Trajectory of Isotope Hydrology Programme in Bhabha Atomic Research Centre

Water Security through Isotope Techniques

K. Tirumalesh[1] and U.K. Sinha*
[1]*Isotope Hydrology Section, Isotope and Radiation Application Division*
Bhabha Atomic Research Centre (BARC), Trombay, Mumbai-400085, INDIA
E-mail for Correspondence: tirumal@barc.gov.in

Prologue

The development of the Isotope Hydrological Program (IHP) by Bhabha Atomic Research Centre (BARC), is a fascinating story of scientific innovation, linking nuclear technology to Nation's water security and growing awareness on peaceful applications of atomic energy. Since its inception, BARC has conducted a pioneering research on radioisotope applications for practical hydrological problems and later broadened its scope to include environmental isotopes. This timely expansion enabled BARC to lead numerous studies on groundwater sources, water pollution, paleoclimate, urban hydrology, transboundary aquifers (aquifer: geological formation that holds and conducts water), geothermal resources, climate change impacts and also contribute to several water programs of National interest. As India grapples with escalating water challenges, isotope hydrology is poised to remain an essential scientific tool, empowering data-driven, informed decision-making for the sustainable management and protection of the Nation's most vital resource: water. This review presents the historical evolution of BARC's IHP, its contributions to the development of isotope hydrological techniques, National programs, technical cooperation, capacity building and global partnerships. It also outlines the trajectory of current isotope hydrological research and future road map.

The concept

Isotope Hydrology is a scientific discipline that leverages natural variations in stable and radioactive isotopes in water molecules and dissolved substances to investigate the origin, movement, age, and interactions of water in the hydrological cycle. Its origin date back to the mid-20th century, when advances in mass spectrometry enabled precise measurement of isotopic ratios, particularly of stable isotopes like deuterium (^{2}H) and oxygen-18 (^{18}O) facilitating their use as tracers in hydrological studies. Concurrently, the development of techniques to measure cosmogenic radioisotopes allowed for evaluating water dynamics across various hydrological components.

Over the decades, isotope hydrology has significantly evolved, driven by progress in nuclear science, analytical chemistry, GIS–remote sensing, environmental monitoring, and atmospheric modeling. Today, isotope techniques are integral to research in frontier areas such as bioremediation, glaciology, climatology, and ecology. Furthermore, Isotope hydrology plays a crucial role in advancing several United Nations Sustainable Development Goals (SDGs) by providing essential data on the origin, age, quality, and movement of water resources. This scientific approach supports progress toward SDG 3 (Good Health & Well-Being), SDG 6 (Clean Water & Sanitation), SDG 7 (Affordable & Clean Energy), SDG 11 (Sustainable Cities & Communities), SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land), all of which are closely linked to the sustainable management and protection of water resources.

Inception

Dr. Homi J. Bhabha, the visionary behind India's Atomic Energy Programme, emphasized the peaceful applications of nuclear science in agriculture, industry, and medicine. In alignment with this vision, BARC has been instrumental in introducing nuclear techniques for societal benefits and expanding the footprints of isotope applications into water resource domain. By the early 1960s, the Isotope Division at BARC initiated the use of radioisotopes as tracers to address practical hydrological challenges. These efforts gained momentum with the commissioning of the research reactor CIRUS at Trombay, which ensured a steady supply of radioisotopes for tracer applications. Initial R&D was focused

* *Dr. Uday Kumar Sinha, Former Head of Isotope Hydrology Section, IRAD, RC&IG superannuated from service in 2023.*

Fig.1: Top Row: Field experiments carried out by senior officials of Isotope Hydrology Section, BARC. Bottom Row: Initial facilities at Isotope Hydrology Section, BARC.

on radiotracer methodologies for evaluating dam and reservoir seepage, leakage pathways, soil moisture, and sewage dispersion marking the formal introduction of isotope applications into the Indian scientific and water management landscape.

Recognizing the hydrological potential of cosmogenic radioisotopes like ^{3}H & ^{14}C, BARC established specialized facilities for low-level activity measurements. Simultaneously, the need for analyzing naturally occurring isotopes of hydrogen and oxygen became evident, given their utility in identification of water sources.

In the early 1980s, under the leadership of Dr. Vasudeva Kilara Iya, former Director of the Isotope Group, BARC and "Pitamahah of Isotopes" the environmental isotope laboratory at HIRUP, Trombay, and a low-level counting facility at the BARC hospital premises were established. These developments formally marked the inception of the IHP at BARC.

Early Research and Development

The pioneering work in isotope hydrology was carried out by Dr. Vasudeva Kilara Iya, Dr. K. Krishnamurthy, and Dr. Srikantham Malukondeshwara Rao (Dr. S.M. Rao) during 1960s and 1970s. Several radiotracer techniques were developed to address real-time hydrological challenges across India. Key applications included river flow measurements, dam seepage investigations, groundwater recharge assessments, and thermal water flow quantification.

One of the earliest studies was conducted in 1962 on the Mutha River using ^{82}Br as a tracer, demonstrating the feasibility of radioisotope-based flow measurements (CWPRS, Pune). A subsequent study on the Tapi River near Surat in 1963 confirmed the accuracy of this technique even for high discharge rates (up to 1250 m^3/s). These successful demonstrations led to applications at several critical sites, including the Ganga Canal, Uttar Pradesh (1967), Tons River in Uttar Pradesh (1969), Bhira Power Station in Maharashtra (1973), Beas River in Himachal Pradesh (1979), and Teesta River in Sikkim (1992). Radiotracers were proven to be effective in mountainous terrains where conventional methods were less suitable. Further, radiotracers were also applied to quantify the flowrates of thermal spouts in Manikaran.

