. I take this opportunity to wish you all a happy and productive year!

Pradeep AGGARWAL

World Water Day 2002

The Agency celebrated World Water Day 2002 with the theme of "Water for Development".

Dr. Mohamed ElBaradei, IAEA Director General launched the event, stressing the role of science and technology for use and management of water resources. As the lead UN agency, the IAEA initiated and coordinated a range of activities and events. They included:

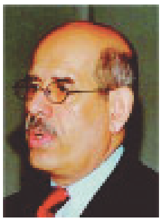
- The World Water Day 2002 web site, which served as an information clearinghouse and reference centre for national, regional and international organizations around the world.
- A celebration at the Vienna International Centre on 22 March to officially launch World Water Day 2002
- A press release distributed worldwide that highlighted the challenges of water for development with the viewpoints of the heads of regional and international organizations;
- An art exhibition on Water for Development by children from schools in Uganda and Austria;
- A dialogue on Water for Development with distinguished speakers from governments, non-governmental organizations, and intergovernmental agencies.

All 23 UN agencies with interests or programmes in the water sector collaborated in these efforts. The web site was accessed more than 30,000 times during the January–March 2002 period. Nearly 3,000 copies of the promotional materials were distributed in multiple languages and many more were downloaded from the web site. A summary report on World Water Day 2002 was printed and distributed widely.

Honourable Mrs. Bijoya Chakravarty, Minister of State for Water Resources, India addressing the gathering at the inaugural session of the World Water Day 2002 on 22 March 2002 at the Vienna International Centre.

The following are the excerpts from speeches made by representatives of various organizations during the inaugural ceremony and the panel discussions.

"...The IAEA has the honour today of being the lead organization in the United Nations family to coordinate WWD2002 activities. I am pleased to inaugurate the event in the company of so many young people who have used their artwork as you can see here on display, to express their ideas about the theme of 'Water for Development'....".



Dr. Mohamed ElBaradei, Director General, IAEA, during his inaugural speech.

"...Science and technology have a significant role to play in management and development of water resources...Nuclear technology has contributed to expand the fresh water resources by using 'Isotope Hydrology'... I would like to compliment the IAEA under the leadership of the present Director General, Dr. ElBaradei, for the excellent efforts made in this particular field..."

Hon. Ms. Bijoya Chakravarty, Minister of State for Water Resources, India, during the inaugural session.

"...I would like to congratulate the International Atomic Energy Agency for spearheading this year's celebrations and for organizing various activities in order to make this day very colourful...All these will go a long way in informing the whole world about the importance of water in development activities..."

Hon. Ms. Maria Mutagamba, Minister of State for Water Resources, Uganda, during the inaugural session.

"...In 1992, the Rio Declaration on Environment and Development proclaimed in Principle 21: 'The creativity, ideals and courage of the youth of the world should be mobilized to forge a global partnership in order to achieve sustainable development and ensure a better future for all'... As we can all see in this exhibition, the IAEA has managed to do exactly this around the issue of water..."

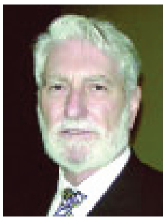
H.E. Mr. Thomas Stelzer, Ambassador of Austria to the International Organizations in Vienna, while inaugurating the art exhibition.

"...The IAEA has made major strides in recent years to move beyond its traditional national partners – the national atomic energy authorities – and to work with national water authorities. This ensures that isotope hydrology techniques are brought to bear when they can add value to national and regional water development programmes..."

H.E. Mr. Kenneth Brill, Ambassador of the USA to the International Organizations in Vienna, during the panel discussion.

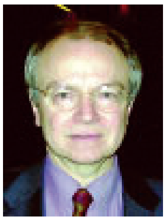
"...And 30 years have passed since Indira Gandhi declared at the UN Environment Conference in Stockholm that poverty unites, and that battle against poverty is also a struggle against environment...Access to good quality water and proper sanitary conditions are an essential element in the battle to eradicate poverty..."

Ms. Margot Wallstroem, Commissioner, Environment European Commission during the panel discussion.



"...It is the institutional frame not only for pollution control and the protection of water bodies but it sets also a common platform for sustainable use of ecological resources and coherent and integrated river basin management..."

Mr. Joachim Bendow, Executive Secretary, International Commission for the Protection of the Danube River, during the panel discussion.



"...Goals of the ADC in Water & Sanitation are: Water and sanitation for all – quantity & quality, equitable access; Protection of water resources – water, soil, vegetation, water balance; Reliability of supply – technical, operational, financial..."

Mr. Guenther Stachel, Deputy Head of the Austrian Development Cooperation during the panel discussion.

"...Environmentally sustainable ways of meeting our water needs are available, achievable and worthwhile..."

Mr. Paul Steele, Chief Operating Officer of WWF International during the panel discussion.

"...Let us not forget that we are all water users, creatures whose origin is in water. It is also the mandate of this agency to promote peaceful applications for the unprecedented breakthroughs in nuclear science that the twentieth century yielded...".

Mr. Werner Burkart, IAEA Deputy Director General, and Head of the Department of Nuclear Sciences and Applications, during the panel discussion.

"...For over 40 years, the IAEA has assisted its Member States in developing and applying techniques to better understand and manage water resources. Isotope Hydrology is becoming an essential tool for national water authorities..."

Mr. Qian Jihui, the then IAEA Deputy Director General and Head of the Department of Technical Cooperation during the panel discussion.

Isotopes in large river basins: A global research initiative

Rivers constitute an important freshwater resource and are an important linkage in the global hydrological cycle, returning about 35% of continental precipitation to the oceans. Much of the world's population has relied on rivers for trade, industry, agriculture, water supplies, etc. For sustainable management of water supply, agriculture, flood-drought cycles, ecosystem and human health, there is a basic need for improving the scientific understanding of water cycling processes in river basins and the ability to detect and predict impacts of climate change on water resources.

In 2002, the Agency launched a coordinated research project on "Design criteria for a network to monitor isotope composition of runoff in large rivers" that supports sampling and isotope analysis of river discharge, and builds on complimentary monitoring of the IAEA/WMO Global Network for Isotopes in Precipitation (GNIP) operated since 1961. The project is aimed at developing and testing isotope methods for quantitative analysis of water balance and related processes, for tracing environmental changes, and ultimately for establishing an operational "Global Network for Isotopes in Rivers (GNIR)".

In recent years, many international and national hydrology research programmes have focused on large river basins. One such example, the Global Energy and Water Cycle Experiment (GEWEX) are focusing on large river basins as an appropriate and overlapping scale for study of both atmospheric and hydrological processes and modeling. GEWEX aims to provide an order of magnitude improvement in the ability to model global precipitation and evaporation as well as an accurate assessment of the sensitivity of atmospheric radiation and clouds to climate change. While GEWEX, and other international efforts have extensively explored water and energy budget methods and modeling, they have not widely employed isotope tracer techniques, due largely to lack of available isotope data for major components and fluxes of the continental hydrological cycle (including river discharge), and uncertainty regarding the capability of the approach. Improvement of isotope monitoring also supports a wide range of multidisciplinary international programmes such as the International Geosphere-Biosphere Programme's (IGBP) Food, Water and Carbon Commissions, and UNESCO's International Hydrological Programme (IHP). At the national level, initiatives such as the Water Cycle Dynamics and Prediction (WCDP) programme of U.S. Department of Energy have promoted further interest in integration of isotope tracers for characterizing variability in the hydrological cycle, as a diagnostic tool for model development, and for discriminating between natural and anthropogenic variability in the water cycle.

