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BARC newsletter

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- Isotope Hydrology
- Radiotracer Applications
- Water Sustainability
- Global Partnerships

HARNESSING ISOTOPES FOR *Smarter Water Management*

BARC Newsletter
March-April 2025
ISSN: 0976-2108
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About the Illustrations on the Front and Back Covers

The front cover illustrates the diverse isotope hydrology activities recently undertaken by BARC, along with the state-of-the-art analytical facilities available at Trombay facility.

The back cover features photographs highlighting isotope hydrology field investigations and the initial mass spectrometer setup deployed in BARC's isotope hydrology program.

Advancing Water Security through Isotope Hydrology

Water, as a precious and finite resource, demands efficient management and conservation. India's diverse climatic and hydrological ecosystems present unique challenges in achieving sustainable water resource management, particularly in realizing SDG-6's goal of universal access to clean water and sanitation by 2030.

The Bhabha Atomic Research Centre (BARC), Department of Atomic Energy, has been championing isotope technology's benefits among rural and urban communities while fostering public participation in water resource management.

The Radiochemistry & Isotope Group (RC&IG) at BARC has developed expertise in isotope hydrology, driving directed research in nuclear and radiochemistry to address critical water challenges. Over the past decade, extensive hydrological studies/investigations have been conducted utilizing isotope techniques to *trace groundwater recharge sources and flow dynamics, identify contamination pathways and plan effective remediation approaches,* across various regions of India, yielding substantial societal benefits.

This BARC Newsletter issue focused on "Application of Isotope Techniques in Hydrology" represents a timely publication aligned with DAE's vision for water security. It covers pertinent topics, including isotope hydrology, water resources, contamination mitigation, climate change impacts and community-based water resources management.

By addressing frontline challenges and proposing science-backed solutions, it is expected that this publication will serve as a vital resource for engineers, researchers, policymakers and practitioners. It underscores the importance of isotope hydrological techniques in bridging the gap between scientific innovation and groundwater management, ensuring water security for current and future generations.

I commend the contributing authors, associate editor, and SIRD editorial team for their exceptional efforts and camaraderie in creating this thematic issue in a time-bound manner.

Dr. Y. K. Bhardwaj
Associate Director
Radiochemistry and Isotope Group
Bhabha Atomic Research Centre

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Harnessing Isotopes *for* Smarter Water Management

Water security stands as a cornerstone of sustainable development, particularly for India where rapid population growth, urbanization, and climate change exert immense pressure on freshwater resources. India's water landscape spans wide-ranging diversity from glacial-fed rivers to arid zones, from dense urban centers to remote agricultural regions embedding stark variability in water availability and demand. Managing these resources equitably requires precise scientific tools beyond conventional methods.

Isotope hydrology has emerged as a transformative approach to understanding and managing complex water systems. By measuring isotope ratios of oxygen and hydrogen in water molecules, along with nitrogen, carbon, and sulfur in dissolved salts, scientists can determine water sources, identify contaminants, and assess resource sustainability. These insights inform and contribute to targeted conservation strategies and pollution remediation efforts.

BARC's isotope hydrological programme, initiated in the 1970s, has contributed to deeper understanding of water resources across India leading to sustainable water management practices. Recent applications have expanded to evaluating groundwater resources in urban centers and water-scarce regions, determining natural aquifer recharge rates, and developing augmentation plans to prevent "zero water day" scenarios.

This thematic Newsletter focuses on **"Water Resources and Role of Isotope Technology - Global and Indian Perspective."** It presents articles that showcase important contemporary themes: water quantity and quality assessment, isotope hydrological techniques, surface-groundwater interactions, climate change impacts, global water scenarios, institutional collaborations, and policy frameworks. The article collection presents case studies and research that highlight nuclear-based techniques in water resource assessment and protection, demonstrating the synergy between scientific advancement and practical application. Each contribution comes from eminent authors with extensive practical experience in water resources and isotope hydrology.

As water conservation becomes increasingly urgent, this issue serves as a platform for knowledge exchange, capacity building, and scientific collaboration. The greater integration of isotope hydrology into national water management frameworks can empower scientists and policy makers to address India's water challenges with enhanced precision and foresight, strengthening resilience, equity, and long-term sustainability.

I trust these insights will inspire further research, innovation, and implementation pan-India water landscape. My sincere gratitude to all authors for their valuable contributions and commitment to this vital field.

Dr. K. Tirumalesh
Head, Isotope Hydrology Section
Isotope & Radiation Application Division
Radiochemistry and Isotope Group


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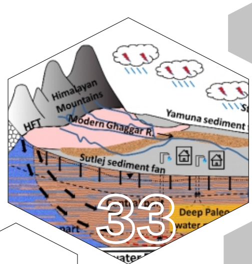
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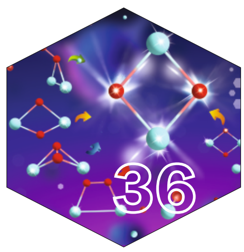
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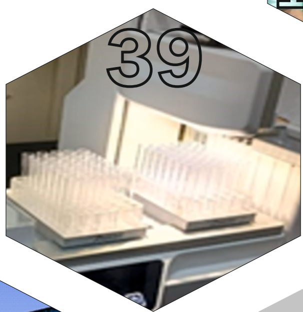
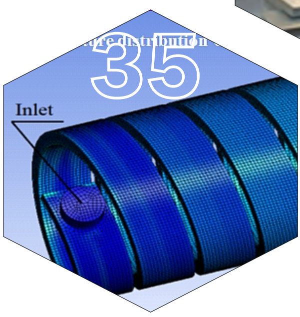
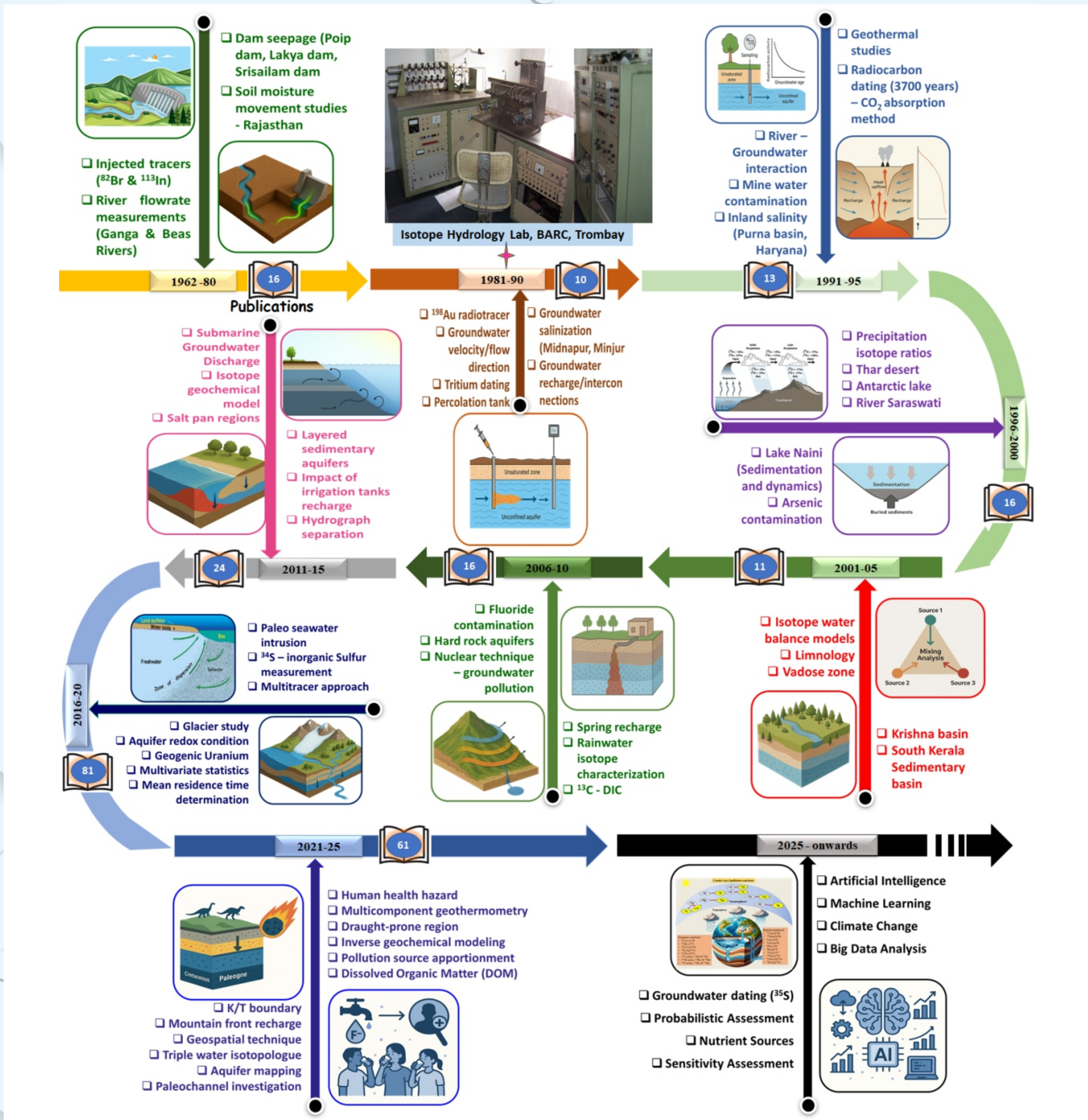




ARTICLES OF FORTHCOMING ISSUE

- New Research Highlights from BARC-TIFR Pelletron Facility & Future Developments
- Glimpses of National Technology Day 2025 program in BARC
- Proceedings of Conferences, Symposia, Workshops and Theme Meetings
- Technology Management
- News and Events
- Homage to Dr. M.R. Srinivasan, Former Chairman, AEC & Secretary, DAE

Isotope Hydrology in Atomic Energy Programme - A Journey



Infographic credits: Dr. K. Tirumalesh, Head, IHS, IRAD, RC&IG conceptualized and supervised the data presented in this infographic, with assistance from Bhumika Kumari (Senior Research Fellow, HBNI) and Shri Annadasankar Roy, Scientific Officer, IHS, IRAD, RC&IG.

Author Disclaimer: The infographic highlights major and novel isotope hydrological research activities for each time period; not all activities are included for brevity. Publications listed up to 2000 encompass symposia, conferences, workshops, and reports, sourced from online databases, BARC internal reports, and archival documents. Source: https://www.osti.gov/etdeweb, https://inis-temp.iaea.org, https://inis.iaea.org, https://doi.org/10.1007/BF02839166, ISBN 978-81-8942 2-33-2, https://doi.org/10.1007/978-94-015-7780-9_13. Publication counts are based on available records. From 2000 onward, only peer-reviewed journal articles from ScienceDirect are included. Details of publications up to 1980 are provided.