Radioisotopes were also applied to locate dam seepages. A pioneering study at the Srisailam dam (Andhra Pradesh, 1967) utilized both ^{82}Br and ^{131}I to detect fissures and quantify seepage based on radiation intensity, enabling successful grouting. The next one in this caterogy was a radiotracer study at Aliyar Dam, Tamil Nadu (1967). The results from these studies allowed refinement in theoretical models using Phreatic Curves and Numerov's Equations by Krishnamurthy & Rao (1969). Additional dam investigations included Bhadra and Stupa (Karnataka, 1968), Beas-Sutlej link tunnel (Hazaribagh, 1970), Kadana (Gujarat, 1973) and Lakya (Kudremukh, 1980). Protocols for various other tracers including Indium-EDTA as activable tracer and ^{198}Au (as $HAuCl_4$) were standardized and applied to other project sites such as, Salal hydroelectric project (Jammu, 1984), Baroda Reservoir (1988), Poip and Chaskaman dams in Maharashtra. It is remarkable to note that by the year 1970, this fledging IHP of BARC had completed about 45 major hydrological investigations benefiting a wide spectrum of users and agencies across the country.

Radiotracer applications were extended to groundwater studies, particularly in arid and semi-arid regions. Initial work in the late 1960s included soil moisture experiments (Iya and Krishnamurthy, 1966). Assessment of groundwater movement for radioactive waste site evaluations in Trombay was conducted by Godse et al. (1970), which helped to distinguish between shallow and deep aquifer flows and estimated groundwater velocities.

Simultaneously, researchers at TIFR (a sister R&D Centre of DAE) undertook fundamental studies on cosmogenic radioisotopes in precipitation. Notable work included the detection of seven different isotopes such as Mg-28, Si-31, S-38, Cl-38, Cl-34m and other short lived radioisotopes in rainwater (Bhandari et al., 1966), and tritium measurements across Indian precipitation (Athavale & Lal, 1967). Groundwater dating in India using ^{3}H, ^{14}C, and ^{32}Si was pioneered by Rama et al. (1966) and Lal et al. (1970). Similarly, radon applications were explored for tracing monsoonal recharge during early 1970s.

A significant boost in radiotracer research came with the commissioning of the 100 MW DHRUVA reactor in Trombay in 1985, enhancing radioisotope production capacity. By the 1990s, radiotracer technologies had matured, becoming integral to India's water and power infrastructure.

Establishment of Isotope Hydrology Laboratory at Trombay

The advent of mass spectrometry, with its ability to measure subtle variations in stable isotopic ratios (^{2}H/^{1}H and ^{18}O/^{16}O), significantly advanced the isotope applications in hydrology. Between 1982 and 1984, BARC established an Isotope Hydrology Laboratory at HIRUP, Trombay. With support from the IAEA, two dedicated mass spectrometers (602E VG ISOGAS mass spectrometers) were installed: one equipped with CO_2–H_2O equilibration for $^{18}O/^{16}O$ analysis and the other with a reduction unit for $^{2}H/^{1}H$ measurements. Standard protocols for sample preparation, measurement, and QA/QC were formulated during this period.

Concurrently, a dedicated radioisotope laboratory was set up in the basement of BARC Hospital for environmental radioisotope analysis, specifically for tritium (^{3}H) and radiocarbon (^{14}C). The laboratory featured modules for pre- and post-distillation, low-temperature electrolysis, neutralization, CO_2 preparation line, and liquid scintillation counters. Most of these modules were designed and fabricated indigenously. Tritium measurement protocols were quickly standardized, achieving a detection limit of 0.5 TU. Protocol development for ^{14}C took longer, but by the late 1970s, radiocarbon dating of groundwater was operational. Notably, Nair et al. (1980) reported groundwater ages of up to 39,000 years. Routine analyses of ^{3}H and ^{14}C supported a wide range of studies on groundwater age dating, aquifer dynamics and groundwater sustainability.

Additionally, a high-purity germanium detector was commissioned for the measurement of ^{210}Pb and ^{137}Cs, enabling lake sedimentation rate assessments. Continuous improvements in measurement precision and accuracy were made for both stable and radioactive isotopes.

The establishment of these facilities positioned BARC as a national leader in isotope hydrology research. Many key aspects of water resources such as, tracing water sources, inter-connections among water bodies, groundwater dating, lake sedimentation, rainwater harvesting, sustainability of deep groundwater, geothermal resources, river basin studies, etc., were pursued passionately thereafter.

Addressing Hydrological Problems

A wide spectrum of field studies employing stable isotopes ($\delta^{2}H$, $\delta^{18}O$) and radioisotopes (^{3}H, ^{14}C) was carried out to develop and apply isotope techniques for addressing hydrological issues across varied geological settings in India, from mountainous regions and alluvial plains to hard rock terrains.

One of the early investigations (1985–86) assessed groundwater contributions to the Ganga River between Haridwar and Narora by monitoring $\delta^{18}O$ at eight stations over 10 months. The results enabled quantification of groundwater inflow to the river. A concurrent study (1986–88) on percolation tanks in Hinganigada (CWPRS, Pune) revealed that adjoining wells derived up to 50% of recharge from tank infiltration. In Jhamar Kotra, Udaipur, isotopes elucidated interactions among the reservoir, phosphate mine, and groundwater. In the Cauvery delta (1985), inter-aquifer connectivity was investigated.