Isotopes of particular interest for hydrological studies include the stable isotopes of water (^{18}O, ^{2}H), and exhibit systematic variations in precipitation and various hydrological components as a result of isotope fractionations that accompany phase changes and diffusion. River discharge signatures provide insight into the basin-integrated hydroclimate forcings on water cycling such as precipitation variability (i.e. changes in condensation temperature, latitude/altitude of precipitation, air mass mixing and recycling, distance from ocean source, and seasonality) and evaporation from the river or contributing sources such as soil water, wetlands, lakes, and reservoirs. Coupled with measurement of isotopes in water sources, river discharge signatures can also provide a clearer focus on groundwater recharge/discharge processes, water balance, and snow and glacier melt water mixing. Tritium (^{3}H), has also proven to be useful for the study of river basin processes. Tritium concentrations in precipitation peaked in the 1960s in response to atmospheric nuclear weapons testing, creating an event marker that can be used to estimate water residence times. Although tritium levels have declined considerably in the past decade, recent advances have also been made to extend the usefulness of tritium by explicit measurement of the parent-daughter ratio of ^{3}H–^{3}He.

In humid basins, precipitation processes are the primary signal traced by river discharge. Spatial variations in ^{18}O in river discharge across many parts of the contiguous United States, which are strongly correlated with air mass sources, altitude, and continentality gradients, reflect progressive depletion in heavy isotope content in precipitation by fractionation during rainout and moisture recycling over the North American continent. Evidence that such precipitation input signals are not static is found from long-term isotope records of the European rivers. Pronounced seasonal variations in stable isotope content are also observed due to oscillations in mixing proportions of precipitation and shallow runoff with snow, glacial melt water and groundwater, which is also traced by the seasonality in tritium. Interannual variations in these processes reflect the inherent decadal variability of precipitation processes. Comparison of tritium in the Danube River with precipitation at Vienna reveals a stronger seasonality signal in precipitation due to the buffering effect of groundwater and glacial meltwater mixing on the river signatures. A persistent lag in tritium decay in Danube River reflects a mean basin residence time estimated to be close to 3 years with evidence of interannual variability.

Synoptic surveys along the main courses of large rivers can also be useful for estimating the contribution and mixing of tributary sources as well as influx of irrigation or wastewater return at different times during the year and can be used to gauge the progressive downstream

Large river basins being studied within the coordinated research project

River	Length (km)	Basin Area (km^2)	Climate Zone	Discharge (m^3/s)
Amazon	4327	5853804	Tropics	207682
Mississippi	4185	3202959	Temperate	19396
Parana	2748	2661392	Temperate	16936
Lena	4387	2417937	Arctic	15210
Niger	3401	2240019	Tropics	8925
Zambezi	2541	1988756	Tropics	9005
Yangtze	4734	1794243	Temperate	29583
Mackenzie	3679	1712738	Arctic	9192
Ganges	2221	1628405	Tropics	40025
St. Lawrence	3175	1266642	Temperate	15156
Indus	2382	1143101	Temperate	3332
Murray-Darling	1767	1031512	Temperate	256
Orange	1840	943577	Temperate	145
Yukon	2716	852029	Arctic	6425
Colorado	1808	807573	Temperate	21
RioGrande	2219	804791	Temperate	120
Danube	2222	788002	Temperate	6612
Columbia	1791	724025	Temperate	7570
Jordan	1068	268913	Temperate	87
Rhine	1018	165058	Temperate	2345
Yobe	—	84138	Tropics	

water loss by evaporation in arid or semi-arid regions. Mean isotope content, which is overprinted by a pronounced seasonality signal, reflects variations in the cumulative runoff ratios and evaporation regime, such that oxygen-18 is enriched by several permil above the average content in basin precipitation. In basins with substantial contributions from both evaporation and transpiration (e.g. Canadian and Scandinavian Shields) it is also possible to monitor partitioning of these fluxes in the basin integrated discharge signals. Synoptic tracer distributions, including carbon (^{13}C and ^{14}C), nitrate (^{15}N and ^{18}O), strontium, boron, sulphur, chloride, lithium and other isotopes, are also potentially useful for labeling solute and pollution sources, and for study of hydrological controls on water quality. This suggests that seasonal and longer-term isotope signals in river discharge can provide additional insight into hydrological and related biogeochemical processes in large river basins.

The research project involves the participation of 17 research groups who, in co-operation with the IAEA, have developed field programmes to collect water samples from large rivers and to perform a range of isotopic analyses. Hydrological regimes under investigation include arctic, temperate and tropical areas, the arid zone, lowland and alpine drainages, and hyporeic and endoreic drainages. Initially, the project includes monitoring of isotope signals in runoff from an integrated area equal to 22% of the continental land surface that accounts for approximately 33 % of estimated continental discharge. The common intersection of interest of the participants is application of the stable isotopes of water to trace hydrological processes and water balance. Tritium is also being applied to study selected large river basins where long-term datasets exist or where tritium concentrations in river water are found to be substantially different than present levels in local precipitation. Individual groups within the study maintain diverse special interests in understanding linkages between water and nutrient cycling, pollution sources, salinity controls and other water quality issues, as well as climate and environmental change detection, particularly where long-term data sets are available. This research project, one of several being led by the IAEA's Isotope Hydrology Section, endeavours to develop and test the application and transferability of isotope techniques in a wide range of hydrological settings over the next 5 years. This initiative will expectedly contribute to better scientific understanding of water cycling processes at the large scale, and seeks to clarify the potential value and limitations of incorporating isotope techniques in a global river network.

The Agency has recognized the need for long-term strategic planning in the application of isotope techniques to River Basin Management. The first step in this planning process took place in the form of a thematic planning meeting that included participants from Latin America, North America, Europe, Africa and Asia to formulate a long term action plan for technical cooperation in the field. Initially, the water resources management issues from the Danube, Mekong, Rio de la Plata and Nile rivers will be considered. An action plan was developed outlining the scope and possible implementation approaches for further consideration.

For further infromation, please contact: Pradeep Aggarwal at p.aggarwal@iaea.org or Jeffrey Turner at j.turner@iaea.org

Editor's note

To Receive a free copy of Water & Environment Newsletter, please write to: Isotope Hydrology Section, International Atomic Energy Agency, Wagramerstrasse 5, P.O. Box 100, A-1400, Vienna, Austria. Tel: +43-1-2600 21736, Fax:+43-1-26007

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Contributions to the newsletter are welcome. For contributions and suggestions, please contact: Kshitij Kulkarni at k.kulkarni@iaea.org

Isotopes in water and carbon cycle dynamics – the LeafNet network

The Earth's climate and its variations play an important role in controlling the global distribution and availability of water resources. Climate change due to anthropogenic influences, such as greenhouse gas emissions, and land use changes, are expected to alter water, carbon and related biogeochemical cycles. This will inevitably affect present and future climate and water resources availability.

The hydrological and carbon cycles are intricately coupled. For example, carbon exchange between the land biosphere and the atmosphere is sensitive to water availability and in contrast with prevailing assumptions, recent studies show that soil moisture, not temperature, is often the controlling parameter over the large flux of ecosystem respiration. Further, water percolation is now shown to carry significant amounts of CO_2 to depth in some ecosystems. Evapotranspiration is a major component in the energy/water budget of the land surface that is strongly dependent on ecosystem CO_2 exchange (and vice versa). Evapotranspiration is also an important, but poorly known, component in water recycling between the land surface and the atmosphere, which is strongly influenced by vegetation cover characteristics. There is, therefore, a clear need to integrate water and carbon cycle studies in ecosystem and global studies. A global-scale concerted effort that has focused mainly on the carbon sink and sources in the land biosphere has developed recently in the framework of FluxNet. This is a global network of more than 150 forest sites that continuously measure CO_2, water and energy exchange between ecosystems and the atmosphere. Studies in this network are already linked to other global-scale programmes such as the International Geosphere-Biosphere Programme (IGBP)-Global Change and Terrestrial Ecosystems (GTCE)- The Biosphere - Atmosphere Stable Isotope Network (BASIN), as well as Land-Use and Land-Cover Change (LUCC), Biospheric Aspects of Hydrological Cycle (BAHC) and International Global Atmospheric Chemistry (IGAC) and Large-Scale Atmosphere Biosphere Experiment in Amazonia (LBA). The ecosystem-scale studies provide critically needed information on the exchange of carbon between the land biosphere and the atmosphere. Notably, they also provide the means to investigate the processes that underlie changes in the ecosystem fluxes of carbon, water and energy over time and space.