Trajectory of Isotope Hydrology Programme in Bhabha Atomic Research Centre

Water Security through Isotope Techniques

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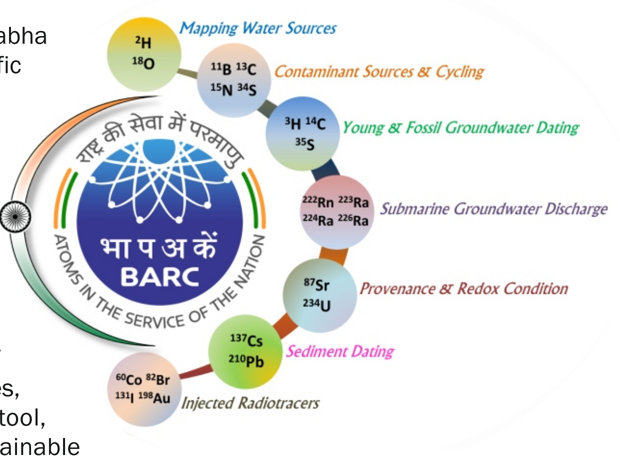
Prologue

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

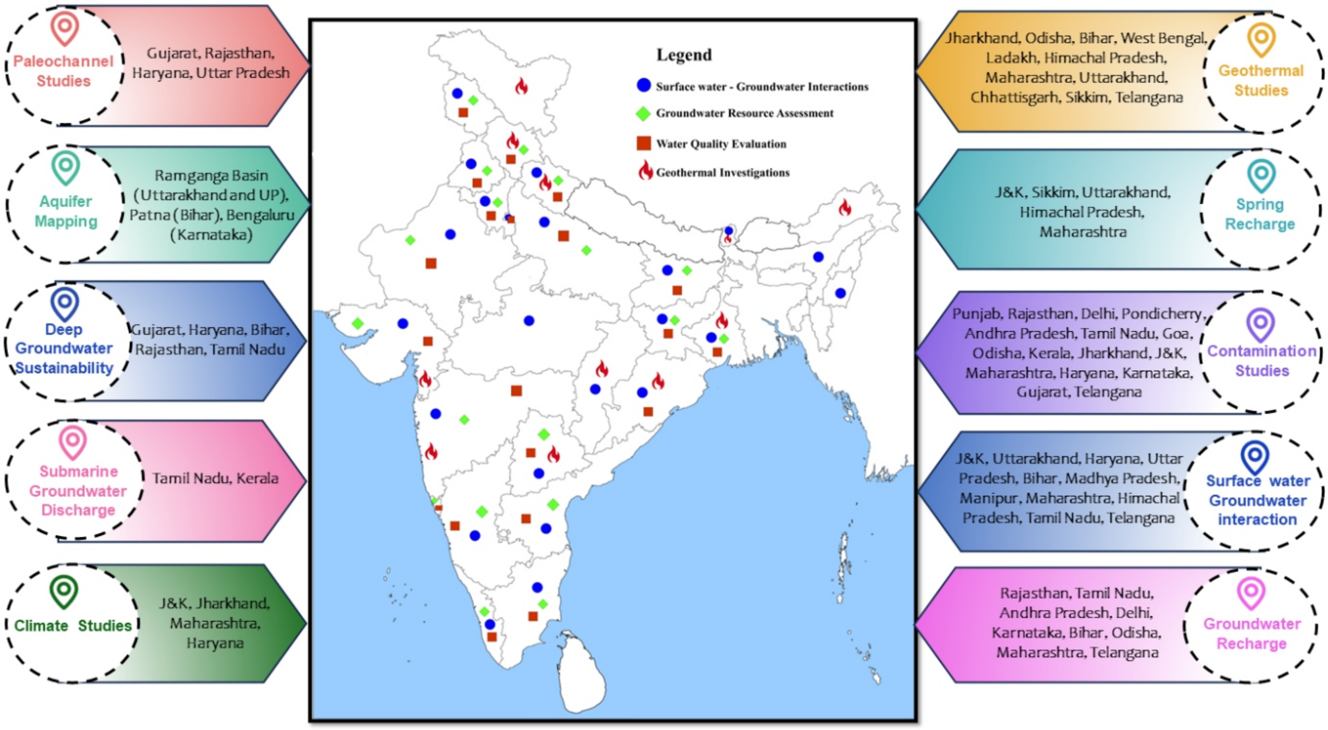


Fig.2: Footprints of Isotope Hydrological Studies conducted by BARC across India.

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),

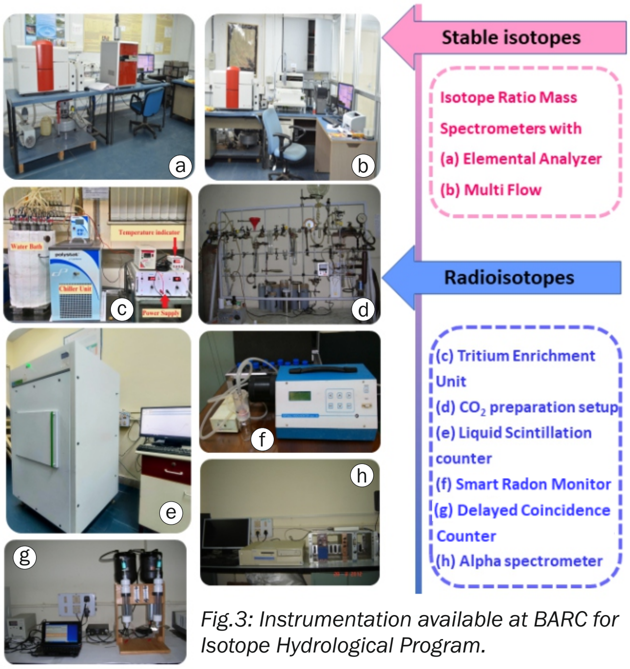


Fig.3: Instrumentation available at BARC for Isotope Hydrological Program.

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 21^{st} 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.

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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

भूजल प्रबंधन के लिए नाभिकीय तकनीक

1

पर्यावरणीय रेडियोआइसोटोप का उपयोग करके भूजल काल-निर्धारण

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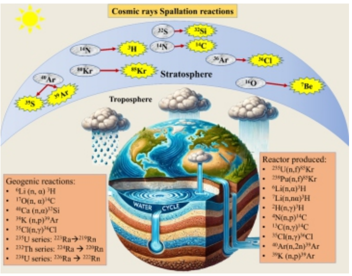

विभिन्न न्यूक्लाइडों का उत्पादन

सारांश

भूजल एक महत्वपूर्ण संसाधन है, और इसके धारणीय प्रबंधन के लिए पुनःभरण दरों, प्रवाह गतिक एवं आवासी काल की उचित समझ की आवश्यकता होती है। पर्यावरणीय रेडियोआइसोटोप महीनों से लेकर लाखों वर्षों तक विभिन्न समयमानों पर भूजल के कालनिर्धारण हेतु शक्तिशाली उपकरणों के रूप में काम करते हैं। यह लेख भूजल आयु निर्धारण में ट्रिशियम (^{3}H), क्रिप्टोन-81/85 ($^{81/85}$Kr), आर्गन-39 (^{39}Ar), सिलिकॉन-32 (^{32}Si), कार्बन-14 (^{14}C), और आयोडीन-129 (^{129}I) सहित प्रमुख रेडियोआइसोटोप के अनुप्रयोग का अन्वेषण करता है। प्रत्येक आइसोटोप भूजल के परिवर्तन में अनूठी अंतर्दृष्टि प्रदान करता है, जो आधुनिक/हाल के (महीनों से वर्षों), पुराने और जीवाश्म भूजल (सदियों से सहस्राब्दियों) के बीच अंतर को सक्षम बनाता है। कई आइसोटोप अनुरेखणों को एकीकृत करके, भूजल प्रणालियों की अधिक व्यापक समझ प्राप्त की जा सकती है, जो जल संसाधन प्रबंधन और संदूषण जोखिम मूल्यांकन में मदद कर सकती है, जो जलवायु परिवर्तन और बढ़ती वैश्विक मांग के सामने भूजल की दीर्घकालिक स्थिरता सुनिश्चित कर सकती है।

Nuclear Techniques for Groundwater Management

1

Groundwater Dating using Environmental Radioisotopes

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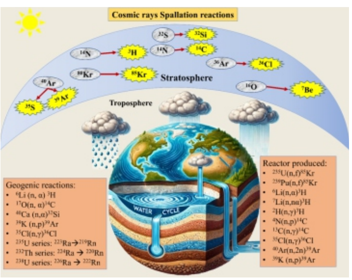

Production of various nuclides

ABSTRACT

Groundwater is a vital resource, and its sustainable management requires a proper understanding of recharge rates, flow dynamics, and residence times. Environmental radioisotopes serve as powerful tools for dating groundwater over various timescales, from months to millions of years. This article explores the application of key radioisotopes, including Tritium (^{3}H), Krypton-81/85 ($^{81/85}$Kr), Argon-39 (^{39}Ar), Silicon-32 (^{32}Si), Carbon-14 (^{14}C), and Iodine-129 (^{129}I) in groundwater age determination. Each isotope provides unique insights into groundwater movement, enabling the differentiation among modern/recent (months to years), old and fossil groundwater (centuries to millennia). By integrating multiple isotopic tracers, a more comprehensive understanding of groundwater systems can be achieved, which can help in water resource management and contamination risk assessment ensuring long-term sustainability of groundwater in the face of climate change and increasing global demand.

KEYWORDS: *Groundwater, Environmental radioisotope*

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Background

Water is fundamental to life, supporting ecosystems, biodiversity, and human civilization. However, uneven distribution, population growth, urbanization, and industrial expansion are placing immense pressure on water resources. With global demand expected to exceed supply by 40% by 2030, the risk of water scarcity is rising. Ensuring long-term availability requires sustainable management strategies, particularly in the face of climate change. A deep understanding of aquifer replenishment and residence time is essential for effective policy development. Isotopes play a key role in this process, offering valuable insights into water origins, movement, and recharge while also helping assess climate change impacts.

Radioisotopes are unstable nuclei that decay through alpha, beta, or gamma radiation at a known rate. Once introduced into a system, changes in their concentration provide valuable insights into residence time and environmental processes. Radioisotopes are produced through various natural and artificial processes, including radiogenic decay, geogenic release, cosmogenic interactions, and anthropogenic activities (Table 1). Each process contributes to the presence of radioisotopes in the environment, making them useful for groundwater dating and other scientific applications. Radiogenic produced isotopes are formed by the natural radioactive decay of long-lived parent isotopes (produced at the time of earth's formation) present in the Earth's crust. For example, Helium-4 (^{4}He) is generated from the decay of Uranium-238 (^{238}U) and Thorium-232 (^{232}Th) in rocks, gradually accumulating in groundwater. Radon-222 (^{222}Rn), a decay product of Uranium-238, is released from rocks into groundwater and is commonly used to study water flow. The other way is geogenic production of radioisotopes in the earth crust. These isotopes include Radiocarbon ($^{17}O(n,\alpha)^{14}C$), Tritium ($^{6}Li(n,\alpha)^{3}H$), Silicon-32 ($^{40}Ca(n,\alpha)^{32}Si$), Argon-39 ($^{39}K(n,p)^{39}Ar$), and Chlorine-36 ($^{35}Cl(n,\gamma)^{36}Cl$) are naturally in the Earth's crust and are mobilized into groundwater through weathering, leaching, and rock-water interactions (Fig.1). Then, there are cosmogenic produced radionuclides. High-energy cosmic rays interact with atmospheric producing radioisotopes that enter groundwater through precipitation or surface infiltration. Radiocarbon and tritium are dominantly forms in the atmosphere through the interaction of cosmic rays with nitrogen. Other cosmogenic radionuclides include Argon-39, Silicon-32, Chlorine-36, Beryllium-7, Krypton-85 and Sulphur- 35 that are used for dating groundwater on months to millennial timescales (Table 1). The radioisotopes are also added into environment through anthropogenic activities such as nuclear tests, reactor operations, and industrial processes introduce artificial radioisotopes. These include Tritium, Radiocarbon, Chlorine-36, Argon-39 and Krypton-85 (^{85}Kr). All these isotopes provide unique insights into groundwater movement, enabling the differentiation among modern/recent (months to years), old and fossil groundwater (centuries to millennia) (Fig. 2).

The information obtained using isotopic techniques enhance decision-making, improve conservation efforts, and provide a scientific foundation for sustainable water use (IAEA, 2006). Integrating isotopic analysis into hydrological studies enables governments to develop effective policies. Groundwater sustainability depends on understanding residence times to balance extraction with recharge. Determining how long groundwater has been underground helps guide water use, assess contamination risks, and ensure long-term availability.

Isotopes for Very Short Residence Time (days to months)

Understanding groundwater residence time in the range of days to months is crucial for assessing rapid recharge, contamination risks, and groundwater-surface water interactions. It helps detect pollution events, manage drinking water sources, and evaluate aquifer vulnerability. This knowledge supports sustainable water use and protects ecosystems dependent on groundwater flow (Cook & Herczeg, 2000). Radon-222 (^{222}Rn) is a naturally occurring radioactive isotope with a half-life of 3.8 days, produced from uranium-238 decay in rocks and sediments, dissolving into groundwater as it moves through uranium-bearing formations. It is measured using smart radon meter (Fig.3a). Due to its continuous generation and rapid decay, ^{222}Rn is widely used to investigate groundwater-surface water interactions, groundwater flow rates, preferential flow paths and recent recharge events. However, factors such as geological radon sources and degassing influence its effectiveness. Another short-lived isotope used is radium particularly ^{223}Ra (half-life: 11.4 days) and ^{224}Ra (half-life: 3.66 days) for understanding water-rock interactions, transport dynamics, fresh-saline water interactions, residence times, SGD, and mixing processes in aquifers (Moore, 2000). It is measured using radium delayed coincidence counter (Fig. 3b).