Groundwater salinization studies using environmental isotopes were initiated in the 1980s in regions such as Minjur (north of Chennai), Midnapore (West Bengal), and Delang–Puri sector (Odisha). These investigations identified both contemporary seawater intrusion and paleo-marine influences such as Holocene marine transgressions, in addition to dissolution of marine sediments as contributors to salinization. Similar studies were conducted in Haryana and the Purna Basin (Maharashtra), with isotopic signatures indicating saline water contributions during interpluvial dry phases. In later years, groundwater salinzation in Tiruvanmiyur aquifer (Chennai) and coastal Nagapattinam region (Tamil Nadu) were investigated using isotope and hydrochemical tools. The results helped in demarcating the saline impacted zones and the potential causes for salination. Sustainability of deep aquifers in western Rajasthan was studied using a combination of injected radiotracers and environmental isotopes across Barmer (1986–87), Bikaner (1987–88), Bilara (1991–92), and Jaisalmer (1995–97). These studies provided key insights into recharge mechanisms and renewal rates of deep aquifers.

Lake and estuarine sediment cores dated using ^{210}Pb and ^{137}Cs were used to reconstruct recent environmental changes. Studies were conducted in Lake Naini (Uttar Pradesh), Lake Sasthamcotta (Kerala) and the results revealed sediment accumulation rates and the impacts of climate variability and land-use alterations on lake systems.

Combined isotope and hydrochemical studies addressed groundwater contamination issues across multiple States in India. Arsenic contamination in Murshidabad, Nadia, Midnapore and North/South 24 Parganas (West Bengal, 1996–99) and fluoride in Bagalkot (Karnataka, 2001–2003) were investigated. Isotopes helped in the identification of the sources, transport pathways, and geochemical behavior of these geogenic contaminants.

Further investigations addressed recharge dynamics in major river basins, impacts of the 2004 tsunami on coastal aquifers, effects of mining and irrigation return flows, and lithostratigraphic delineation of the Cretaceous–Tertiary boundary and impact of Deccan volcanism in Peninsular India using isotopic and rare earth element profiles.

Augmenting Isotope Toolkit

Between 2000 and 2010, significant advancements were made in expanding the isotope hydrology toolkit. Standardized sampling and analytical protocols were developed for measuring carbon-13 (^{13}C) and sulfur-34 (^{34}S) isotopes in dissolved carbonates and sulfates, respectively. The ^{13}C isotope aids in identifying the sources of dissolved inorganic carbon and is instrumental in refining radiocarbon age models. The ^{34}S isotope is useful in distinguishing between marine, terrestrial, and microbial sulfate sources.

The installation of a new isotope ratio mass spectrometer (IRMS, EUROPA GEO 2020), enabled broader multi-isotope studies and improved analytical capabilities for stable isotope applications.

In the domain of environmental radioisotopes, radon (^{222}Rn) analysis in water (Durridge RAD7) was introduced to delineate groundwater–surface water interactions, including identifying groundwater inflows into rivers, surface water recharge to aquifers, and submarine groundwater discharge (SGD) in coastal zones.

Additionally, a suite of radiotracers including ^{60}Co (as $K_3Co(CN)_6$), tritium (^{3}H as HTO), and chemical tracers such as LiBr was applied to investigate soil water movement, enhancing the understanding of vadose zone hydrodynamics and contaminant transport. Studies were conducted using radiotracers and environmental isotopes to delineate saline sources and dynamics of salt water movement at Mahim, Kalwa regions of Thane, Maharashtra. Similar integrated studies were conducted in IREL, Kerala to identify the movement of contaminated water using point dilution technique and multiple well methods.

Upscaling to Regional Studies

Beginning in 2008, isotope hydrology was extended to regional-scale applications through a pilot study on spring-shed management in the Himalayan region. For the first time in