Stable isotopes have much to contribute in this research and are slowly but increasingly integrated into conventional flux measurements. Specifically, one of the major limitations in understanding seasonal and inter-annual variations in biosphere-atmosphere fluxes is in partitioning the net fluxes into their gross components. The net CO_2 flux between a forest and the atmosphere reflects the effects of CO_2 uptake by photosynthesis and CO_2 release by respiration. Large evapotranspiration fluxes from an ecosystem represent a combination of canopy transpiration and soil evaporation. Measurements of concentrations alone (CO_2 or water vapour) are not sufficient to deconvolute these net fluxes into their components. It was shown in recent years that inclusion of stable isotopes measurements help overcome these limitations.

One of the more recent developments in the application of stable isotopes in ecosystem research is the use of ^{18}O in CO_2. The $^{18}O_{CO2}$ signals in atmospheric CO_2 are a powerful tool in distinguishing CO_2 fluxes from leaves (canopies) and from the soil. This is because the oxygen isotopic composition of CO_2 is strongly influenced by that of water with which it is in contact. The hydrological cycle, in turn, imposes unique isotopic labeling on soil and leaf water. Further, the water vapour flux through vegetation also carries a unique isotopic ^{18}O signal that can be traced in the atmosphere. This signal can be used to partition transpiration from soil evaporation, and to identify ecosystem contribution to regional atmospheric moisture.

In spite of the great potential there are only a few measurements of ^{18}O in ecosystem studies. Laboratories that have already specialized in stable isotope methodology made these measurements. Major gaps and uncertainties remain in the application of ^{18}O in global-scale studies. One example is the comparison of model simulation of ^{18}O discrimination of ecosystems around the world. Such modeling is considered to provide the best estimates but when compared with the available ground-based experimental data, large discrepancies are observed. For example, measurements of ^{18}O in the Amazon basin provided ^{18}O discrimination values of 18 and 20 ‰ as compared with the model simulated data for that region of 7.5 and 12.5 ‰, respectively. Clearly the models must be improved with data that are not currently available.

In advancing the ^{18}O approach it is easy to recognize other critical gaps that are needed to improve knowledge and modeling efforts. For example, leaf water is an important crossroad for ^{18}O signals. It is the source of labeling not only for ^{18}O in atmospheric CO_2 but also in atmospheric O_2 as well as in plant organic matter during photosynthesis. But most estimates of leaf water in current global models are entirely based on meteorological calculations (using the well known Craig and Gordon model). There are a very few isotopic measurements of air vapour above plant canopies, that are critical for evaluating ecosystem contributions to water recycling, and local and regional hydrological budgets. There has never been an attempt to constrain model estimates in these areas with experimental data on a large scale. While the IAEA has played a critical role in mapping precipitation water there are few data to constrain estimates of the isotopic changes while going from regional precipitation to water in ecosystem evapotranspiration, or in the surface soil layer and leaf water as well as in the air vapour above ecosystems.

Assembly of the advisory group meeting on "Isotopes in Integrated Climate System" recognized the unique position of the IAEA in advancing the use of stable isotopes in ecosystem research. The panel focused on the role of isotopes in advancing the linkage between the carbon and water cycles.

The proposed network, called LeafNet, will collect a new and unique global-scale data set on the ^{18}O content of water in the surface soil, stem, leaf and canopy air vapour. The sampling network will comprise some selected sites from the existing FluxNet consisted of more than 150 land ecosystem sites globally that can provide extensive supplementary meteorological and flux (CO_2, water and energy) data. The programme will be coordinated by the IAEA and its laboratory will serve as the central analysis laboratory together with several other cooperating laboratories. The data set will fill an important gap in extending isotopes in precipitation data to the ecosystem, soil-plant-atmosphere pathway. This, in turn, will provide the first large-scale data set needed to constrain model estimates of ^{18}O in atmospheric CO_2 (used to trace photosynthesis and respiration carbon fluxes), allow estimates of soil evaporation and plant transpiration contributions to local hydrological budgets, and assess its relationship to carbon cycling at the same locations. The proposed program, while adding new information, will well integrate with existing global scale programmes of the IGBP-GTCE-BASIN, Global Network for Isotopes in Precipitation (GNIP), LUCC, BAHC, IGAC among others.

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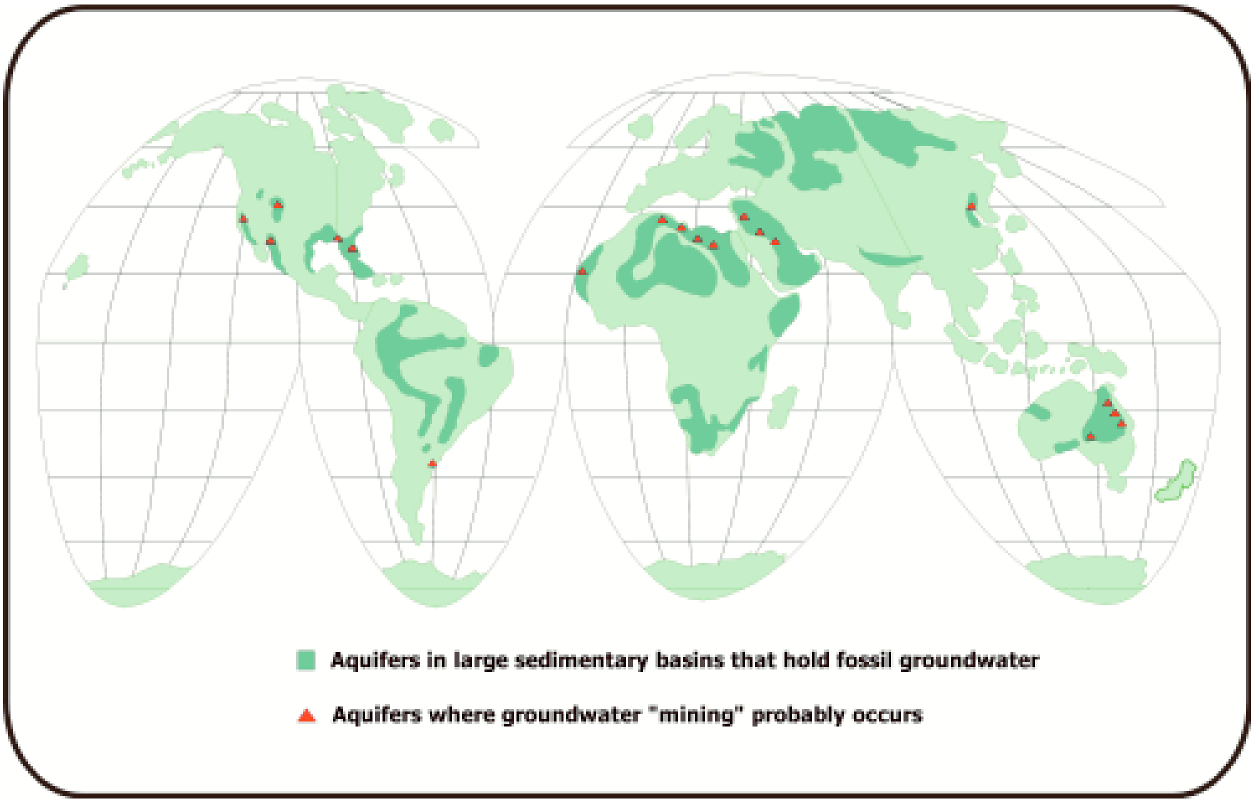
Mapping palaeowaters

Water resources in many parts of the world are severely stressed as witnessed by declining water levels. Over wide areas abstractions are exceeding natural recharge and it is apparent from scientific studies that palaeowaters are being mined in many in arid and semi-arid areas. Isotope studies have been particularly useful in understanding occurrence and origin of palaeowaters. Sufficient information from around the world now exists for the synthesis.