Sulfur-35 (^{35}S) is a short-lived radioactive isotope (half-life: 87 days) effective for dating very young groundwater, typically within weeks to a year. It is produced naturally in the

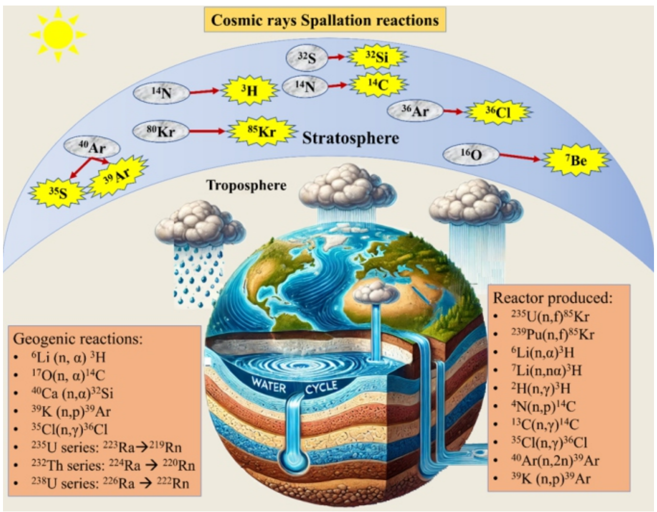

Fig.1: Production of various nuclides.

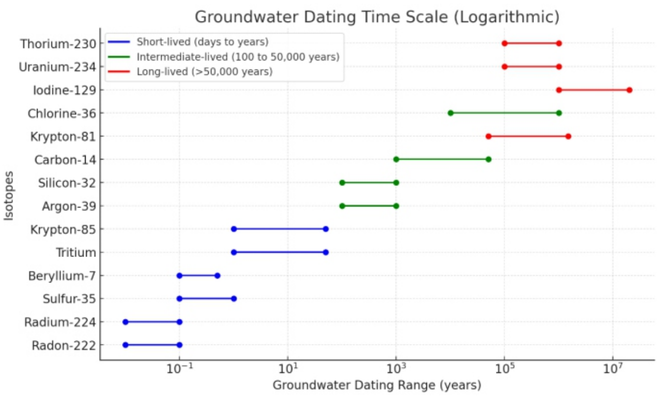

Fig.2: Logarithmic time scale of groundwater dating radionuclides, grouped by short-, intermediate-, and long-lived isotopes.

Table 1: Various radionuclides used for estimation of groundwater residence time.

Radionuclide	Natural Production & Reactions	Reactor Production & Reactions	Half-life	Decay Type	Energy (keV)	Groundwater Dating Range
Radon-222 (^{222}Rn)	Decay of Uranium -238	N/A	3.8 days	Alpha decay	5,590	Days to weeks
Radium -223 (^{223}Ra)	Decay of Uranium -235	Neutron activation: ^{222}Rn(n,γ)^{223}Ra	11.4 days	Alpha decay	5,780	Days to weeks
Radium-224 (^{224}Ra)	Decay of Thorium -232	Neutron activation: ^{223}Ra(n,γ)^{224}Ra	3.66 days	Alpha decay	5,790	Days to weeks
Sulfur-35 (^{35}S)	Cosmic-ray spallation ^{40}Ar(n,α)^{35}S	Neutron activation of Sulfur-34: ^{34}S(n,γ)^{35}S	87 days	Beta decay	167	Weeks to a year
Beryllium -7 (^{7}Be)	Cosmic-ray spallation ^{16}O (p,X)^{7} Be	Proton irradiation of Lithium: ^{7}Li(p,n)^{7}Be	53.3 days	Electron capture	477.6	Weeks to months
Tritium (^{3}H)	Cosmic-ray interaction ^{14}N(n,p)^{3}H	Fission in nuclear reactors, bomb testing	12.3 years	Beta decay	18.6	Years to 50 years
Krypton-85 (^{85}Kr)	N/A	Fission of Uranium-235/Plutonium -239	10.76 years	Beta decay	687	1 to 50 years
Argon-39 (^{39}Ar)	Cosmic-ray interaction ^{40}K(n,2n)^{39}Ar	Neutron activation of Argon-38: ^{38}Ar(n,γ)^{39}Ar	269 years	Beta decay	565	100 to 1,000 years
Silicon-32 (^{32}Si)	Cosmic-ray spallation ^{40}Ar(p,8n)^{32}Si	N/A	172 years	Beta decay	225	100 to 1,000 years
Carbon-14 (^{14}C)	Cosmic-ray interaction ^{14}N(n,p)^{14}C	Neutron activation of Nitrogen-14 in reactors	5,730 years	Beta decay	156	1,000 to 50,000 years
Krypton-81 (^{81}Kr)	Cosmic-ray spallation ^{84}Kr(n,4n) ^{81}Kr	N/A	229,000 years	Beta decay	129	50,000 to 1.5 million years
Chlorine-36 (^{36} Cl)	Cosmic-ray interaction with Argon-40 and neutron activation of Calcium-40: ^{35}Cl(n,γ)^{36} Cl, ^{40}Ca(n,α)^{36}Cl	Neutron irradiation of Chlorine-35: ^{35}Cl(n,γ)^{36}Cl	301,000 years	Beta decay	714	10,000 to 1 million years
Iodine-129 (^{129}I)	Cosmic-ray spallation of Xenon-128: ^{128}Xe(n,γ)^{129}Xe → β⁻ → ^{129}I	Neutron activation of Iodine-128 in reactors	15.7 million years	Beta decay	194	1 million+ years
Uranium-234 (^{234}U)	Decay of Uranium -238	N/A	245,500 years	Alpha decay	4,770	100,000 to 1 million years
Thorium-230 (^{230}Th)	Decay of Uranium -234	N/A	75,380 years	Alpha decay	4,686	100,000 to 1 million years

atmosphere by cosmic ray interactions and enters groundwater primarily through precipitation. It's measured after separation of dissolved sulphur followed by counting in liquid scintillation counter (Fig.3c). Because of its short half-life, ^{35}S is ideal for studying recent recharge, infiltration rates, and rapid groundwater flow in shallow aquifers (IAEA, 2013). A key application of ^{35}S is identifying seasonal recharge patterns. By measuring its concentration in groundwater, one can determine whether water has infiltrated within the past few months, helping assess aquifer replenishment and water sustainability. It is also useful for tracing contaminant movement, identifying sources and timescales of pollution transport in groundwater systems. Beryllium-7 (Be-7) is also applied in short-term groundwater dating due to its 53.3-day half-life. It is produced by cosmic-ray spallation in the atmosphere and attaches to aerosols before depositing via precipitation. Be-7 is particularly valuable in monitoring stormwater infiltration, runoff contributions, sediment transport, and erosion rates, providing insights into hydrological and environmental changes.

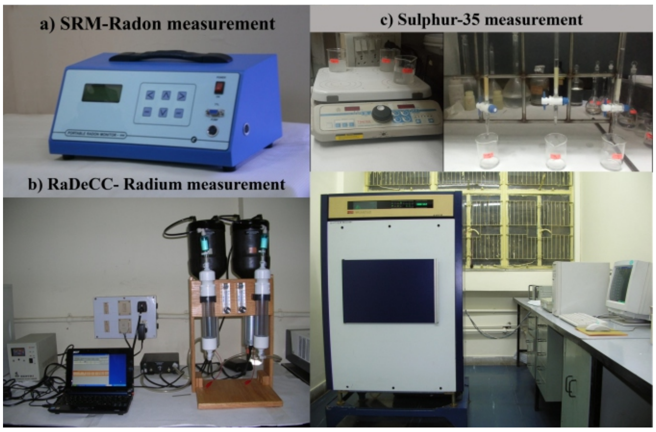

Fig.3: Measurement of isotopes for very short residence time.

Isotopes for Short Residence Time (months to few years)

Tritium (^{3}H) is a radioactive isotope of hydrogen with a half-life of approximately 12.3 years, making it a key tracer in hydrogeological studies (Cartwright & Morgenstern, 2016) for dating young groundwater within a range of years to five decades. It is naturally produced in the upper atmosphere through cosmic ray interactions and enters the hydrological cycle via precipitation. Tritium in groundwater may also be from

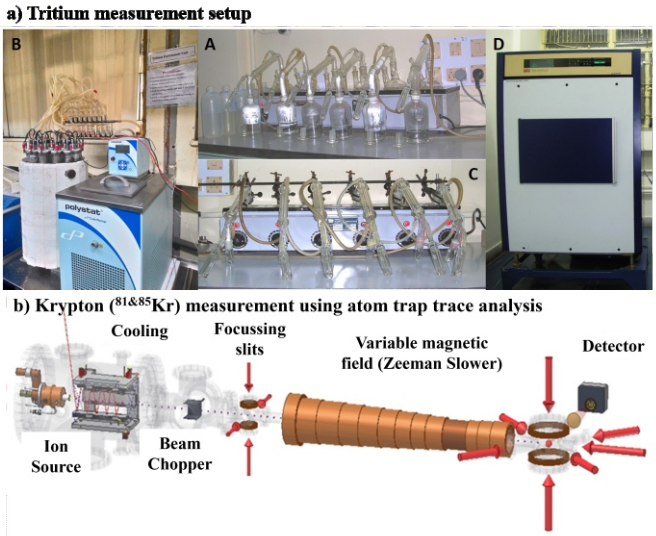

Fig.4: Measurement of isotopes for short residence time.

nuclear weapons testing and anthropogenic activities such as paint industries, nuclear reactors, and atmospheric releases. Tritium concentration in precipitation varies with latitude, geography, and time, with higher levels in the Northern Hemisphere due to more natural production at the poles. Continental precipitation generally has higher tritium concentrations than marine precipitation due to proximity to atmospheric sources and reduced dilution. Due to low natural concentrations, tritium is electrolytically enriched before measurement using a liquid scintillation counter (Fig.4a).

Tritium is particularly useful for estimating recharge rates by tracing precipitation infiltration into aquifers. It also helps track groundwater movement and mixing, providing crucial information about flow dynamics and residence times. This is especially important in aquifers where old and young waters mix due to natural hydrological processes or human activities such as pumping. Tritium enables both qualitative and quantitative groundwater dating, distinguishing modern from older water and estimating recharge times based on tritium decay, aiding hydrological and environmental studies. Models like piston flow, exponential mixing and dispersion models are used for estimating groundwater age using tritium. The piston flow model assumes groundwater moves as a discrete unit through the aquifer without mixing while exponential mixing model applies to unconfined or well-mixed systems, where older and younger water blend, resulting in a distribution of groundwater ages rather than a single value. The dispersion model accounts for flow variations, considering the effects of diffusion and mixing along the flow path. Additionally, the tritium-helium ($^3H/^3He$) method refines age estimates by measuring helium-3 produced from tritium decay, significantly improving groundwater dating accuracy (Schlosser et al., 1988).

Krypton-85 (^{85}Kr) is an inert radioactive isotope with a half-life of 10.76 years, making it a valuable tracer for dating young groundwater in the range of 1 to 50 years (Ekwurzel et al., 1994). It is an anthropogenic isotope primarily released into the atmosphere from nuclear fuel reprocessing with well-documented atmospheric concentration since the 1950s. However, measuring ^{85}Kr requires specialized noble gas mass spectrometry (Fig. 4b), making it more complex and costly.

Apart from radioisotopes, certain gases are used for residence time estimation in correlation with radioisotopes. These gases, including chlorofluorocarbons (CFCs) and sulphur hexafluoride (Sf6), serve as valuable tracers for young groundwater dating, typically within 10 to 70 years (Solomon & Cook, 2000) their atmospheric histories are well documented.

Isotopes for Intermediate Residence Time (centuries to ten thousand years)

Groundwater residence times of centuries to tens of thousands of years reveal paleoclimate conditions, recharge history, long-term flow patterns, solute transport, and water-rock interactions. They help assess fossil groundwater sustainability and natural geochemical evolution. The most suitable tracers in intermediate time range are Argon-39 (^{39}Ar), Silicon-32 (^{32}Si), and Carbon-14 (^{14}C) (Table 1). Among them, Carbon-14 is the most widely used due to its extensive applicability, well-documented production mechanisms, and established correction models for accurate age determination.

Argon-39 (^{39}Ar) is an inert radioactive isotope with a half-life of 269 years, making it particularly useful for dating groundwater within the range of 100 to 1,000 years (Loosli, 1983a). It is produced in the atmosphere through cosmic ray interactions, subsequently enters the hydrological cycle through gas exchange with the atmosphere. ^{39}Ar is present in extremely low concentrations, making its detection challenging, but the development of Atom Trap Trace Analysis (ATTA) (Fig.5a) has significantly improved detection sensitivity (Jiang et al., 2012). However, due to the technical complexity and high costs of measurement, its application in groundwater studies remains limited. Silicon-32 (^{32}Si) is a lesser-known isotope used for groundwater residence time within the 100 to 1,000-year range (Palcsu et al., 2018). It is produced in the atmosphere by cosmic ray spallation and is incorporated into the hydrological cycle via dissolved silicate minerals in precipitation. However, due to its low abundance and (Fig. 5b) difficulties, its application in groundwater studies is still in its early stages.