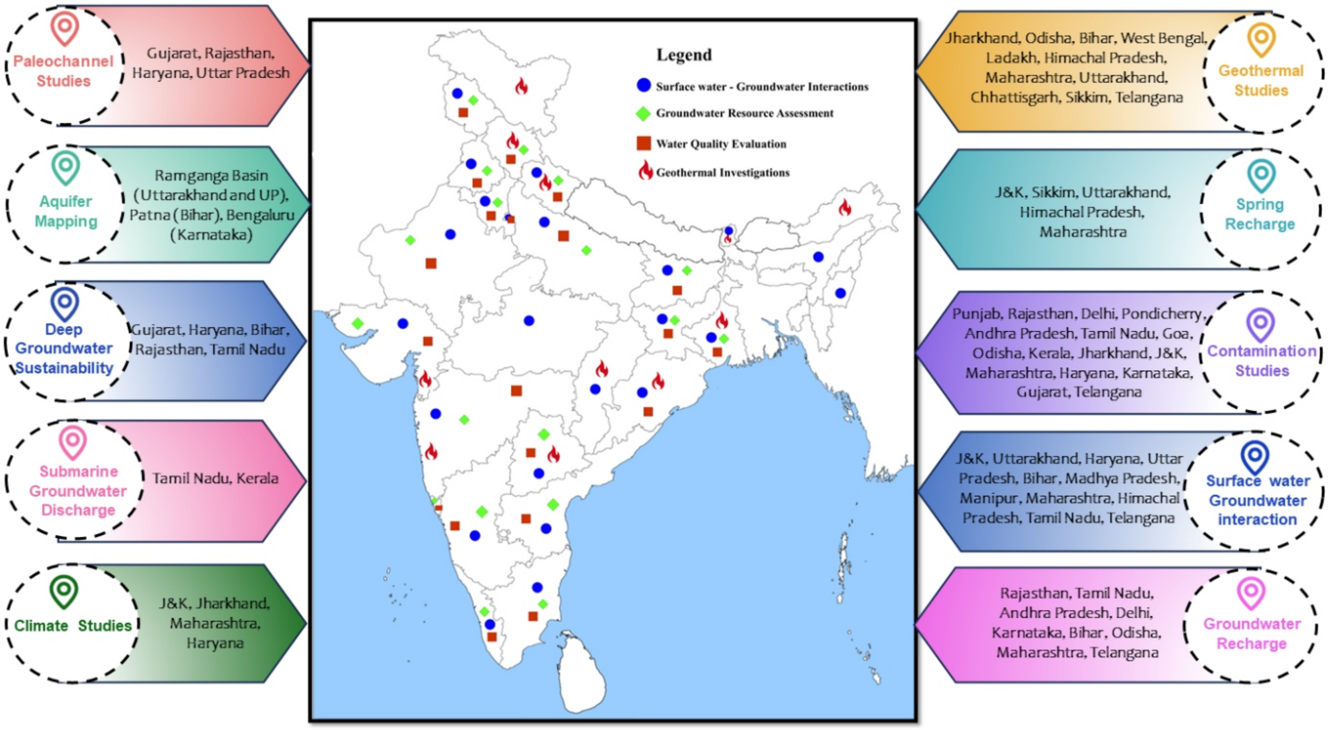

Fig.2: Footprints of Isotope Hydrological Studies conducted by BARC across India.

India, the isotope-altitude effect was employed to identify the recharge zones of drying springs in mountainous regions. The construction of artificial recharge structures at these identified altitudes led to enhanced spring discharges during dry periods. This initiative was subsequently scaled up between 2010 and 2020 across several Himalayan states, including Himachal Pradesh, Uttarakhand, Sikkim, Jammu & Kashmir, Assam, and Maharashtra. Over 100 spring systems were studied, and actionable recommendations were provided to State and Local Agencies for sustainable spring-shed development.

Submarine Groundwater Discharge (SGD) and wetland studies were also undertaken along the coastal belts of Tamil Nadu and Kerala. These studies, using isotope tracers (^{222}Rn, ^{226}Ra, ^{223}Ra, etc), quantified freshwater discharge into the marine environment and also provided insights into nutrient recycling and groundwater– seawater interactions in coastal ecosystems.

Isotope investigations were instrumental in evaluating geogenic contaminants such as arsenic, fluoride and heavy metals across various regions southwestern Punjab, central Rajasthan, deltaic Bengal, the middle Ganga Plains, industrial zones like Talcher (Odisha), Anpara thermal power plant (Sonebhadra, Uttar Pradesh), and hard-rock terrains of the Deccan Plateau. Isotopic signatures helped distinguish between anthropogenic and geogenic sources and traced the geochemical pathways and dynamics of contaminant migration.

Comprehensive studies on groundwater distribution, dynamics, and renewability were carried out in major river basins including the Ganga, Yamuna, Ghaggar (North and Northwest India), and the Cauvery and Krishna basins (South India). The aquifer mapping project in Patna (Bihar) provided critical insights into the flow dynamics, inter-aquifer connectivity, and recharge sources in a multi-tiered aquifer system. Notably, a previously unrecognized third aquifer was identified, possessing a distinct chemical and isotopic signature. This information is vital for long-term groundwater sustainability and arsenic-safe water sourcing in the Middle Ganga Plain.

Isotope and hydrochemical tools were applied to evaluate groundwater recharge mechanisms and the performance of natural and artificial recharge structures in semi-arid regions including Chitradurga (Karnataka), Nalgonda (Telangana), Ramanathapuram, Madurai (Tamil Nadu), and Buldhana (Maharashtra). These studies identified dominant recharge pathways, assessed the efficacy of recharge interventions as well as recommended sustainable actions.

As part of the Jal Shakti Abhiyan, a pilot study in Srikakulam district, Andhra Pradesh, utilized isotope-enabled End Member Mixing Analysis (EMMA approach) to identify effective recharge mechanisms in drought-prone area. The success of this study demonstrated the utility of isotope applications in groundwater management and encouraged replication in other vulnerable regions. Similar studies were extended to Nuapada district (Odisha) and Gaya district (Bihar).

A regional-scale study was also conducted across northwestern India covering parts of Himachal Pradesh, Haryana, Punjab, Rajasthan, and Gujarat to assess groundwater dynamics along paleochannels. Radiocarbon dating revealed groundwater recharge histories spanning the last 30,000 years, confirming the presence of fossil groundwater. These findings highlighted the urgent need for sustainable groundwater management in water-stressed, agriculture-intensive regions and underscored the potential of groundwater archives in reconstructing past climatic and environmental changes.

Additionally, extensive studies were conducted in India's geothermal provinces including Arunachal Pradesh (Dirang, Tserchu, Thingbu, Kipti, Sorbe), Odisha (Atri, Tarabalo, Athmalik, Taptapani), Gujarat (Lalpur, Unai, Vankiya, Lasundra, Tuwa, Dholera), Himachal Pradesh (Manikaran, Tattapani, Vashisht, Kalath, Tattapani), Ladakh (Puga, Chumathang),

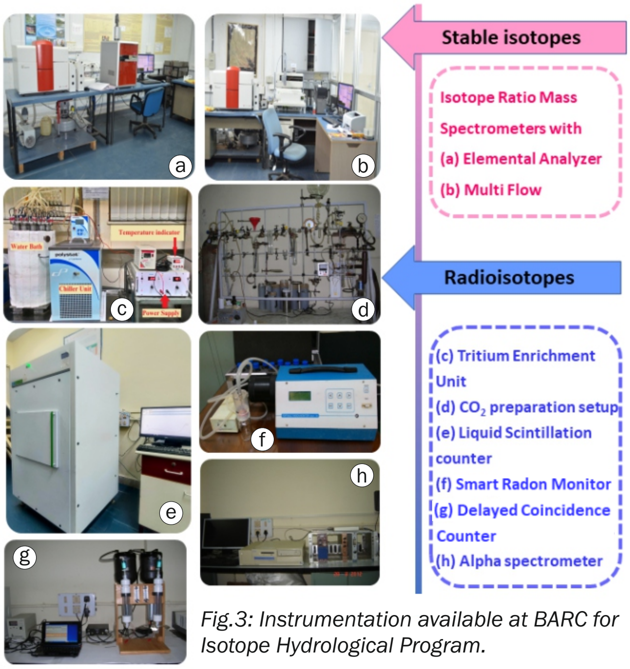

Fig.3: Instrumentation available at BARC for Isotope Hydrological Program.