A new initiative has been launched by the Agency for mapping of palaeowaters in order to bring together information from various sources on the global distribution of non-renewable groundwaters in a series of maps and with supporting text. The aim is to create an understanding on the finite nature of these resources and to provide a basis for policy makers for the management of these resources.

The term "palaeowater" is used as it was introduced by isotope hydrologists in the 1960s to distinguish those groundwaters low in radiocarbon and having a strongly negative stable isotopic ($\delta^{18}O$, $\delta^{2}H$) signature indicating recharge under colder climates than present. In addition to the Pleistocene groundwaters, the term may also include groundwaters of the Holocene age, with intermediate radiocarbon activities (about 8 ka BP) and which are not part of the recent hydrological cycle. Abrupt climate changes in the mid-Holocene around 4 ka BP also led to significant changes in recharge to groundwaters in some regions. In the present project, mapping of all such groundwaters will be included.

The data collected through isotope hydrological field studies carried out within the framework of national and/or regional technical



Global distribution of fossil waters (modified from Margat, J., 1990. "Les gisements d'eau souterraine", La Recherche, No 221, 590-596.)

co-operation projects implemented by the Agency as well as those accumulated by many other organizations engaged in groundwater investigations in arid and semi-arid regions form an excellent archive and a key starting point. Compilation and incorporation of the isotope data into GIS-based digitised format will produce maps, which could be used for various purposes. The hydrogeological map of the world (WHYMAP), on 1:25,000,000 scale, is being constructed under the responsibility of the Commission of Geological Map of the World (CGMW) of the International Association of Hydrogeologists (IAH) in cooperation with UNESCO. This map, depicting large groundwater basins of the world, is thought as the base map for a GIS-based maps dealing with isotope data and other related information on the groundwater in various parts of the world. The outputs of these efforts are also expected to form valuable inputs for the international efforts to update and improve the estimates of global groundwater resources.

The programme will be co-ordinated by the Agency with the working group represented by UNESCO, IAH and other organizations. The working strategy has been evolved on presentation of simplified yet verifiable forms of maps on different scales, global and regional/ national. The initial tasks will be the selection of thematic layers for the GIS system as suggested by the working group as well as the compilation of available data. The second phase will include the build up of the comprehensive isotope database to be used in the WHYMAP system.

A global map based on the available previous data will be produced as a working map and then improved upon in due course. For the regional approach some representative areas comprising one or more countries in each of the six regions will be chosen. Complimentary to the maps will be aquifer cross-sections in representative areas and an illustrating text. Easy access to the maps is planned through an exposure over the Internet. In addition to the educational and research purpose, these maps are expected to serve the needs of policy makers at international and national levels, NGOs, media and stakeholders of all descriptions among others.

For further infromation, please contact Bill Wallin at b.wallin@iaea.org

Application of isotope technicques for sustainable development and management of shared aquifer systems

In continuation of the Agency's efforts to address water management issues in the African region, technical co-operation projects related to aquifer systems shared by several countries in Northern Africa have been initiated in collaboration with UNESCO and UNDP/GEF. These projects focus on isotope hydrological investigations of:

- Nile Basin Aquifer System shared by Democratic Republic of Congo, Egypt, Ethiopia, Kenya, Sudan, United Republic of Tanzania and Uganda.
- Nubian Aquifer System shared by Chad, Egypt, Libya and Sudan.
- North Western Sahara Aquifer system shared by Algeria, Libya and Tunisia.
- Iullemeden Aquifer System shared by Mali, Niger and Nigeria.

Isotope techniques will be employed to understand the recharge/discharge processes as well as groundwater dynamics for sustainable development and management of these aquifer systems. Successful implementation is expected to lead to a social-economic development of the region.

The Dead Sea – A challenging research opportunity

The Dead Sea, a 76 km long and 16 km wide terminal lake of Jordan River system between Israel and Jordan covering an area of 1050 km^2, occupies the lowest part of the active Syrian-African rift. The northern part is very deep, reaching at one point a depth of about 400 m. The southern bay is, on the contrary, very shallow, averaging hardly a depth of about 11 m. The formation of the Dead Sea valley dates from the late Tertiary / early Quaternary period, in which the western part of this region, owing to profound tectonic disturbance of the strata, sank far below the eastern part. Even today, this valley is still sinking by as much as 30 cm/a. On the geological time scale this is very fast.

The Dead Sea region was occupied by a sequence of lakes, whose volumes and water levels varied, throughout the history of the rift. The best-known change occurred during the transition period between the Pleistocene and the Holocene (between the Lisan Lake and the present Dead Sea). The water level at the maximal extension of the Lisan Lake was at least 230 m above that of the present Dead Sea.

The Dead Sea depression (Fig.1) is a very prominent feature. It is the lowest of all the continental depressions with the water level standing at about – 415 m (i.e. below mean sea level). This is in marked contrast to Lake Assal in the Afar Triangle at – 156 m, the Qattara Depression in northwestern Egypt at – 145 m, Death Valley in the western United States at – 86 m, the Salina Gaulicho in Argentina at – 40 m, the Caspian Sea at – 28 m, and South Australia's Lake Eyre at – 16 m. Adjacent areas to it are very arid (annual precipitation of 70 mm) and favourable for the preservation of materials like the Dead Sea Scrolls of Qumran. The runoff pattern in this region is characterized by flash floods, which occur in the large wadis during the winter months. Groundwater flows into the Dead Sea from the surrounding aquifers or through springs. Submerged springs, issuing from the Dead Sea floor, are also known to exist. Due to the recent recession of the Dead Sea shore, some of these originally submerged spring outlets are presently located above the Dead Sea water level.

Figure 1: Dead Sea region (adopted from: National geographic Society, 1995, Atlas of the world, Washington, USA)

Since the Dead Sea is lower than the land around it, no water can drain out (Fig.2). The hot desert sun evaporates the water about as fast as it flows in from the river, leaving behind salt and other minerals. The Dead Sea solution is noted not only for its high salinity of 340 g/L but mainly for its chemical composition. The Dead Sea brine is of Mg-Ca-K-Na and Cl-Br type, derived from the highly evaporated seawater of Gulf of Sedom (evaporative marine gulf of Pliocene age). This residue underwent various modifying and mixing processes, combined with multiple progressive and regressive evaporation cycles, with periodic precipitation of halite and occasionally of carnallite. The salts dissolved in the Dead Sea consist of sodium chloride, magnesium chloride, calcium chloride, potassium chloride, and magnesium bromide. The chloride of magnesium gives the water a very loathsome taste and the chloride of calcium an oily appearance. Due to the high density of the Dead Sea brine, the human body will not sink below the surface, thus people can easily float on the surface of Dead Sea. The presence of so much salt explains well the weird name of the sea, save for a few microbes, no organic life can exist in it. Any fish carried in from the Jordan River die instantly when they reach the Dead Sea.