Carbon-14 (^{14}C) is the most widely used isotope for dating groundwater with residence times ranging from 1,000 to 50,000 years. It has a half-life of 5,730 years, making it suitable for studying long-term groundwater movement, paleoclimate conditions, and aquifer recharge dynamics (Clark & Fritz, 1997). The isotope is produced in the upper atmosphere through cosmic ray interactions forming radioactive carbon dioxide ($^{14}CO_2$), which then integrates into the biosphere and hydrological cycle through atmospheric exchange and biological activity. ^{14}C in groundwater is measured using Liquid Scintillation Counting (LSC) or Accelerator Mass Spectrometry (AMS). Measurements using LSC involves converting dissolved inorganic carbon into benzene or absorbing carbon dioxide into organic compound (Fig.5c) and detecting beta emissions, requiring large sample volumes and having lower sensitivity. AMS, in contrast, directly counts ^{14}C atoms relative to stable carbon isotopes, allowing for smaller sample sizes and higher precision. However, global variations in atmospheric ^{14}C concentration have occurred due to factors such as solar activity, geomagnetic field fluctuations, and anthropogenic influences, including fossil fuel combustion, geochemical interactions and nuclear testing. When water infiltrates the ground, it can dissolve carbonate minerals, introducing dead carbon into solution, thereby diluting the original ^{14}C activity and leading to age overestimation (Vogel, 1970). There are several correction models that address the issues like the Pearson model, Vogel model, Fontes & Garnier model etc. Additionally, mixing of old and young groundwater complicates dating, as the measured ^{14}C activity represents a composite age rather than a discrete recharge event.

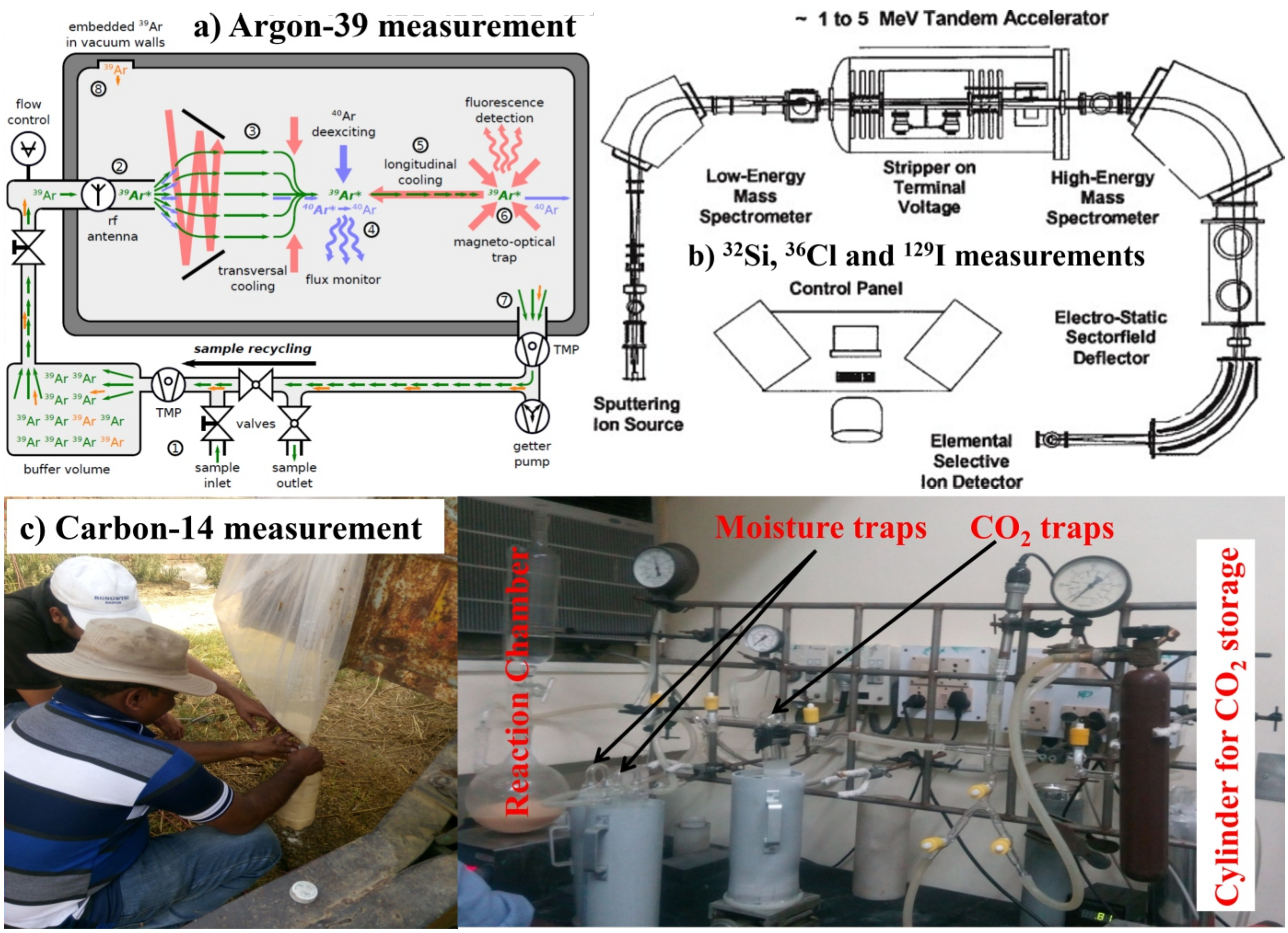

Fig.5: Measurement of isotopes for intermediate residence time.

Isotopes for Long Residence Time (ten-thousand years to million's years)

Groundwater with residence times from tens of thousands to millions of years provides insights into deep crustal fluid evolution, tectonic & geothermal processes, and long-term geochemical & aquifer stability. It supports studies of fossil water reserves and ancient water-rock interactions. Isotopes such as krypton-81 (^{81}Kr), chlorine-36 (^{36}Cl), iodine-129 (^{129}I), and uranium-series isotopes ($^{234}U/^{238}U$, $^{230}Th/^{234}U$, ^{222}Rn) are widely used. ^{81}Kr is an inert noble gas isotope produced by cosmic ray spallation, with a half-life of 229,000 years, making it ideal for dating groundwater between 50,000 and 1.5 million years (Loosli, 1983b). However, measuring ^{81}Kr is complex, requiring Atom Trap Trace Analysis (ATTA), a highly sensitive laser-based technique capable of detecting ultra-low concentrations in groundwater samples (Jiang et al., 2022; Fig.4b). Due to its low natural abundance, large sample volumes of several hundred litres are often needed, which can be challenging. Chlorine-36 (^{36}Cl), with a half-life of 301,000 years, is used to date water between 10,000 and 1 million years. Accelerator Mass Spectrometry (AMS) is the primary method for ^{36}Cl measurement, allowing detection at extremely low concentrations (Fig.5b). However, ^{36}Cl dating is complicated by subsurface production and potential mixing with younger water, leading to age uncertainties. Iodine-129 (^{129}I), with a half-life of 15.7 million years, is another useful isotope for groundwater dating beyond 1 million years, measured using AMS and is particularly valuable in systems with iodine-rich brines. However, anthropogenic sources from nuclear reprocessing and bomb testing have increased ^{129}I concentrations limiting its application for old groundwater dating. Uranium-series isotopes, including $^{234}U/^{238}U$ and $^{230}Th/^{234}U$, are used for dating water up to 1 million years (Osmond & Cowart, 1992). Their use relies on the decay of uranium and thorium isotopes in groundwater, measured using ICP-MS or alpha spectrometry. However, uranium-series dating is affected by chemical interactions with aquifer materials, which can alter isotopic ratios and introduce uncertainty in age estimates. Despite their limitations, these isotopes collectively provide crucial information for understanding long-term groundwater movement, recharge history, and the stability of deep aquifers over geological timescales. The combination of noble gas isotopes, halogens, and uranium-series isotopes enhances the accuracy of groundwater age determinations, supporting sustainable water resource management in arid and fossil aquifer systems.

Conclusion

As water scarcity and contamination become global challenges, the integration of isotope hydrology into water resource management will be essential for ensuring long-term groundwater availability and ecosystem protection. Estimating groundwater residence time helps assess recharge rates, manage water resources, and prevent overextraction. It aids in contamination risk evaluation, differentiates modern from fossil water, and informs climate change impact studies. Accurate dating supports sustainable groundwater management, ensuring long-term water availability for agriculture, industry, and human consumption. This article provides an overview on all the possible isotopes, their production, measurements, their application for dating different time ranges and limitations.

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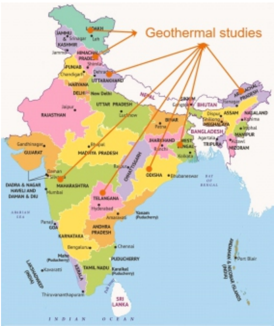
भू-तापीय अध्ययन में आइसोटोप का अनुप्रयोग

2

भारत में भू-तापीय संसाधनों की खोज में आइसोटोप तकनीक

सितांगशु चटर्जी *
आइसोटोप जल विज्ञान अनुभाग, आइसोटोप एवं विकिरण अनुप्रयोग प्रभाग, भा.प.अ. केंद्र, ट्रांबे-४०००८५, भारत



भारत के प्रमुख भू-तापीय प्रांत जहां बीएआरसी द्वारा एकीकृत समस्थानिक भू-रासायनिक जांच की गई थी

सारांश

मआइसोटोप तकनीक के अनुप्रयोग ने भारत में भू-तापीय प्रणालियों की समझ को अत्यंत प्रगत बनाया है जो तापीय जल की उत्पत्ति, विकास और धारणीयता को समझने के लिए शक्तिशाली उपकरण प्रदान करता है। स्थिर (^{2}H, ^{18}O, ^{13}C, ^{34}S, ^{11}B, ^{87}Sr) और रेडियोधर्मी (^{3}H, ^{14}C) आइसोटोप दोनों भू-तापीय जलविज्ञान में प्रमुख अनुरेखक के रूप में कार्य करते हैं, जो शोधकर्ताओं को पुनःआवेशी स्रोतों को निर्धारित करने, आवासी काल का अनुमान लगाने, मिश्रण प्रक्रियाओं का आकलन करने आदि में सक्षम बनाते हैं। भारत में सात प्रमुख भू-तापीय प्रांतों में फैले लगभग 400 तापीय स्प्रिंग हैं, जिनमें से प्रत्येक भू-क्षेत्र की दृष्टि से विविध स्थितियों में स्थित है।

ऑक्सीजन और हाइड्रोजन (δ^{18}O, δ^{2}H) के स्थायी/संतुलित आइसोटोप विश्लेषण इस बात की पुष्टि करते हैं कि भारतीय भू-तापीय जल की मुख्य रूप से उल्कामय से उत्पत्ति हुई है। ये आइसोटोप पुनःभरण ऊंचाई का अनुमान लगाने और स्थैतिक एवं गतिक भू-तापीय प्रणालियों के बीच अंतर करने में भी सहायता करते हैं। डीआईसी के कार्बन आइसोटोप अनुपात (δ^{13}C) प्रमुख अपक्षयन प्रक्रियाओं और CO_2 के स्रोतों की पहचान करने में मदद करते हैं, जबकि सल्फर (δ^{34}S) और बोरॉन (δ^{11}B) आइसोटोप विलीन विलेयों की उत्पत्ति के बारे में मूल्यवान संकेत प्रदान करते हैं और समुद्री को गैर-समुद्री प्रभावों से अलग करते हैं।

ट्रिशियम (^{3}H) और कार्बन-14 (^{14}C) जैसे रेडियोजेनिक आइसोटोप का उपयोग तापीय जल के औसत पारगमन समय (एमटीटी) का अनुमान लगाने के लिए किया जाता है जबकि ट्रिशियम हाल के पुनःभरण और लघु भूजल के साथ मिश्रण की पहचान करने में मदद करता है, ^{14}C काल-निर्धारण, विशेष रूप से सिलिकेट-होस्टेड प्रणालियों में, तनुकरण संशुद्धियों रहित गहरे और पुराने तापीय जल में आवासी काल का विश्वसनीय अनुमान प्रदान करता है। कुल मिलाकर, आइसोटोप तकनीकें भारत के भू-तापीय अनुसंधान में अपरिहार्य उपकरणों के रूप में उभरी हैं, जो धारणीय विकास और भू-तापीय संसाधनों के उपयोग के लिए मजबूत ढांचा प्रदान करती हैं।

Application of Isotopes in Geothermal Studies

2

Isotope Techniques in Exploring Geothermal Resources in India

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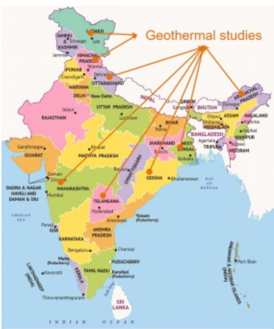

Major geothermal provinces in India where integrated isotope geochemical investigations were conducted by BARC

ABSTRACT

The application of isotope techniques has significantly advanced the understanding of geothermal systems in India, offering powerful tools for deciphering the origin, evolution, and sustainability of thermal waters. Both stable (^{2}H, ^{18}O, ^{13}C, ^{34}S, ^{11}B, ^{87}Sr) and radioactive (^{3}H, ^{14}C) isotopes serve as key tracers in geothermal hydrology, enabling researchers to determine recharge sources, estimate residence times, assess mixing processes etc. India hosts nearly 400 thermal springs distributed across seven major geothermal provinces, each situated in geotectonically diverse settings.