Maharashtra (Tural, Rajwadi, Ganeshpuri, Vajreshwari, Akololi, Nimboli, Sativali, Koknere, Unhavare, Jalgaon, Dhule), Telangana (Manuguru, Pagaderu, Bugga), West Bengal (Bakreswar, Tantoloi) and Uttarakhand (Tapoban, Badrinath, Gaurikund) covering around 100 geothermal sites. Isotope analyses provided valuable information on the recharge timing, source characteristics, and interactions between thermal and non-thermal waters, forming the scientific basis for planning sustainable geothermal resource utilization.

Technological Advancements

Between 2015 and 2025, isotope hydrology research at BARC witnessed significant technological innovations aimed at advancing the understanding of hydrological processes across India. Emphasis was placed on developing novel isotope-based methods and computational models to address emerging water resource challenges under varying climatic and anthropogenic pressures.

A major breakthrough was the application of triple oxygen isotopologue analysis (^{16}O, ^{17}O, ^{18}O) in high-altitude atmospheric water vapor collected from the Chhota Shigri Glacier (~3800 m) using a laser isotope analyser (PICARRO, L2140-I). This state-of-the-art technique enabled differentiation between moisture sources, such as the Indian Summer Monsoon and western disturbances. Multi-tracer investigations in glacial catchments further revealed that glacier ice melt dominated streamflow during peak summer, whereas snowmelt significantly contributed during early summer and monsoon months.

The EMMA approach was developed using isotope data tailored to suit the AKRUTI program activities in water-stressed regions. Algorithms developed in MATLAB and C++ facilitated quantification of contributions from multiple water sources and enabled source apportionment of pollutants, distinguishing between sewage, industrial effluents, and agricultural runoff. This methodology provided a robust framework for informed water quality management in several remote locations of Maharashtra including Buldhana, Raigad, Ratnagiri districts. Currently isotope tools are being used to determine efficacy of Bore Blast Technique in improving groundwater recharge in arid region of Karnataka, through creating more fractures in the host rock.

The isotope toolkit was substantially expanded with the inclusion of non-conventional isotopes such as boron ($^{11/10}B$) and strontium ($^{87}Sr/^{86}Sr$) measured using Thermal Ionization Mass Spectrometry (TIMS). These isotopes proved invaluable in tracing pollution sources, deciphering water–rock interactions, and understanding the chemistry and origin of geothermal waters.

The deployment of Continuous-Flow Isotope Ratio Mass Spectrometer (CF-IRMS, Isoprime 100) enabled simultaneous determination of stable isotope ratios of carbon ($\delta^{13}C$), nitrogen ($\delta^{15}N$), and sulfur ($\delta^{34}S$) in dissolved organic matter (DOM). This analytical capability led to deeper insights into the biogeochemical cycling of nutrients, eutrophication in lakes, and fate of organic contaminants, offering an integrated approach to studying aquatic ecosystem health and anthropogenic impacts. Adding to this, introduction of Smart Radon Monitor (SRM), a technologically advanced real time, portable, radon monitor, an indigenous product of DAE has accelerated the research on groundwater-surface water interactions and sub-marine groundwater discharge studies in several parts of India.

Advances in geochemical modeling using PHREEQCi and NETPATH, combined with multivariate statistical tools such as Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA), became widely adopted during 2010-2020. These models supported the quantitative interpretation of complex geochemical processes and played a pivotal role in improving water quality assessment and management strategies.

Lumped Parameter Models (LPMs) based on tritium (^3H) data were extensively used to evaluate mean transit times (MTTs) in groundwater systems, springs, and geothermal water flows. These studies helped estimate flow dynamics and recharge rates, contributing significantly to understanding aquifer sustainability and long-term groundwater management.

Further, detailed measurements of $^{234}U/^{238}U$ activity ratios in groundwater across alluvial aquifers in Punjab and Rajasthan offered insights into uranium mobilization processes. These studies elucidated mechanisms such as dilution, leaching, mixing, recoil, and radioactive decay, which are critical for assessing factors favoring uranium mobilization into groundwater.

The integration of isotope hydrology with remote sensing and GIS tools opened a new frontier with the development of isoscapes-spatial distributions of isotopic compositions across landscapes. These isoscapes provide vital inputs for national-scale hydrological modeling, monsoon dynamics, and water balance assessments. The use of HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) model in conjunction with high-frequency rainwater isotope monitoring facilitated source tracing of atmospheric moisture and enhanced understanding of cyclonic systems and extreme hydro-meteorological events, especially along the eastern and western coasts of India.

Together, these advancements have substantially enriched the national isotope hydrology capacity, enabling comprehensive investigations of complex water systems and informing sustainable water resource management under the challenges posed by climate variability and anthropogenic stressors.

Capacity Building and Contributing to National Programs

India's diverse hydrogeological landscape from the

Fig.4: Building international collaborations through various programs.

glaciated Himalayas and peninsular hard rock terrains to expansive alluvial plains demands a multidisciplinary and region-specific approach to water resource management. Recognizing this complexity, BARC has played a pivotal role in mainstreaming isotope hydrology by fostering capacity-building and forging institutional collaborations across the country.

To facilitate pan-India adoption of isotope technologies, BARC nurtured strong partnerships with a wide range of stakeholders, including State and Central R&D institutions, water authorities, universities, and NGOs. These collaborations involved not only technical support but also financial assistance and manpower development, thereby ensuring the long-term sustainability and scalability of isotope-based investigations.