The Dead Sea is now under dramatic environmental stress as the water that used to feed the lake is diverted for industry, agriculture and domestic use in both Israel and Jordan. Between 1930 and 1990, the water level fell an alarming 20 m. With the declining water level and increasing salinity, there was a complete overturn of the stratified waters in 1979, destroying the stratification and introducing oxygenated waters to the fossil waters in the basin depths. Since 1981 and during some periods before 1981, the yearly evaporation from the Dead Sea has exceeded the yearly precipitation and runoff, which lead to a decline of the water level of 0.8 m/a. In the same years the Dead Sea brine became saturated with respect to halite and other salts. Consequently, precipitation of halite started leaving behind a higher portion of the more soluble salts, especially MgCl of which the Dead Sea brine is particularly rich. Between 1983 and 1990 the salinity of the Dead Sea was 277 g(salts)/kg (brine) and the density of the brine was 1.2355 g (brine)/cm^3. The rate of decrease in salinity has been 0.26 g (salts)/kg (brine) per annum. The deposition of salts occurs mainly on the periphery of the lake. The deposition rate was found to be 27 g/cm^2.a.

Isotopes in the Dead Sea

Since the early 1960s, investigations of the Dead Sea and its environment benefited considerably from measurements of stable and radioactive isotopes in water of the Dead Sea, its inflow (rain, spring and river water) and adjacent groundwater.

Stable isotopes ^{2}H and ^{18}O in Dead Sea brine require special care in sample measurement and interpretation due to very high salinity. For such brines there is a remarkable difference in the measured δ values related to an activity and a concentration scale, respectively. For Dead Sea brine with a density of 1.2355 g/cm^3 (σ25 = 235.5 ‰), the difference in δ^2H is about 18 ‰ and the δ^2H concentration value is close to +9 ‰ (Fig. 3). The slope of the "evaporation line" of Dead Sea water on an activity scale, i.e. the ratio $\Delta\delta^2H_a/\Delta\delta^{18}O_a$ between the inflow water and those of the brine, is more in line with data from other lakes. For the Dead Sea prior to the 1960s this slope was found to be 5.6.

In addition to the stable isotopes of hydrogen and oxygen, stable isotopes of boron, carbon and sulphur have also been used to study a

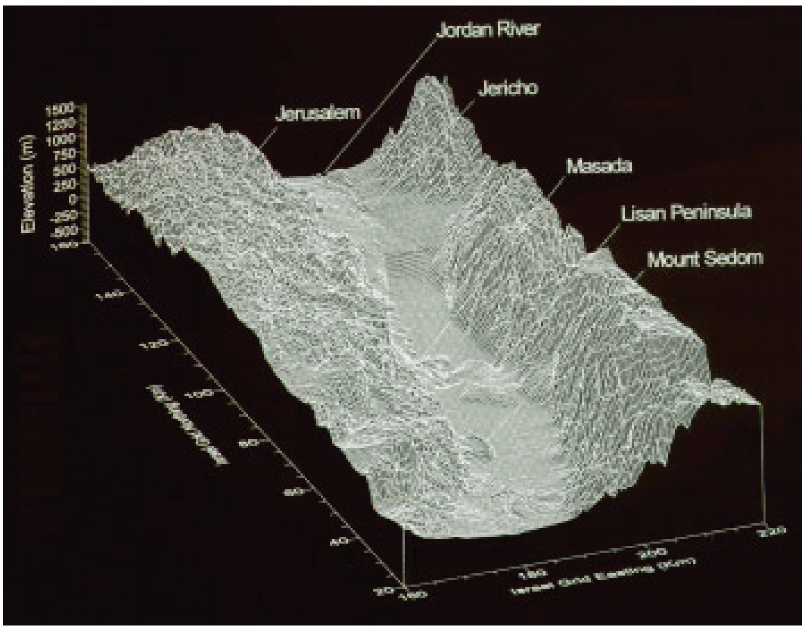


Figure 2: Three dimentional "fish-net" block diagram of the Dead Sea area, based upon the DTM data: The Dead Sea and environs, with a grid spacing of 300 x 700 m. View is toward N20°E from an elevation of 25°. (adopted from Hall, 1997)

variety of processes in the Dead Sea and its environment. These studies include the evolution of brines and associated thermal springs, isotopic input through river water, springs and precipitation, geochemical and hydrological processes in the coastal environment of the Dead Sea and biogeochemical processes in the Dead Sea ecosystem.

Radioactive isotopes such as environmental tritium, radiocarbon and ^{36}Cl have contributed to the better understanding of the history and dynamics of the lake and its environment. Radiocarbon measurements show that before the 1979 overturn the deep water in the Dead Sea was very stable and isolated (Fig.4) as also shown by tritium measurements. The lower ^{14}C concentration of deeper water before the overturn in 1979 signifies that the stable stratification must have lasted for centuries. By 1980, the deep water had lost its separate character completely, as shown by the ^{14}C content of the deep-water samples at this time. By 1990, the ^{14}C content of the then well-mixed Dead Sea had decreased by only 2 pMC, even though the atmospheric ^{14}C content had been more than 40 pMC higher than that of the Dead Sea since the beginning of the 1960s. This finding points to a rather small air-water exchange of CO_2 and to a ^{14}C-poor input from the "Salty Springs Carrier", a water carrier (established in the mid 1960s) collecting high-salinity water from springs on the northwestern shore of the Lake Kinneret and eventually disposing it in the Dead Sea. The relative proportion of this input increases with the decline of the input component represented by water released from Lake Kinneret.

^{36}Cl and ^{14}C were measured in saline groundwater of the Dead Sea area to study the chloride source and the age of the brines. The $^{36}Cl/Cl$ in the saline groundwater ranged from $(7 - 15)\cdot 10^{-15}$, the Dead Sea water average was $12.8\cdot 10^{-15}$ and halite samples from halite layers in a borehole gave an average of $10.9\cdot 10^{-15}$. The similarity among these $^{36}Cl/Cl$ ratios indicates a common chloride source and a significant contribution of chloride from rainwater. From this data it has been concluded that groundwater brines are the result of direct infiltration of brines from a precursor lake of the Dead Sea, the Lake Lisan. This lake covered the area in the past from which the groundwater samples were taken. It underwent several evaporation stages precipitating halite and infiltrating brines of varying chemical composition. The saline groundwater had a relatively low ^{14}C content (between 3.8 pMC and 26 pMC) as compared to that of fresh groundwater (50 pMC to 60 pMC) and Dead Sea brine (80 pMC). The tritium concentrations of both saline and fresh groundwater near the Dead Sea have been very

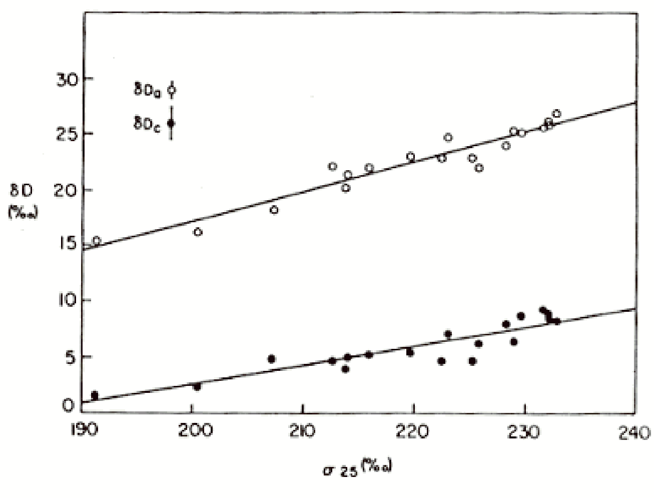


Figure 3: Plot of δ^2H (activity and concentration values) vs. salinity of the Dead Sea samples, given in units of σ_{25} ($\sigma_{25} = (\rho_{25} - 1)\cdot 10^3$, ρ_{25} being the density of the solution at a temperature of 25°C (from Horita and Gat, 1989).