Stable isotope analyses of oxygen and hydrogen (δ^{18}O, δ^{2}H) confirm that Indian geothermal waters are predominantly meteoric in origin. These isotopes also aid in estimating recharge altitudes and differentiating between static and dynamic geothermal systems. Carbon isotope ratios (δ^{13}C) of dissolved inorganic carbon (DIC) help to identify dominant weathering processes and sources of CO_2, while sulfur (δ^{34}S) and boron (δ^{11}B) isotopes provide valuable clues regarding the origin of dissolved solutes and distinguish marine from non-marine sources.

Radiogenic isotopes like tritium (^{3}H) and carbon-14 (^{14}C) are used to estimate the mean transit time (MTT) of thermal waters. While tritium helps in identifying recent recharge and mixing with younger groundwater, ^{14}C dating, especially in silicate-hosted systems, provides reliable estimates of residence time in deeper and older thermal waters without requiring dilution corrections.

Overall, isotope techniques have emerged as indispensable tools in India's geothermal research, offering robust frameworks for sustainable development and utilization of geothermal resources.

KEYWORDS: *India, Thermal waters, Stable isotopes, Radioisotopes*

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Introduction

Isotopes (both stable and radioactive) play a fundamental role in geothermal studies, providing invaluable information regarding the origin, evolution, and sustainability of geothermal resources [1,2,3]. The application of isotope techniques enables researchers to trace fluid movement, determine the age of geothermal waters, assess reservoir characteristics, and identify interactions between different water sources. The various isotopes that are commonly used in geothermal exploration include ^{2}H, ^{18}O, ^{13}C, ^{87}Sr, ^{11}B, ^{34}S, ^{3}H and ^{14}C etc. Stable isotopes of oxygen ($^{18}O/^{16}O$) and hydrogen ($^{2}H/^{1}H$) provide valuable insights into the recharge mechanisms, identify mixing processes between thermal and non-thermal groundwater, and help to quantify isotopic fractionation associated with phase changes such as evaporation and boiling. The carbon isotopic ratio ($^{13}C/^{12}C$) of the dissolved inorganic carbon (DIC) indicates the source of dissolved carbon. Sulfur-34 (^{34}S) and oxygen-18 (^{18}O) of dissolved sulfate (SO^{4}) are very useful to trace the origin of salinity, while the boron isotopic ratio ($^{11}B/^{10}B$) helps to identify the source of dissolved boron. Additionally, strontium isotopes ($^{87}Sr/^{86}Sr$) provide better constraints on the nature of reservoir rocks with which thermal water interacts. Among various radiogenic environmental isotopes, tritium (^{3}H) serves as a dating tool for relatively modern thermal waters, while carbon-14 (^{14}C) is used to compute the mean transit time of the older geothermal waters.

India hosts nearly 400 thermal springs distributed across seven major geothermal provinces: the Himalayan region, West Coast region, Son-Narmada-Tapi (SONATA) region, Cambay region, Godavari Valley region, Mahanadi region, and Sohana region, each characterized by distinct geotectonic settings. Comprehensive isotope geochemical studies have been carried out in several states including Arunachal Pradesh, Uttarakhand, Maharashtra, Gujarat, Odisha, Himachal Pradesh, Telangana, West Bengal etc. to evaluate the sources and dynamics of geothermal waters for planning sustainable geothermal energy exploitation (Fig.1) [4-12]. A brief overview of the role and outcome of the isotope studies in geothermal areas is provided in this article.

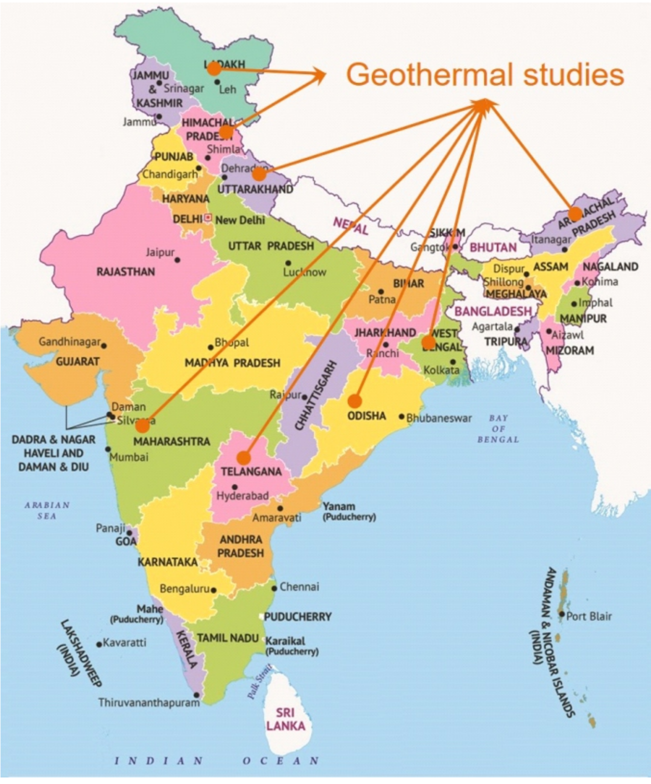

Fig.1: Map showing major geothermal provinces in India where integrated isotope-geochemical investigations were conducted by Bhabha Atomic Research Centre.

Materials and Methods

Isotope ratio mass spectrometer (IRMS) is generally used to measure the stable isotope ratio of light elements like $^{2}H/^{1}H$, $^{18}O/^{16}O$, $^{13}C/^{12}C$, $^{34}S/^{32}S$ whereas thermal ionization mass spectrometer (TIMS) is used to measure the isotope ratio of elements like $^{11}B/^{10}B$ and $^{87}Sr/^{86}Sr$. Liquid scintillation spectrometry (LSC) is generally used to determine the absolute concentration of environmental radioactive isotopes like tritium and carbon-14. The detailed measurement methodology of the various isotopes has been described elsewhere [4, 9, 12].

The symbol 'δ' (delta) is universally used to denote the variance in the isotopic ratio (R) of the reference standard compared with that of the sample according to eqn. 1:

$$\delta = \{(R_{sample} - R_{standard})/R_{standard}\} * 1000 \quad (1)$$

where '$R_{standard}$' refers the $^{18}O/^{16}O$, $^{2}H/^{1}H$, $^{13}C/^{12}C$, $^{34}S/^{32}S$, $^{11}B/^{10}B$ of the standard and the 'R_{sample}' represents $^{18}O/^{16}O$, $^{2}H/^{1}H$, $^{13}C/^{12}C$, $^{34}S/^{32}S$, $^{11}B/^{10}B$ of the sample. Currently, 'VSMOW' (Vienna Standard Mean Ocean Water) acts as a primary standard material for measuring the $^{18}O/^{16}O$ and $^{2}H/^{1}H$ in water whereas VPDB (Vienna Pee Dee Belemnite), VCDT (Vienna Canon Diablo Troilite), NBS-951 act as a primary reference material for measuring the $^{13}C/^{12}C$, $^{34}S/^{32}S$, $^{11}B/^{10}B$ of the sample respectively.

Role of Stable Isotopes

Origin of thermal water

Before the widespread application of mass spectrometry methods, thermal waters were generally considered to be of juvenile or magmatic origin [13]. However, a pivotal shift in understanding occurred with the work of Craig and his colleagues [14,15], who demonstrated that the $\delta^{2}H$ values of thermal waters from several prominent geothermal fields closely matched with those of local meteoric water (Fig.2). This observation provided compelling evidence that geothermal waters are predominantly of meteoric origin, infiltrating the subsurface and subsequently gaining heat as they circulate at depth through faults and fracture networks.

While the hydrogen isotopic composition ($\delta^{2}H$) of thermal waters matched closely with that of local precipitation, a systematic enrichment in oxygen-18 ($\delta^{18}O$) was observed, resulting in a positive shift from the meteoric water line. This phenomenon, commonly referred to as the "oxygen-18 shift,"

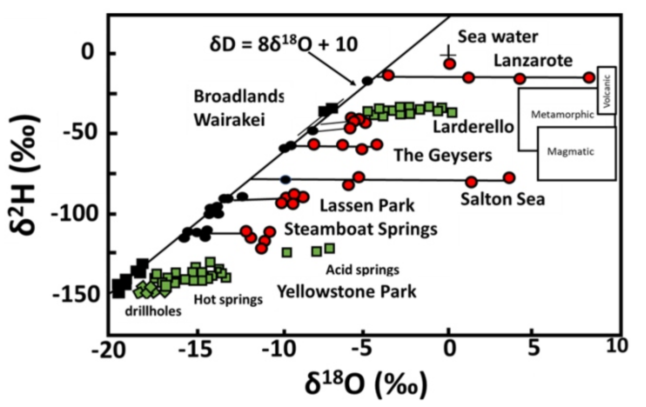

Fig.2: $\delta^{18}O$-$\delta^{2}H$ plot of various types of thermal waters. Thermal waters show significant ^{18}O shift from GMWL [16].

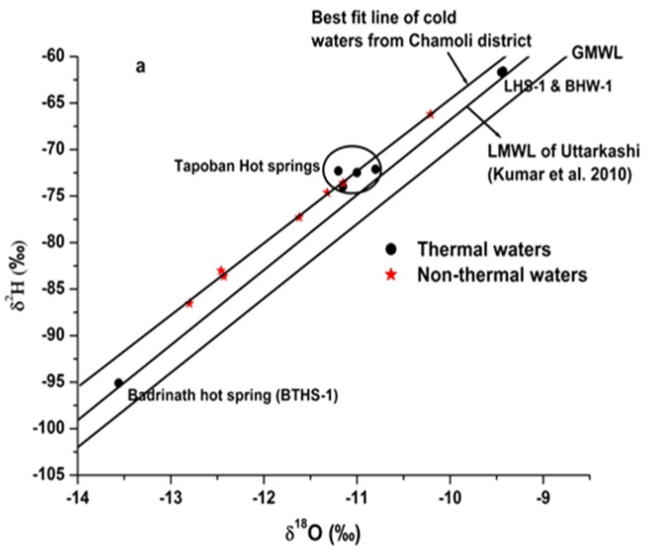

Fig.3: $\delta^{18}O$-$\delta^{2}H$ plot of thermal and non-thermal waters of Uttarakhand geothermal area, India [10].

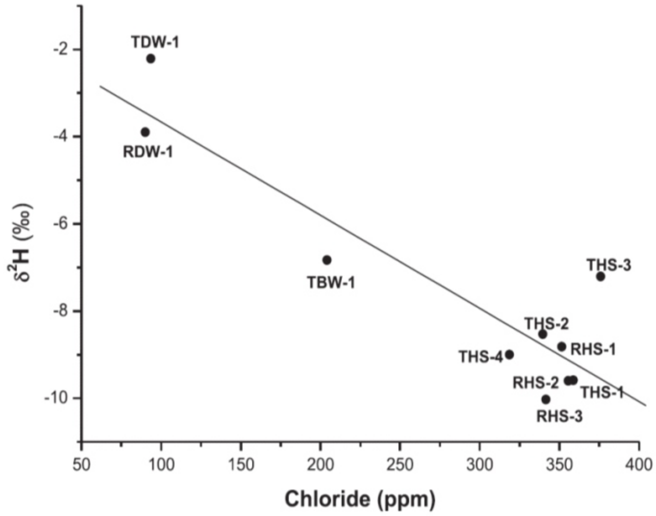

Fig.4: Linear relationship between δ^2H and chloride in Tural-Rajwadi geothermal field, Maharashtra, India [11].