In the 1990s, premier hydrology institutes such as the NIH, Roorkee, and the CWRDM, Kozhikode, began integrating isotope techniques into their research frameworks with BARC's guidance. Over time, these institutions evolved into regional hubs for isotope hydrology, further expanding the reach of isotopic tools.

BARC, in partnership with the BRNS, DAE, supported the establishment of state-of-the-art isotope laboratories at HESCO, Dehradun, and JNU, New Delhi. These labs, equipped with Laser Isotope Analyzers and Liquid Scintillation Counters, conduct both basic and applied isotope hydrology research.

Recognizing the need for skilled human resources, BARC has been instrumental in training professionals through various academic and field-based initiatives. Two schools on "Isotope Tracer Techniques in Water Resources Development and Management" were organized at national level jointly with CWRDM under the DST-SERC scheme. Additionally, BARC has conducted numerous specialized training courses for scientists and engineers from institutions such as CGWB, offering theoretical knowledge as well as hands-on experience with isotope measurement instruments.

The successful application of isotope techniques in national programs such as the Jal Shakti Abhiyan generated widespread interest among water authorities, leading to the adoption of isotope sampling protocols by CGWB. This integration is now recognized as essential for the advancement of IHP at the national level.

BARC has also engaged extensively with academic institutions through BRNS-funded collaborative projects. These include partnerships with IITs (Kharagpur, Mumbai, Indore, Guwahati), JNU (New Delhi), IISER Kolkata, FMU (Odisha), Annamalai University (Tamil Nadu), University of Kashmir (J&K), PU (Chandigarh), NGRI (Hyderabad), and Bangalore University (Karnataka), etc. These collaborations have not only advanced scientific research but also facilitated doctoral PhDs in isotope hydrology.

Similarly, numerous NGOs (e.g., BAIF, DHAN Foundation, WaterAid, CGWS, CDD, HESCO) and R&D organizations (e.g., NDDB, MSSRF, PRL, GSI, CWPRS, IITM, NIH) have received BARC's technical guidance for implementing isotope hydrology in field investigations. State-level water departments across the country have also benefited from tailored support in the context of regional water management.

BARC's contributions have been especially valuable to several national water programs, such as, Jal Shakti Abhiyan-Supported isotope-based assessment of recharge mechanisms in water-stressed regions, Paleochannel Investigations - Helped identify and plan revival of ancient river courses to enhance shallow groundwater storage in northwestern India, NAQUIM - Provided critical data on groundwater origin, flow dynamics, and sustainability, contributing to the development of area-specific groundwater management plans and Geothermal resources evaluation - Contributed to deeper understanding of thermal water flows and their sustainability. Through these sustained efforts, BARC has not only extended the frontiers of isotope hydrology in India but also laid a strong institutional and technical foundation for its long-term application in national water security and sustainability planning.

Global Partnerships

The hydrological applications of isotopes were discussed for the first time by a panel of international experts in November 1961 in Vienna at IAEA Headquarters. Following this, several International Symposia on Isotopes in Hydrology, Soil Physics and Irrigation were conducted by FAO and IAEA, at Vienna, Istanbul and Tokyo. These early initiatives played a pivotal role in paving the way for the emergence of isotope hydrology as a robust and enduring scientific discipline. Since the inception of IHP, BARC has played a significant role in advancing global collaborations through active participation in various IAEA-coordinated initiatives. These efforts span Coordinated Research Projects (CRPs) on a wide range of hydrological themes such as arid zone hydrology, unsaturated zone dynamics, deep aquifer sustainability, urban hydrology, irrigation return flows, groundwater recharge through artificial structures among others.

BARC has consistently demonstrated leadership in the field of isotope hydrology within the Regional Cooperative Agreement (RCA) framework. Over the past two decades, it has contributed extensively to nearly all major RCA projects including RAS-8084, RAS-8097, RAS-8104, RAS-8108, RAS-7022, RAS-7030, RAS-7035, and RAS-7040. Notably, BARC is currently the lead institution for the ongoing RCA project RAS-7043, titled *"Evaluating the Efficacy of Artificial Recharge to Groundwater in Water Scarce Regions using Isotope Techniques."* This leadership role underscores BARC's technical expertise and regional commitment to sustainable groundwater management.

As a recognized regional centre for isotope hydrology, BARC regularly hosts training courses, workshops, and expert missions under IAEA programs. These capacity-building initiatives have benefited scientists and professionals from over a dozen countries in Asia and Africa, including Sri Lanka, Malaysia, Bangladesh, Vietnam, Thailand, Myanmar, the Philippines, and Ethiopia and several other countries. Through these activities, BARC has significantly contributed to enhancing technical capabilities in isotope applications for water resources in developing countries.

In addition to its collaboration with IAEA, BARC is an active contributor to global isotope data repositories such as the GNIP and GloWAL. Data provided by BARC serve as essential baselines for hydrological modeling, climate variability studies, and moisture source identification at regional and global scales. BARC also provides analytical support for measuring stable and radioactive isotopes to countries in need — such as Sri Lanka, Vietnam, Malaysia, Thailand, and Bangladesh — assisting them with data interpretation to draw meaningful conclusions.

BARC has also engaged in collaborative research with prestigious international institutions such as the USGS and the BGS under various research fellowships and knowledge exchange programs. These partnerships have facilitated enhanced scientific cooperation and advancing isotope hydrology.

Through these global partnerships, BARC continues to contribute substantially to international knowledge systems, while simultaneously bringing global best practices to bear on India's water security challenges.

Challenges

While isotope techniques offer powerful tools for hydrological investigations, several scientific, technical, and institutional challenges continue to limit their broader application in India and elsewhere.