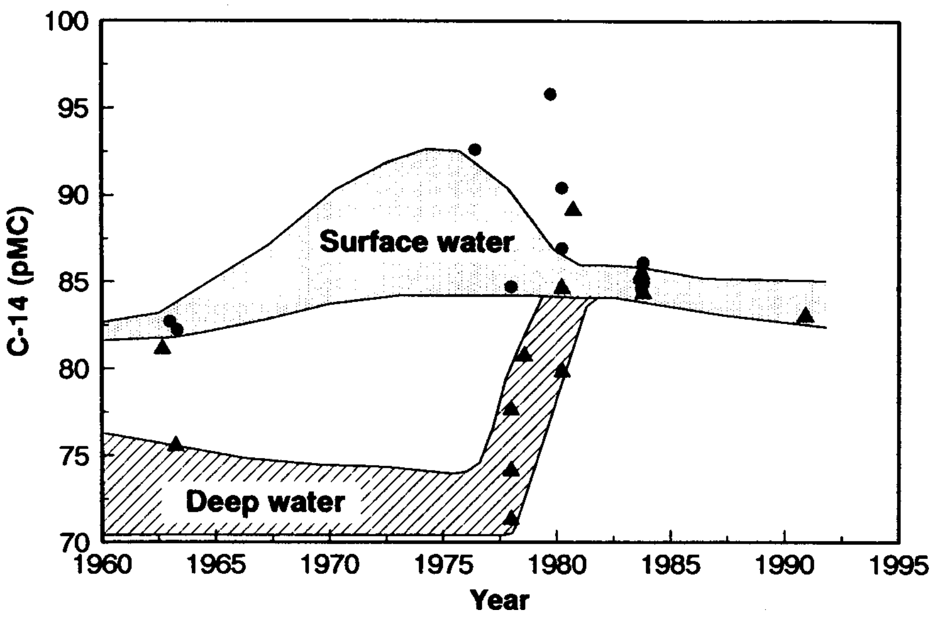


Figure 4: Plot of all ^{14}C analyses over time. Circles mark surface waters and triangle deep waters. Boundaries of the presumed change in ^{14}C of surface and deep waters with time are indicated. After 1980, surface and deep waters are within the same boundary (from Talma et al., 1997).

low in comparison to the tritium content of the Dead Sea (about 8 TU). This finding indicates that the formation of the saline groundwater by percolation of the Lake Lisan brines took place more than 9000 years ago.

Recent observations show that the water level of the Dead Sea dropped from 1995 to 2001 by further 7.5 m, reaching now 415.65 m below sea level. To avoid the drying up of the Dead Sea, Israel and Jordan started discussions on the realization of a proposal made already years ago, namely to re-rise the Dead Sea level through establishing a pipeline from the Read Sea to the Dead Sea. The project is estimated to cost about US $ 700 million. Such a project would require a detailed understanding of the Dead Sea and its environment to predict their response to a re-lifting of the water level by water of different chemical and isotopic composition. This is certainly a new challenge to the Dead Sea research including the use of isotope and geochemical approaches. The ever-changing nature of this system, one of its most fascinating features, will continue to provide challenging research opportunities.

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Groundwater in southern and eastern Africa

In March 1998, scientists and water resource managers from seven African countries met with International Atomic Energy Agency staff in Johannesburg, South Africa to explore how isotope hydrology could help them to manage their groundwater resources. Over the next three years, they used a wide range of techniques to define the potential of regionally important aquifers, assess the vulnerability of their groundwater supplies to pollution, and address other issues facing their national water authorities.

The national case studies under the regional project illustrate three broad areas – groundwater recharge, groundwater – surface water interactions, and pollutant transport – where isotopes contribute to sustainable groundwater development. Isotope data complement standard chemical and physical data on groundwater systems, tracing the origin and movement of water and solutes. Isotopes help build a deeper understanding of how groundwater has behaved in the past and help predict what may happen in years to come; a clear benefit to water resource managers and planners.

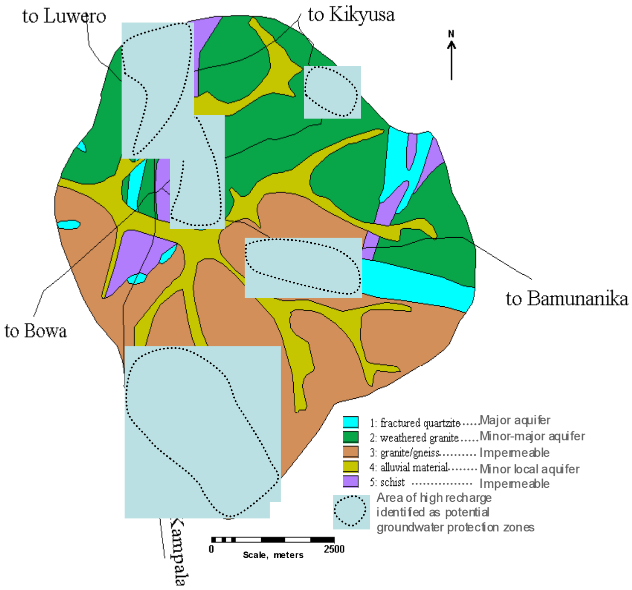
Recharge processes

Recharge represents the amount of groundwater that can be used on a sustainable basis. Isotopes can help locate important recharge areas and define long-term recharge rates. This information benefits water planners, who need to develop groundwater supply systems that meet community needs over the long term.

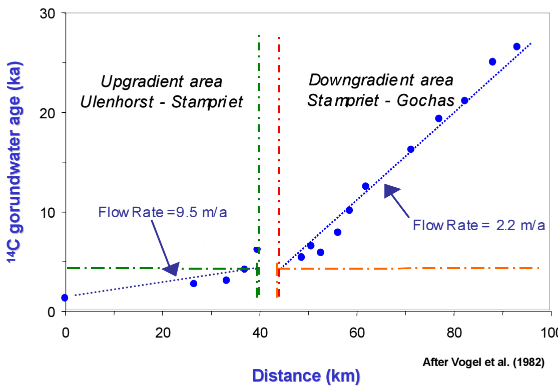
Deforestation and erosion in southern Madagascar impacts runoff, recharge, and other aspects of the hydrological cycle. Isotope data indicate where active recharge is occurring and where recharge is slower, allowing groundwater to become saline.

In unconfined fractured-rock systems, which are tapped for village water supplies in Uganda and many other parts of Africa, tritium is a good indicator of recharge. Fast recharge means more water is available, but also indicates that the water can be rapidly polluted. Project results for the Wobulenzi catchment (below) are being used to define groundwater protection areas to keep pollutants out of the water supply.

In regional confined aquifers, like the Auob aquifer in southern Namibia, radiocarbon data can be used to determine groundwater flow rates. Data from one transect (below) shows that flow



Groundwater Protection Areas, Wobulenzi Catchment, Central Uganda



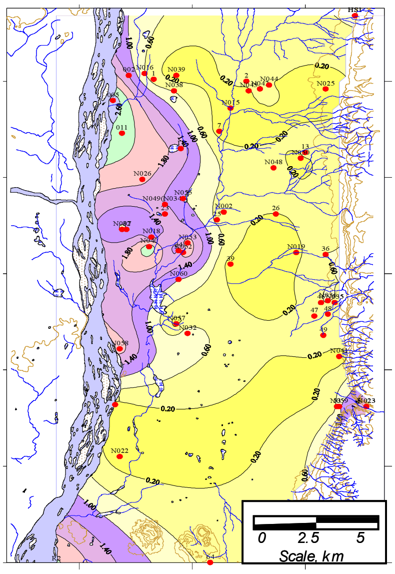
Auob groundwater age and flow rate

Managing alluvial aquifers

Conjunctive use of rivers and alluvial aquifers can help water management by storing water in floods and releasing water in dry periods. Isotopes are useful for distinguishing groundwater from river water and tracing connections between the two so that resource use can be kept in balance with supplies.

rates decrease as water moves through the aquifer. This result is an important constraint on numerical models of the aquifer that are being developed as management tools.