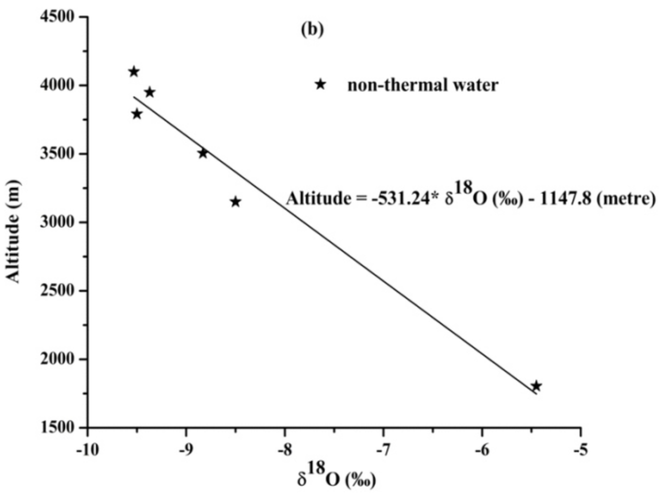

Fig.5: Altitude effect calculated from the non-thermal waters collected from the Arunachal Pradesh geothermal area, India [5].

arises from isotopic exchange processes between water and aquifer-hosted minerals primarily silicates or carbonates under elevated temperatures. The extent of this $\delta^{18}O$ enrichment is indicative of the degree of water-rock interaction, which is strongly temperature-dependent and provides important insights into the thermal history and evolution of geothermal fluids.

The extent of ^{18}O shift depends on several factors, including rock mineralogy (whether carbonate or silicate rocks), fluid-rock interaction duration, reservoir temperature, water-to-rock ratio etc. [17]. As a result, not all the thermal springs around the globe exhibit this kind of oxygen-18 shift. For example, boiling thermal waters (surface temperature ~93^{0}C) from Uttarakhand geothermal area of India, hardly show any measurable oxygen-18 shift (Fig.3) [10].

Mixing Phenomenon

Oxygen-18 and deuterium also serve as effective tracers for identifying the mixing process in geothermal systems. A strong linear correlation between δ^2H and chloride (Cl^-) concentrations is often interpreted as robust evidence of mixing, as both δ^2H and Cl^- typically behave conservatively and are not significantly altered by water-rock interaction or other subsurface geochemical processes. This type of mixing phenomenon has been observed in Tural-Rajwadi geothermal field (Maharashtra) where thermal water gets mixed with non-thermal waters to produce a range of spring compositions (Fig.4) [11].

Estimation of Recharge Altitude

Stable isotopes like $\delta^{18}O$ and δ^2H are also useful in estimating the recharge altitudes of thermal springs situated in high altitude areas. Recharge altitude can be roughly determined using $\delta^{18}O$-altitude and/or δ^2H-altitude plots, typically developed from rainwater samples collected at different elevations. In Arunachal Pradesh geothermal area, an altitude gradient of -0.19‰ per 100 m for $\delta^{18}O$ was observed (Fig.5) [5]. Using this, recharge altitudes of thermal springs in Tawang District were estimated at 6100–6900 m. This range is notably close to the elevation of Gorichen Peak (6858 meters), the highest peak in Arunachal Pradesh. These findings strongly indicate that precipitation occurring near Gorichen Peak plays a significant role in recharging the thermal springs in the Tawang District of Arunachal Pradesh, India.

Static vs. Dynamic Geothermal Systems

Stable isotopes like $\delta^{18}O$ and δ^2H are also effective in distinguishing between static and dynamic geothermal systems. In static systems, limited recharge leads to constant stable isotopic compositions over time and the age of thermal waters are found to be typically old [17]. Conversely, dynamic systems experience ongoing recharge from precipitation, resulting in noticeable isotopic shifts and younger water ages [17]. For example, the Odisha geothermal area shows a static system, with almost constant isotopic values between 1995 and 2016 and ^{14}C ages ranging from 13,300 to 20,700 years BP before present) (Fig.6a) [12]. In contrast, the Badrinath geothermal area (Uttarakhand) demonstrates a dynamic system, with progressively depleted isotope values from 1996 to 2022, indicating recharge from high-altitude glacier melt (Fig.6b).

Tracing DIC Source

$\delta^{13}C$ ($^{13}C/^{12}C$ isotopic ratio) is a powerful tracer in geothermal studies because various carbon reservoirs (i.e. biogenic methane, magmatic CO_2 or carbonate rocks) exhibit entirely different isotopic signatures. The key applications of $\delta^{13}C$ values are given Table 1.

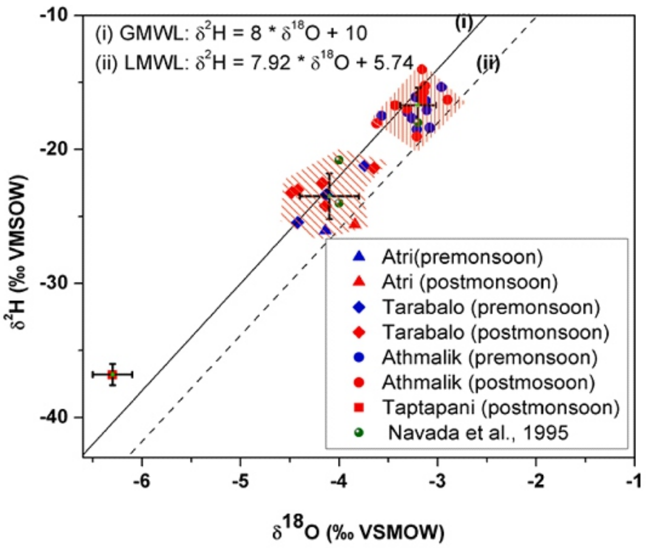

Fig.6a: $\delta^{18}O$-δ^2H plot of the Odisha geothermal area [12].

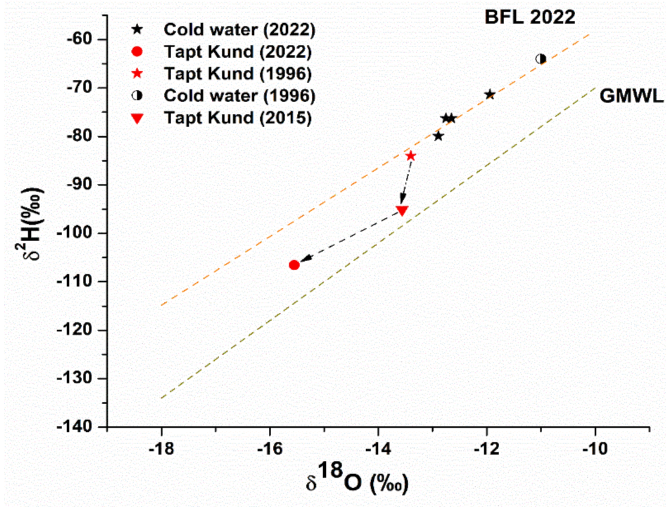

Fig.6b: δ18O-δ2H plot showing the change in isotopic composition of Badrinath thermal water.

For example, the $\delta^{13}C$ values of dissolved inorganic carbon (DIC) in the thermal waters from Manuguru geothermal region ranged from -17.5 to -24.4‰, with an average of -20.57‰ relative to VPDB. This $\delta^{13}C$ value clearly indicates that the DIC of the thermal waters are primarily governed by the silicate weathering, with little or no evidence of calcite dissolution [7].

Tracing Salinity Source

$\delta^{34}S$ and $\delta^{11}B$ isotopes are effective tracers for identifying the sources of salinity in thermal waters. The $\delta^{34}S$ values of sulfur species can range from -30‰ to +35‰, reflecting varied geochemical origins [9]. For example, in the Tural-Rajwadi geothermal area (Maharashtra), $\delta^{34}S$ values of dissolved sulfate (+19.6 to +20.43‰ VCDT) closely match marine sulfate, indicating seawater influence due to coastal proximity [9]. Similarly, $\delta^{11}B$ values also help to distinguish marine from non-marine contributions (Fig.7). In the Gujarat geothermal region, waters from sites like Dholera and Tulsishyam showed high $\delta^{11}B$ values (+40.5‰ to +46‰), suggesting relic seawater or diagenetically altered marine sources [4]. In contrast, lower $\delta^{11}B$ values (+26‰ to +31‰) in Varana and Maktupur region indicate non-marine inputs, likely from anthropogenic sources such as agricultural return flow [4].

Thus, these isotopic tools serve as definitive indicators of source heterogeneity and aid in the reconstruction of the hydrogeochemical evolution of the geothermal system.

Table 1: Role of $^{13}C/^{12}C$.

$\delta^{13}C$ Component	Application	Average $^{13}C/^{12}C$ values
DIC (Dissolved Inorganic Carbon)	Identify dominant weathering processes between silicate and carbonate sources	
	Determines source of soil CO_2	• C_3 plants: $\delta^{13}C \approx -26‰$ (temperate forests) • C_4 plants: $\delta^{13}C \approx -12‰$ (grasslands/savannas) [18]
CO_2 Gas	Differentiates between CO_2 sources	• Atmospheric: $\delta^{13}C \approx -8.1‰$ [18] • Magmatic (mantle-derived) • Carbonate decarbonation • Organic matter oxidation • Microbial methanogenesis
Methane (Ch_4)	Distinguishes between various methane sources	• Thermogenic (high-temp breakdown of organic matter) • Biogenic (microbial activity) • Abiotic (e.g., graphite water reactions)

Role of the Environmental Radioactive Isotopes

Environmental radioactive isotopes also known as natural or cosmogenic radionuclides (e.g. tritium [^3H], carbon -14 [^{14}C]) are extremely useful in assessing the sustainability of geothermal systems.

Transit time (Residence time) Estimation

Tritium (^3H), with a half-life of 12.32 years, is a useful tracer for estimating the mean transit time (MTT) of younger waters (<50 years). However, its application in geothermal systems is rather limited due to typically long residence times (>50 years) and low tritium levels. However, in systems where thermal waters mix with modern groundwater, tritium can still provide meaningful estimation of mean transit time (MTT). For instance, in the Thane geothermal region (Maharashtra), the estimated MTTs of the younger water components in Ganeshpuri and Akloli thermal waters were found to be 70 ± 5 years and 90 ± 14 years, respectively [6]. Similarly, the estimated MTTs of the younger water components in Tural and Rajwadi thermal springs were found to be 28.0 ± 12.0 years and 29.5 ± 12.5 years, respectively [8].

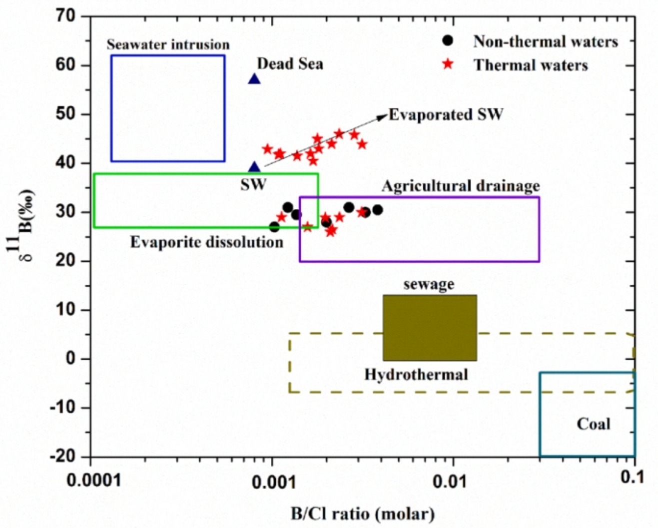

Fig.7: Bi plot of $\delta^{11}B$ vs. B/Cl molar ratio to elucidate different salinity sources [4].

On the other hand, radiocarbon (^{14}C), with a half-life of 5730 years, is better suited for dating older thermal waters. While ^{14}C results can be skewed by carbon-free sources like volcanic CO_2 or carbonate dissolution, geothermal systems in silicate dominant area allow more reliable age estimates due to minimal dilution. In the Manuguru geothermal area (Telangana), ^{14}C ages ranged from ~9,950 to 18,660 years BP (before present), reflecting recharge during the late Pleistocene to early Holocene [7]. Similarly, in the Mahanadi region, corrected ^{14}C ages of 13,300–20,700 years BP (before present) point to recharge during the Last Glacial Maximum (LGM) [12].