A major constraint is the high cost and complexity of analytical instrumentation. Stable isotope analyses require advanced equipment such as Isotope Ratio Mass Spectrometers (IRMS) and Laser Spectroscopy-based Analyzers, which are expensive to procure, operate, and maintain. Techniques involving radioisotopes and non-traditional isotopes also demand specialized infrastructure and high-purity reagents, while noble gas analysis (e.g., ^{39}Ar, ^{85}Kr) is limited to only a handful of facilities worldwide due to the requirement of ultra-sensitive and high-end instrumentation such as Atom Trap Trace Analysis (ATTA) or Noble Gas Mass Spectrometers. These limitations restrict the adoption of age-dating tracers in deeper aquifers, particularly critical in arid and over-exploited regions.

Sample preparation protocols are often labor-intensive and time-consuming, requiring high technical skill and stringent quality control. The availability of trained personnel for handling such tasks remains limited, particularly at the state level and among non-specialist agencies.

There is also a pressing need for capacity building in integrating isotope data with conventional hydrological, hydrochemical, and socio-economic frameworks. Interdisciplinary training that bridges isotope hydrology with hydrological modeling, remote sensing, GIS, and water policy is essential to fully leverage the diagnostic and predictive power of isotopes for sustainable water management.

Furthermore, institutional coordination remains inconsistent across central, state, academic, and regulatory bodies. Often, valuable isotope data are underutilized due to fragmented data-sharing mechanisms, inadequate communication between research and operational agencies, and a lack of unified frameworks for incorporating isotope evidence into national-scale decision-making.

Addressing these challenges requires strategic investment in instrumentation, skill development, inter-agency collaboration, and policy-level recognition of isotope hydrology as a mainstream tool in water resource assessment and management.

Future Directions

Isotope hydrology is poised to play an increasingly pivotal role in addressing the complex water challenges of the 21st century, particularly in the context of climate variability, groundwater depletion, and sustainable development. The integration of cutting-edge technology, automation, and interdisciplinary science is expected to redefine how isotopic data are generated, interpreted, and applied.

A major thrust area will be the miniaturization and portability of isotope analytical instruments, enabling on-site field deployment and near real-time data collection. This advancement will support rapid decision-making in remote or resource-constrained regions.

Automation and AI-assisted data analytics are expected to accelerate the processing and interpretation of complex isotope datasets. Coupled with machine learning algorithms, real-time watershed monitoring and source apportionment models can be developed, allowing proactive water resource management and early warning systems for pollution and drought.

The future will also see stronger integration of isotope hydrology with remote sensing and geospatial analysis, enabling the creation of dynamic, high-resolution spatial and temporal isoscapes. These tools will support regional to national scale assessments of groundwater recharge, evapotranspiration fluxes, and ecosystem water use, critical components in climate resilience planning and nature-based solutions. Further, the use of isotope techniques in predictive modeling combining tracer-based constraints with physically based hydrological models will enhance our ability to simulate future water scenarios under different land use, climate, and socio-economic conditions. This will be particularly important for transboundary water management, groundwater sustainability, and wetland restoration.

To realize the full potential of isotope hydrology, greater policy-level uptake of scientific findings will be crucial. Mainstreaming isotope techniques into national water governance frameworks, such as aquifer mapping, river basin planning, and climate adaptation programs, can ensure that evidence-based decisions guide sustainable water management practices.

In essence, the future of isotope hydrology lies in technological innovation, data fusion, and multi-stakeholder collaboration providing actionable insights to secure water for people, ecosystems, and future generations.

Epilogue

The historical evolution of the Isotope Hydrology Program at BARC reflects its profound and enduring contribution to advancing nuclear science for sustainable water resources development and management in India. Over the past five to six decades, BARC has developed and demonstrated a wide array of isotope-based techniques, spanning environmental stable and radioisotopes, injected tracers, isotope-geochemical modeling, and isotope-geospatial integrations. These methodologies have been successfully applied to characterize surface and groundwater systems across India's highly diverse hydrogeological settings from the Himalayan Cryosphere and Alluvial Plains to the Hard Rock terrains.

Importantly, BARC has not only focused on scientific and technical innovation but has also emphasized public outreach and capacity building. The Institute has consistently worked towards demystifying isotope techniques for end users, integrating these tools into state and central agencies, and promoting community engagement. Through training, equipment support, analytical assistance, and collaboration, BARC has enabled local institutions and stakeholders to undertake isotope hydrological studies independently transforming the discipline from a niche application of nuclear science into a mainstream instrument of water governance.

As India faces mounting challenges from climate change, groundwater depletion, pollution, and increasing water demand, the relevance of isotope hydrology is expected to deepen. The next phase will focus on the development of integrated hydro-isotope models that integrate field-based isotope data with remote sensing, geospatial mapping, and socio-economic analytics. Such integrated tools will enhance predictive capability, inform adaptive management strategies, and support evidence-based policymaking.

India's scientific leadership and experience in isotope hydrology also place it in a strong position to contribute to regional and global knowledge-sharing platforms aimed at achieving water-related Sustainable Development Goals (SDG 3,6,7,11,13,14 & 15). With sustained innovation, capacity building, and policy integration, isotope hydrology is set to play a central role in securing India's water future.

Acknowledgement

Authors would like to acknowledge the immense support by present and former colleagues of Isotope Hydrology Section, Dr. Raghunath Acharya, Head, IRAD, Dr. Y.K. Bhardwaj, Associate Director, RC&I Group, Shri Vivek Bhasin, Director, BARC and Dr. Ajit Kumar Mohanty, Secretary, DAE & Chairman, AEC as well as all the collaborating institutions who supported and encouraged Isotope Hydrology Program for over over the past five decades.

Selected References in chronology (prior to 1980)

[1] Iya, V.K., Krishnamurthy, K., Aggarwal, K.S and Gokulan, P.A. "A Preliminary Radiotracer study on Canal Seepage Measurements", AEET/Isotope/10, p.16, 1966.