Isotopes often show a strong contrast between rivers and adjacent groundwater as a result of evaporation and mixing in upstream reservoirs, geographical differences in the sources of water, and differing time scales for river and groundwater flow. These isotope contrasts can be used to quantify gains or losses of river water or to track river water injected into alluvial aquifers for later use. In the Save River valley of southern Zimbabwe, project results (below) show the extent to which tritium-bearing river water (purple) has infiltrated the neighboring groundwater. More irrigation wells may be sited in this area of rapid recharge. The rest of the alluvial aquifer is slowly recharged by runoff from mountains to the east and has a low irrigation capacity.



Tritium distribution in the Save River aquifer, southern Zimbabwe

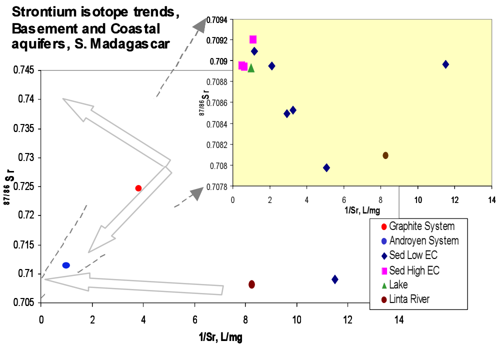
Isotope data show how the Ewaso N'giro River recharges the underlying Merti Aquifer, in the Northeastern Province of Kenya, during rare flood events such as the 1997-98 El Nino

Tracing pollutant transport

Isotopes can identify the sources of groundwater pollution so that corrective actions can be taken. ^{15}N and ^{18}O are useful in tracing nitrate contamination, a serious human health problem in many countries. Strontium isotopes trace water-rock interaction along groundwater flow paths.

Water-rock interaction is a major source of salinity in the interior basement aquifers of southern Madagascar. Strontium (Sr) isotope results (below) clearly distinguish flow paths in the different geologic formations in the Basement and Coastal areas. More detailed study of salts in the rock matrix is planned to confirm the origin of the saline groundwater.

As land use changes in southern Madagascar, organic-bound nitrate can be mineralized and released to groundwater. Isotopes can help distinguish origin of nitrate sources.



Strontium isotope trends, Basement and Coastal aquifers, Southern Madagascar

For further infromation, please contact Cheikh Gaye at c.gaye@iaea.org

News in Brief...

IAEA-UNESCO(IHP) collaboration strengthens

A Memorandum of Understanding was signed between IAEA and UNESCO to launch the Joint International Isotopes in Hydrology Programme (JIIHP) of the two agencies to facilitate the integration of isotope techniques in hydrological sciences at national levels. The steering committee set in place a work plan for 2002-2005 and initiatives were established for the implementation of training activities.

For further information please contact Jeffrey Turner at j.turner@iaea.org

Agency awards

Ms. Laurance Gourcy received the Agency's Distinguished Service Award for her outstanding performance and significant contributions to the success of the Water Resources Programme. Mr. Tanweer Ahmed from the Isotope Hydrology Laboratory received the Agency's award for long, continuous service of 30 years.

For further information please contact Laurance Gourcy at l.gourcy@iaea.org and Tanweer Ahmed at a.tanweer@iaea.org

Isotope Hydrology Laboratory activities

In 2002, more than 2,000 water samples were analysed at the Agency for stable and radioactive isotopes and water chemistry for nearly 40 technical cooperation projects and for the IAEA/WMO precipitation network, GNIP. Inter-laboratory comparisons were conducted to facilitate the improvement of the quality of isotope and chemical analyses being performed in laboratories of the Member States. A total of 82 isotope hydrology laboratories from 31 countries participated in the third stable isotope inter-laboratory comparison exercise by analysing four water samples prepared and calibrated at the Agency.

The distribution of stable isotope reference materials reached an all-time peak during 2002. About 700 units of different reference materials were supplied to more than 150 laboratories worldwide, facilitating the calibration of equipment and improving the quality of stable isotope results.

For further information please contact Manfred Groening at m.groening@iaea.org

New approach in training

A new approach focused around case studies from the participants' home countries was adopted in the provision of training of fellows from technical co-operation projects in isotope hydrology through a training course organized by the Agency at the Joanneum Research – Institute of Hydrogeology and Geothermics (JR-IHG), Graz, Austria and at the IAEA Isotope Hydrology Laboratory. The participants for this five-week training course were drawn from the on-going technical cooperation projects of the Agency. The staff members from JR-IHG and the Agency, and outside experts provided lectures and practical training. It is thought that focused courses such as this one will address the need efficiently.

It is planned to hold this training course every second year at JR-IHG, with the next one to be held in September 2004.

For further information please contact Jeffrey Turner at j.turner@iaea.org

Meetings, training courses and workshops in 2002

Agency meetings

Sustainable utilization of saline groundwater and wastelands for plant production, 20–24 January 2002, Amman, Jordan

Application of isotopic methods to understand groundwater-seawater interactions in the coastal zones, 18–24 March 2002, Sicily, Italy

Design a methodology for using isotope techniques to assess groundwater sustainability, 10–12 April 2002, Vienna

First research coordination meeting of the coordinated research project on "Design criteria for a network to monitor isotope compositions of runoff in large rivers" 13–16 May 2002, Vienna

Final project coordination meeting on sustainable development of groundwater resources, 3–5 June 2002, Vienna

First Steering Committee meeting of the IAEA/UNESCO Joint International Isotopes in Hydrology Programme (JIIHP), 17–19 June 2002, Paris, France

Strengthening of national networks for monitoring isotopes in precipitation, 11–14 September 2002, Rome, Italy

Final project assessment meeting (RCA) on isotope use in managing and protecting drinking water, 21–23 October 2002, Kuala Lumpur, Malaysia

Thematic planning meeting on the role of isotope techniques in river basin management, 2–6 December 2002, Vienna

First research coordination meeting of the coordinated research project on "Nuclear and isotopic techniques for the characterization of submarine groundwater discharge (SGD) in coastal zones", 16–19 December 2002, Vienna

Co-sponsored meetings

Kick-off workshop of the International Association of Hydrological Sciences on initiative for a Decade of Prediction in Ungauged Basins (PUB), 20–22 November 2002, Brasilia, Brazil.

International Symposium on Intensive Use of Groundwater: Challenges and Opportunities, 10–14 December 2002, in Valencia, Spain.

International XXXII IAH & VI ALHSUD Congress on Groundwater and Human Development, Mar del Plata, Argentina, 21–25 October 2002.

Training courses and workshops

Training course on application, advantages and limitation of mathematical models, 4–15 February 2002, Piura, Peru

Regional training course (National & RCA) on advanced numerical groundwater modeling for water resources management, 11–22 March 2002, Hanoi, Vietnam

Regional training course on isotope hydrology with particular emphasis on dam safety, 22–26 April 2002, Tunis, Tunisia

Regional training course on the use of methodologies of isotope hydrology, 6–31 May 2002, Rabat, Morocco

Advanced regional training course on isotope data interpretation, 9–27 Sept. 2002, Argonne, Illinois, USA

Regional training course on radiotracer techniques for geothermal reservoir management, 23–27 September 2002, Miravalles, Costa Rica

Regional training course on the use of methodologies of isotope hydrology, 23 September–11 October 2002, Uganda

Training course on isotope hydrology: principles, applications, data interpretation, field studies and laboratory techniques, 1 September–4 October 2002, Graz & Vienna, Austria

National training course on groundwater modelling using the M3 code, geostatistics and optimization of groundwater monitoring network, 11–22 November 2002, Addis Ababa, Ethiopia

National training course in groundwater field methods, 11–22 November 2002, Addis Ababa, Ethiopia