These examples highlight the combined utility of ^3H and ^{14}C isotopes in assessing both modern and ancient recharge in geothermal systems which in turn throw lights on the sustainability of that particular geothermal system.

Conclusion

Application of multiple isotopic tracers including stable isotopes, tritium, and radiocarbon has significantly enhanced the understanding of geothermal water characteristics in the Indian subcontinent. This comprehensive methodological framework has enabled the interpretation of several critical hydrological processes, including the origin and recharge sources of thermal waters, the identification of the sources of dissolved solutes, and the estimation of residence times. In many instances, isotopic techniques have yielded unique insights that are not readily obtainable through conventional hydrogeological or geochemical methods. Thus, isotope hydrology has proven to be an indispensable tool in the characterization and sustainable management of geothermal resources in India.

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The author wishes to acknowledge Dr. Y. K. Bhardwaj, Associate Director, Radiochemistry and Isotope Group; Dr. R. Acharya, Head, IRAD and Dr. Tirumalesh Keesari, Head, IHS for their constant support and encouragement. The author also wishes to acknowledge the effort and dedication of all the present and former colleagues of the Isotope Hydrology Section of IRAD, BARC) as well as all the collaborators associated with geothermal studies .

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भूजल की धारणीयता

3

आइसोटोप और मॉडलिंग दृष्टिकोण का उपयोग करते हुए उत्तर पश्चिम भारत से एक अति दोहित जलभृत प्रणाली के जलीय पुन:भरण का पुनर्निर्माण

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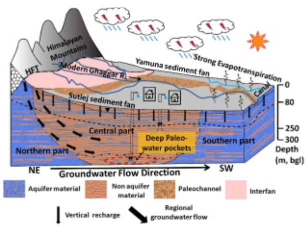

उत्तरी हरियाणा के समग्र जलवैज्ञानिक परिदृश्य का अवधारणात्मक आरेख ([1] के बाद संशोधित)

सारांश

भूजल धारणीयता आधुनिक विश्व के सामाजिक-आर्थिक विकास को नियंत्रित करने वाला एक महत्वपूर्ण प्राचल है। वैश्विक क्षेत्रीय जलभृतों के आइसोटोप अध्ययन जैसे नूबियन सैंडस्टोन, यूएस हाई प्लेन्स और कालाहारी आदि ने हजारों वर्ष पूर्व के प्रमुख जलीय पुनःभरण घटक का संकेत दिया, जिससे इन जल संसाधनों पर निर्भर लाखों आबादी के लिए चिंता बढ़ गई। भारत भी जलभृत प्रणालियों पर अत्यधिक जैसे उत्तर पश्चिम भारतीय जलभृत (एनडब्ल्यूआईए) जिसमें पंजाब और हरियाणा जैसे प्रमुख कृषि प्रधान राज्य शामिल हैं, पर अत्यधिक निर्भर है जबकि इस जलभृत का अंधाधुंध दोहित किया जा रहा है, तथा आगामी पीढ़ियों हेतु इसकी धारणीयता का आकलन नहीं किया गया है। वर्तमान अध्ययन विश्व में इस सबसे तीव्रता से अवक्षय क्षेत्रीय जलभृत प्रणाली की स्थिरता का वैज्ञानिक मूल्यांकन करने के लिए कई आइसोटोप अनुरेखकों का उपयोग करके एनडब्ल्यूआईए के पुनःभरण इतिहास का वर्णन करता है।

Groundwater Sustainability

3

Paleorecharge Reconstruction of an Overexploited Aquifer System from North West India Using Isotope and Modeling Approaches

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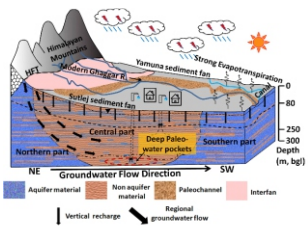

Conceptual diagram of overall hydrological scenario of northern Haryana (modified after [1])

ABSTRACT

Groundwater sustainability is a crucial parameter governing socio-economic development of the modern world. Isotopic studies of global regional aquifers like, Nubian Sandstone, US High Plains, and Kalahari etc. indicated dominant paleorecharge component from thousands of years back, raising concern for millions of population dependent on these water resources. India is also highly dependent on regional aquifers like North West Indian Aquifer (NWIA) system covering major agrarian states like Punjab and Haryana. While this aquifer is being exploited indiscriminately, its sustainability for future generations remains unassessed. The current study unravels recharge history of NWIA using multiple isotopic tracers to scientifically evaluate sustainability of this fastest depleting regional aquifer system in the world.

KEYWORDS: *Paleorecharge, North West Indian Aquifer, Stable & radioisotopes, Isotope modeling, Water resource management*

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Introduction

Over the past 150 years, intense agriculture across the Indo-Gangetic Plains led to severe groundwater depletion, particularly in the NWIA. Gravity Recovery and Climate Experiment (GRACE) satellite data estimated an average depletion rate of 17.7±4.5 km^3/yr, with relatively higher rates in North India reaching up to 54±9 km^3/yr. However, in situ observations reveal spatial heterogeneity in depletion patterns, with 70% of the region showing stable or rising water tables and the rest experiencing severe decline [1-2]. Key hotspots of groundwater depletion in NWIA are noticed mainly in the states of Punjab and Haryana. Given its socio-significance, overexploitation of NWIA might pose serious consequences on agriculture and drinking water security. Traditional tools like geophysical, hydrogeochemical, and numerical models, though accurate, often face limitations at regional scales due to parameter uncertainties and economic constraints [3]. Isotope techniques on the contrary offer deeper insight into recharge mechanisms, source, flow dynamics, and inter-aquifer interactions etc., which are pivotal in formulating broadscale mitigation strategies. Notably, environmental radiotracers such as ^{14}C and ^{36}Cl have been widely used to reconstruct recharge history in global regional aquifers like the Nubian Sandstone (recharged during: 4–20 ka BP), Kalahari Desert (3–40 ka BP), and US High Plains (20-26 ka) [1]. In India, presence of paleowater has been documented in Cambay Basin (~60 ka), Rajasthan (~4.3–9.7 ka), the Middle Ganga Plains (4.7 ka), and the Thar Desert (0.9 to 4.0 ka) [1], raising concerns regarding future security and sustainability of these regional aquifers.

This study addresses the groundwater sustainability issues of the overexploited NWIA, with objectives to investigate regional-scale recharge processes, inter-aquifer connectivity, and the distribution of paleowater resources. While existing studies in the region were largely local, focusing on shallow aquifers representing modern recharge, data on deep groundwater residence time and its recharge mechanism remain unexplored. To bridge this gap, a multi-isotopic study (^2H, ^{18}O, ^{13}C, ^3H, ^{14}C) was conducted on shallow and deep alluvial formations of northern Haryana. The results provide new insights into recharge history, groundwater dynamics, and the sustainability of deep groundwater reserves, especially within northern Haryana. The findings offer valuable insights for future groundwater management and present a conceptual framework for understanding the evolution of recharge processes in the region over past 30,000 years.

Methodology

The study area (Fig.1), part of the Himalayan foreland basin with alluvial deposits, receives fluvial input from the Yamuna in the east and Sutlej in the west (Fig.1). Between 2012 and 2015, water sampling was carried out across ~10,000 km^2 in Yamunanagar, Kurukshetra, and Kaithal districts of Haryana. A total of 54 samples were collected for stable isotopes (^2H, ^{18}O), 41 for ^3H, and 30 for ^{14}C as well as ^{13}C analysis. Field parameters were recorded using a handheld multiparameter kit. Rainwater samples (2015–2017) were collected at Chandigarh for isotopic analysis and establishment of the Local Meteoric Water Line (LMWL). Stable isotope samples were collected in 60 mL HDPE bottles in airtight and bubble free condition. For ^{13}C and ^{14}C analysis Dissolve Inorganic Carbon (DIC) samples were taken as $BaCO_3$ precipitate and for ^3H analysis samples were collected in 500 mL HDPE bottles.

Isotope Ratio Mass Spectrometer (IRMS) and Liquid Scintillation Counter (LSC) instruments were used for stable isotope (^2H, ^{18}O, ^{13}C) and environmental radioisotope (^3H, ^{14}C) analysis respectively.

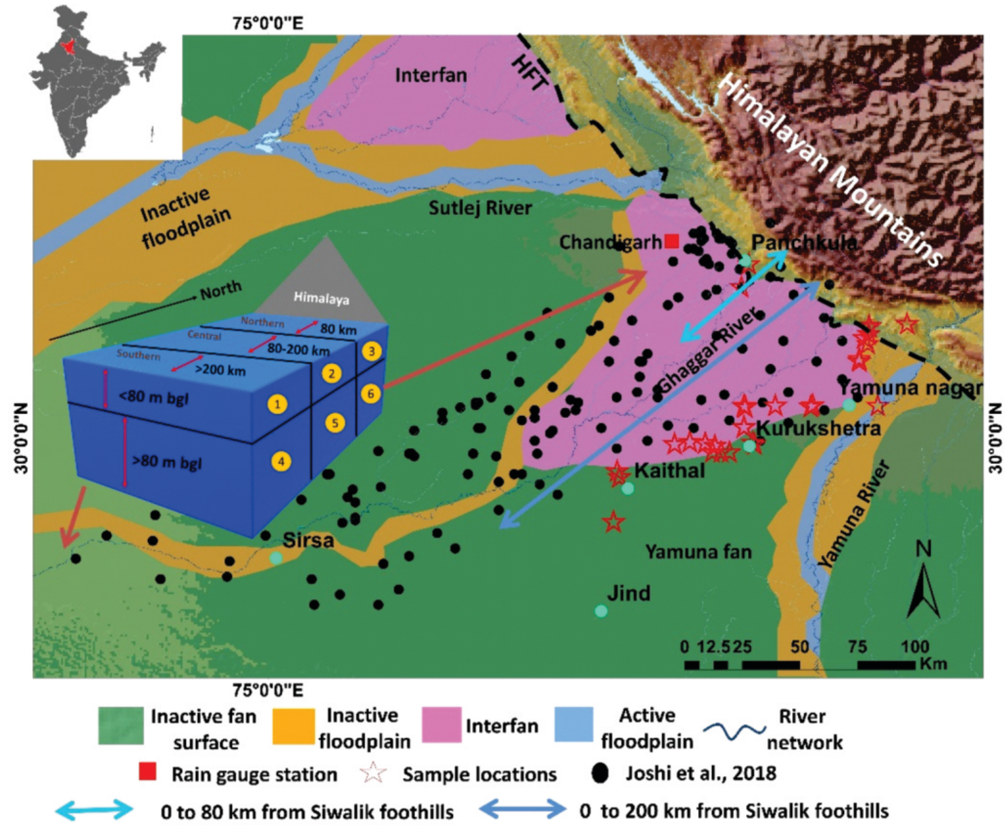

Fig.1: Study area locations overlaid on major geomorphological units of northern Haryana (inset maps include index map of India and 3D conceptual block diagram showing major zonation of the region) (modified after [1]).

For ^{2}H and ^{18}O, Vienna Standard Mean Oceanic Water (VSMOW) and for ^{13}C, Pee Dee Belemnite (PBD) are generally taken as standards for reporting the data.

The ^{3}H results were presented in Tritium Unit (TU), where TU = one atom of ^{3}H in 10^{18} atoms of ^{1}H, and 1 TU corresponds to an activity of 0.118 Bq/kg of water. The ^{14}C activity is expressed in percent modern carbon (pMC), where 100 pMC corresponds to an activity of 13.56 dpm per gm of carbon. Detailed methodology of sampling and analysis of the different isotopes can be found in [1, 5].

For better interpretation the study area was divided conceptually into six blocks (Fig.1). The classification is primarily based upon distinct hydrogeological, and physico-chemical parameters of the different blocks. Spatially the study area was divided into three zones; northern, central and southern zones while depth wise the region was divided into two zones; shallow (<80 m bgl) and deep (>80 m bgl) zones.