[2] Iya, V.K. and Krishnamurthy K. Applications of radioisotopes in the field of water studies in India. Symposium on Groundwater Studies in Arid and Semi-Arid regions, University of Roorkee and Geological Society of India, Bangalore, 1966.

[3] Eapen, A. C., and S. M. Rao. "Open channel flow measurements in India using radioisotopes." Indian Standards Institute Bulletin, 19.8, 358-361, 1967.

[4] Krishnamurthy, K, Aggarwal, K.S., Rajagopalan, R. and Gokulan, P.A., 'A Radiotracer Study on Seepage lines in Aliyar dam' BARC/Isotope 13 p. IS, I967.

[5] Iya, V.K. et al., A radiotracer study on flow path of seepage in coffer dam at Srisailam, int. jour. Applied radiation isotopes vol. 18, pp 349-357, 1967.

[6] Krishnamurthy, K., Aggarwal, K.S., Rajagopalan, R., Gokulan, P.A., A radiotracer study on seepage in Aliyar Dam, New Irrigation Er., 1968.

7. Rao, S.M., Aggarwal, K.S and Rajagopalan R. 'Seepage Studies at Bhadra dam using Radioactive Tracer'. BARC/ ISOTOPE/15 p. I6, I968.

[8] Krishnamurthy K., S M Rao, Theory and experiment in canal seepage estimation using radioisotopes, journal of hydrology, 9, pp 277-293, 1969.

[9] Godse, V. B., et al., Groundwater movement studies in radioactive waste storage site: Trombay. (1970), BARC report – 478, 14p. 1970.

[10] Rao S.M., Use of injected radioactive tracer in groundwater hydrology, proc, Indo German workshop on approaches and methodologies for development of groundwater resources, NGRI, Hyderabad pp 323-341, 1975.

[11] Nair, A.R., Navada, S.V., Rao, S.M. Isotope tracer techniques for soil moisture movement in semiarid regions Conference: Current Trends in Arid Zone Hydrology, Ahmedabad 1978.

[12] Rao, S.M. Nuclear radiation applications in hydrological investigations, Hydrology Journal (UK), 1978.

[13] Nair A.R. et al., Groundwater recharge studies in Maharashtra, development of isotope techniques and field experience in isotope hydrology IAEA, Vienna, pp 803-826, 1979.

[14] Deshpande R G, Rao S M, Jain S K, Nair A R, Proc. Workshop on Nuclear Techniques in Hydrology, NGRI, Hyderabad, pp. 211, 1980

[15] Navada, S.V. Use of indium-EDTA injected activable tracer for hydrological investigations Workshop on Nuclear Techniques in Hydrology, Hyderabad, 1980.

[16] Jain, S.K.; Navada, S.V.; Nair, A.R.; Rao, S.M. Multitracer experiments at Manali to measure discharge of River Beas Workshop on Nuclear Techniques in Hydrology, Hyderabad,1980.

Abbreviations:

AKRUTI: Advance Knowledge and Rural/Urban Technology Implementation
BAIF: Bharatiya Agro Industries Foundation (Pune, Maharashtra)
BGS: British Geological Survey
BRNS: Board of Research in Nuclear Sciences (Mumbai, Maharashtra)
CDD: Consortium for Decentralized Wastewater Treatment Systems Dissemination India (Bengaluru, Karnataka)
CGWB: Central Ground Water Board (Faridabad, Haryana)
CGWS: Centre for Ground Water Studies (Kolkata, West Bengal)
CWPRS: Central Water and Power Research Station (Pune, Maharashtra)
CWRDM: Centre for Water Resources Development and Management (Kozhikode, Kerala)
DAE: Department of Atomic Energy (Mumbai, Maharashtra)
DHAN: Development of Humane Action Foundation (Madurai, Tamil Nadu)
DWMA: District Water Management Agency (Srikakulam, Andhra Pradesh)
DWSS: Department of Water Supply & Sanitation (Chandigarh)
FMU: Fakir Mohan University (Balasore, Odisha)
GloWAL: Global Water Analysis Laboratory Network
GNIP: Global Network of Isotopes in Precipitation
GSDA: Groundwater Surveys and Development Agency (Pune, Maharashtra)
GSI: Geological Survey of India (Nagpur, Maharashtra)
HESCO: Himalayan Environmental Studies and Conservation Organization (Dehradun, Uttarakhand)
IAEA: International Atomic Energy Agency (Vienna, Austria)
IISER: Indian Institutes of Science Education and Research (Kolkata, West Bengal)
IIT: Indian Institutes of Technology
IITM: Indian Institute of Tropical Meteorology (Pune, Maharashtra)
JNU: Jawaharlal Nehru University (Delhi)
MSSRF: M. S. Swaminathan Research Foundation (Chennai, Tamil Nadu)
NAQUIM: National Aquifer Mapping Program
NDDB: National Dairy Development Board (Anand, Gujarat)
NGRI: National Geophysical Research Institute (Hyderabad, Telangana)
NIH: National Institute of Hydrology (Roorkee, Uttarakhand)
NISER: National Institute of Science Education and Research (Pune, Maharashtra)
NWRWS: Narmada, Water Resources, Water Supply & Kalpasar Department (Gujarat)
PRL: Physical Research Laboratory (Ahmedabad, Gujarat)
PU: Panjab University (Chandigarh, Punjab)
PWD: Public Works Department (Tanjore, Tamil Nadu)
SGSWRDC: State Ground and Surface Water Resources Data Centre (Taramani, Tamil Nadu)
TIFR: Tata Institute of Fundamental Research (Mumbai, Maharashtra)
TSGWD: Telangana State Ground Water Department (Hyderabad, Telangana)
USGS: United States Geological Survey