Inter-regional training course on advanced techniques in the application of isotopes and radioactive tracers to geothermal reservoir management, 24 November–7 December 2002, Morelia, Mexico

Lecture course on isotope hydrology for postgraduate course of Hohai University, December 2002, Nanjing, China

Hispano–American Course on Hydrogeology, 30 September–6 December, Montevideo, Uruguay

Workshop on Isotope Indicators, 6–8 February 2002, Rome, Italy

National workshop on isotope hydrology with particular emphasis on stable and radioactive isotopes, 17–28 March 2002, Dhaka, Bangladesh

Regional workshop on dissemination of information on use if isotopes in dam safety and sustainability, 15–19 April 2002, Daejeon, Korea

National workshop on use of isotopes as alternative techniques in dam safety & dam sustainability, 22–26 April 2002, Kuala Lumpur, Malaysia

National training workshop on isotope hydrology, 6–10 May 2002, Nairobi, Kenya

Regional Workshop on use of artificial tracers in hydrogeology, 6–17 May 2002, Quito, Ecuador

National Workshop on Monitoring Network, Bogotá, Colombia

Technical review workshop on sustainable development of groundwater resources, 27–31 May 2002, Vienna

Workshop on managing shared aquifer resources in Africa, 2–4 June 2002, Tripoli, Libya

Workshop on new strategies for integrated science approach to enhance understanding of hydrological and ecological processes across scales, 3–7 July 2002, Warsaw, Poland

Regional workshop on Hydrogeochemistry, 19–30 August 2002, Santiago del Chile, Chile

Regional training workshop on tracer demonstration technique in isotope hydrology with particular emphasis on dam safety, 14–19 October 2002, Colombo, Sri Lanka

Executive seminar for water resources managers on isotope use in managing and protecting drinking water, 24–25 October 2002, Kuala Lumpur, Malaysia

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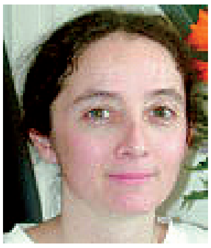

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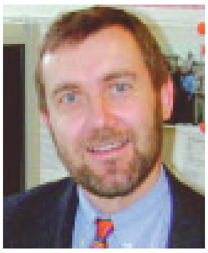

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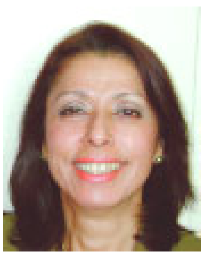

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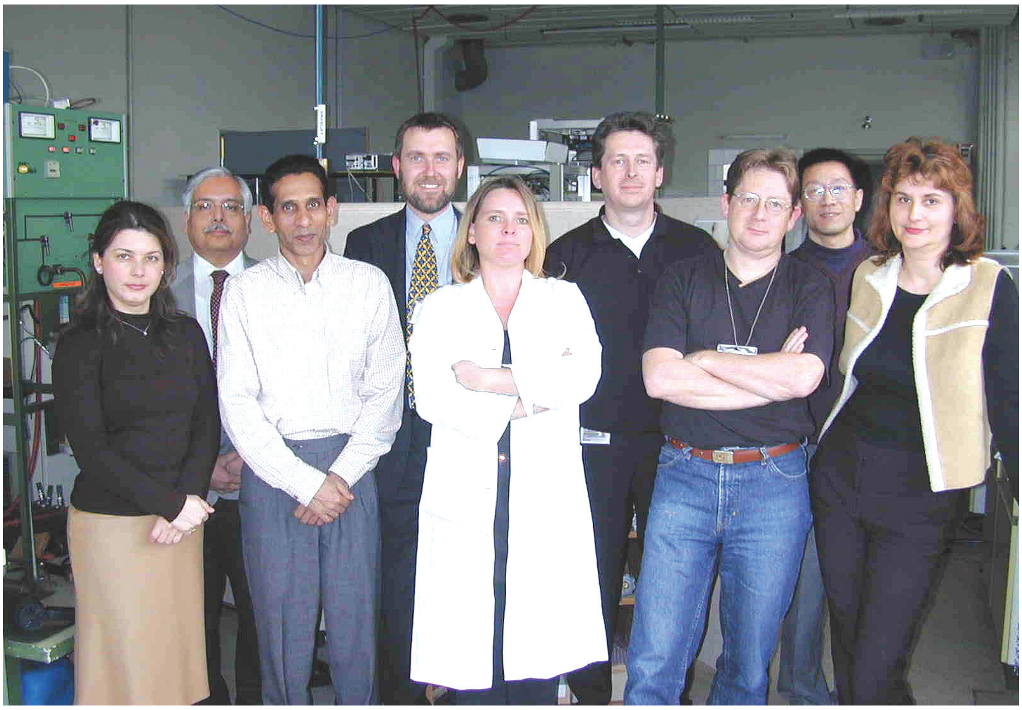

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Ongoing coordinated research projects

- Isotope response to dynamic changes in groundwater systems due to long term exploitation
- Origin of salinity and impacts on fresh groundwater resources: Optimization of isotopic techniques
- Application of isotopes to the assessment of pollutant behaviour in the unsaturated zone for groundwater protection
- Isotopic composition of precipitation in the Mediterranean Basin in relation to air circulation patterns and climate
- Nuclear and isotopic techniques for the characterization of submarine groundwater discharge (SGD) in coastal zones
- Design criteria for a network to monitor isotope compositions of runoff in large rivers

New Publications

- The Study of Environmental Change Using Isotope Techniques, C&S papers Series 13/P
- Use of Isotopes for Analyses of Flow and Transport Dynamics in Groundwater Systems, (CD-ROM)
- The Application of Isotope Techniques to the Assessment of Aquifer Systems in Major Urban Areas, IAEA-TECDOC-1298
- Radionuclide Transport Dynamics in Freshwater Resources, IAEA-TECDOC-1314

International symposium on isotope hydrology and integrated water resources management, 19 - 23 May 2003, Vienna, Austria

The Agency's symposia on the use of isotope techniques in water resources development and management have become a recurrent event held every four years. They have provided an international forum for a comprehensive review of the present state-of-the-art and recent advances made in this specific field as well as a basis for delineation of further research and development needs. This will be an 11th symposium coinciding with the International Year of Freshwater– 2003. Increasing use of isotope techniques over the past four decades, in part due to efforts of IAEA, has enhanced availability and effective use of isotopes to address water resources management issues. On this occasion, the Symposium will address the major themes of the meeting by featuring invited reviews from both pioneering scientists and contemporary experts.

The Symposium will cover a multi-disciplinary spectrum of research and applications of isotope techniques. The isotope specialists, hydrologists, hydrogeologists, geochemists, environmental scientists and water managers are expected to participate. The following themes will be covered:

- Water cycle processes in the atmosphere and hydrosphere, including surface water, groundwater, and watershed-based studies
- Age dating of young groundwaters
- Water, carbon and nutrient cycling processes at the land-ocean-atmosphere interface
- Recent advances in analytical techniques for isotope hydrology
- Field applications of isotopes in groundwater and surface water resources management

More than 150 synopses have been received by the Secretariat of the symposium. It is expected that the Symposium will stimulate the international exchange of information and ideas that will contribute to greater accessibility and enhanced use of isotope techniques in local, regional and global water resources investigations.

Technical Meetings in 2003

Assess the Use of Isotope Techniques for Evaluating Impacts of Irrigation Practices on Groundwater Quality and Quantity

Isotope Response to Dynamic Changes in Groundwater Systems due to Long Term Exploitation

Application of Isotopes to the Assessment of Pollutant Behaviour in the Unsaturated Zone for Groundwater Protection

Isotopic Composition of Precipitation in the Mediterranean Basin in Relation to Air Circulation Patterns and Climate

Origins of Salinity and Impacts on Fresh Groundwater Resources: Optimisation of Isotopic Techniques

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