Results & Discussion

Stable isotope systematics and recharge mechanism

Isotopically shallow groundwater samples (<80 m bgl) show a wider spread, averaging near the local average precipitation isotopic value ($\delta^{18}O$: -6.52‰ and $\delta^{2}H$: -48.60‰). Deeper samples (>80 m bgl) were more depleted, forming two distinct clusters around $\delta^{18}O$: –6.5‰ and –9‰. These patterns suggest two separate aquifer zones divided by a clay layer, with the deeper zone influenced by different recharge processes compared to shallow depth zone (Fig.2a). The $\delta^{18}O$ vs. $\delta^{2}H$ plot showed two distinct clusters (Fig.2b): group (i) from –7.3 to –4.38‰ and group (ii) from –9.41 to –9.01‰. Group (i) included samples from both shallow and deep zones, indicating possible aquifer interconnections. Most samples fell between the LMWL and Western Himalayan Meteoric Water Line (WHMWL), suggesting the influence of Western Disturbances (WD), which are known to produce high d-excess rainfall [6]. Northern zone samples reflected a dominant Western Himalayan (WH) signature, while central zone samples dominantly showed Indian Summer Monsoon (ISM) contribution. A few deep zone samples in the central part fall along WHMWL, implying possible distant regional recharge from Siwalik foothills. Group (ii) samples mostly lay above the WHMWL, except two deep zone samples (>200 m) that showed a mix of WH and local precipitation signatures. Based on isotopic composition recharge during intense monsoons or mixing with high-altitude depleted sources mainly characterise these samples. Fig.2c shows southern zone groundwater samples highly influenced by canal recharge and strong evaporation.

Environmental Radioisotope Distribution and Groundwater Dating

Groundwater samples showed tritium (^{3}H) values ranging from 0.33 to 9.47 TU, with an average of 3.20±2.29 TU. A clear decline in ^{3}H with depth was observed with shallow samples (<80 m bgl) showing higher ^{3}H (2–14 TU), indicating modern

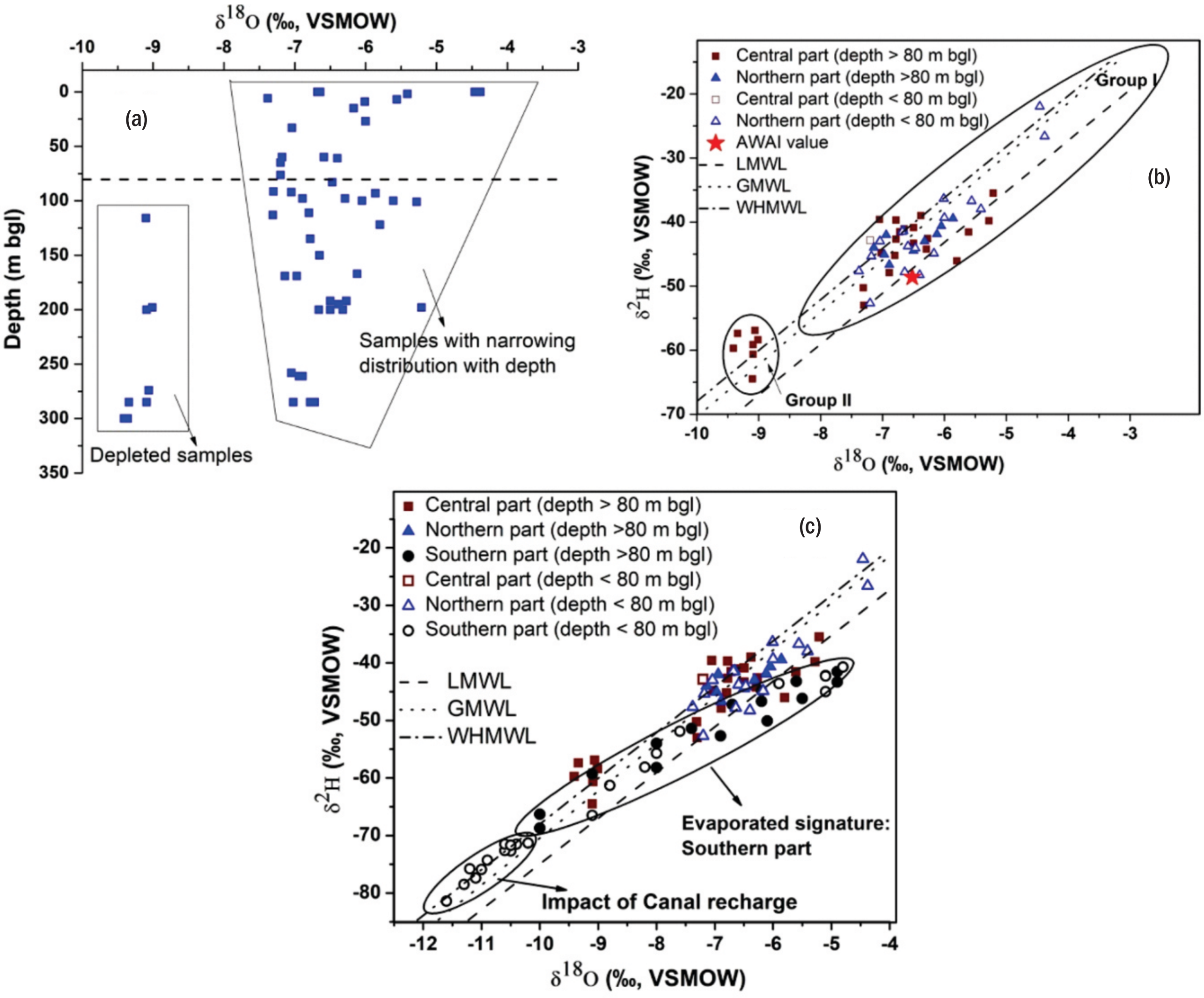

Fig.2: (a) Depth variation of stable isotope data (^{18}O); (b) ^{2}H vs. ^{18}O plot; (c) ^{2}H vs. ^{18}O plot including southern part of the study area (modified after

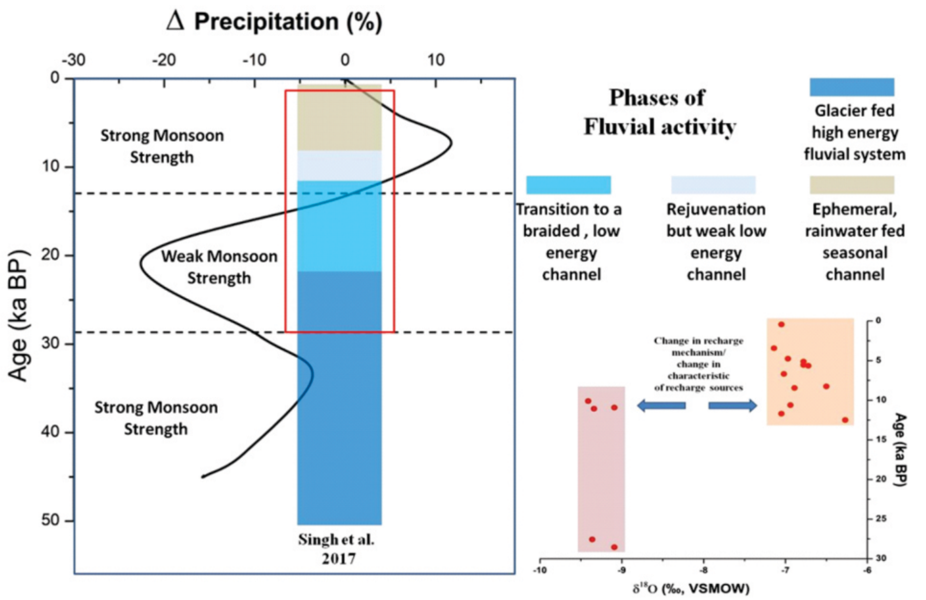

Fig.3: Phases of fluvial activity during last 50 ka and C-14 corrected age vs. ^{18}O plot (modified after [1]).

recharge, intermediate depths (80–250 m bgl) showing mixed signatures (0.33–6 TU) and deeper samples (>250 m bgl) displaying lowest ^3H values (<1 TU), suggesting older recharge. This vertical trend was corroborated by stable isotope depth profiles.

^{14}C values ranged from 1.3 to 120 pMC, with an average of 55 pMC, and showed a decreasing trend with depth. Shallow aquifers (<80 m bgl) showed 67–120 pMC, intermediate zones (80–250 m) showed 1.4–104 pMC, while deep aquifers (>250 m) consistently showed values <27.4 pMC, indicating minimal mixing and dominant paleorecharge. The combined ^3H and ^{14}C data confirm a transition from modern to older water with increasing depth, reflecting distinct recharge processes in different aquifer zones.

Correction of the estimated ^{14}C age values was carried out using ^{13}C values of the collected $BaCO_3$ precipitates based on Pearson model [7]. The corrected age values varied from 0.4 to 28.6 ka BP. A $\delta^{18}O$ vs. ^{14}C plot (Fig.3) was used to assess recharge conditions of paleowater samples. Samples aged from 28.6 to 10.1 ka BP showed narrow $\delta^{18}O$ values (~–9.3‰) and high d-excess (12.1–17.3‰), indicating high-altitude, glacier-fed recharge [6]. In contrast, samples younger than 12.5 ka BP had enriched $\delta^{18}O$ (–7.14 to–6.27‰) and lower d-excess (avg. 11.84±2.78‰), reflecting modern rainfall influence. The isotopic contrast suggests a shift in recharge sources over time.

Paleoprecipitation Reconstruction

The $\delta^{18}O$ values of carbonate nodules ($\delta^{18}O_{nod}$) serve as key indicators of past monsoonal variations, as they reflect the isotopic composition of soil water ($\delta^{18}O_{soil}$), which is closely linked to local rainfall $\delta^{18}O$ ($\delta^{18}O_{rain}$). The temperature-dependent oxygen isotope fractionation between water and calcite is described by Friedman and O'Neil [8] Qualitative estimates of paleoprecipitation $\delta^{18}O$ were reconstructed for the study area using $\delta^{18}O_{nod}$ data from Kanpur [11] and the Ghaggar Plain [12].

Fig.4 shows that $\delta^{18}O_{rain}$ values during Marine Isotope Stage (MIS) 3 (~57–29 ka) were generally enriched compared to the modern annual average precipitation isotope value ($\delta^{18}O$ = –6.56‰), indicating weaker monsoon activity (Fig.3). Most MIS 2 (~29–14 ka) values also appeared enriched, except for a few depleted points around ~19 ka reflecting increased aridity and minimal monsoonal influence. In contrast, Holocene climate conditions remained relatively stable, and rainwater $\delta^{18}O$ values gradually approached modern levels ($\delta^{18}O$= –6.56‰), particularly during the later Holocene period [14].

Paleorecharge History

Reconstructed paleoprecipitation $\delta^{18}O$ values averaged –6.06‰ between 28.7 and 10.1 ka, while groundwater from this period shows a more depleted average of –9.3‰. Moreover, the isotopic shift in groundwater samples during 12 to 10 ka cannot be explained by precipitation recharge alone. This indicates presence of an additional, highly depleted recharge source, likely glacial or snowmelt-fed during 28.7 to 10.1 ka.

Geological and isotopic evidence suggests past existence of a major perennial river, mostly linked to the paleo-Saraswati system in the northern Haryana. Based on the present study and supporting evidence from Optically Stimulated Luminescence (OSL) dating, $^{40}Ar/^{39}Ar$ analysis, Sr-Nd and U-Pb isotopic data [1, 15], the fluvial history of the study area over the past 30,000 years can be divided into four distinct periods (Fig.3). These shifts were controlled by tectonic

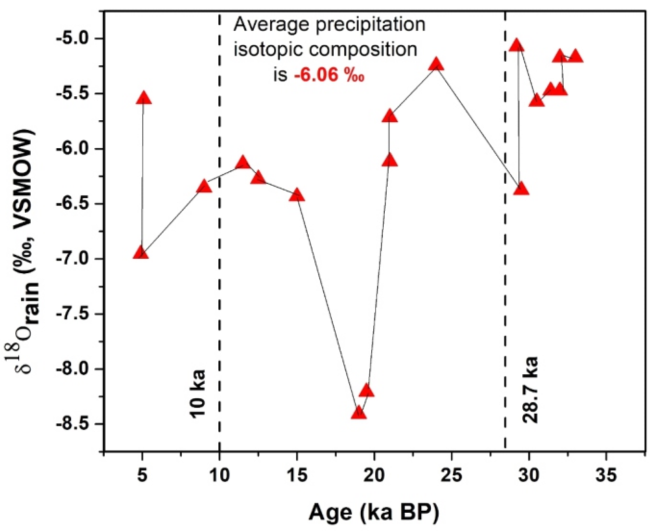

Fig.4: The Paleoprecipitation isotopic composition ($^{18}O_{rain}$) modelled based on ^{18}O data of carbonate nodules ($^{18}O_{nod}$).

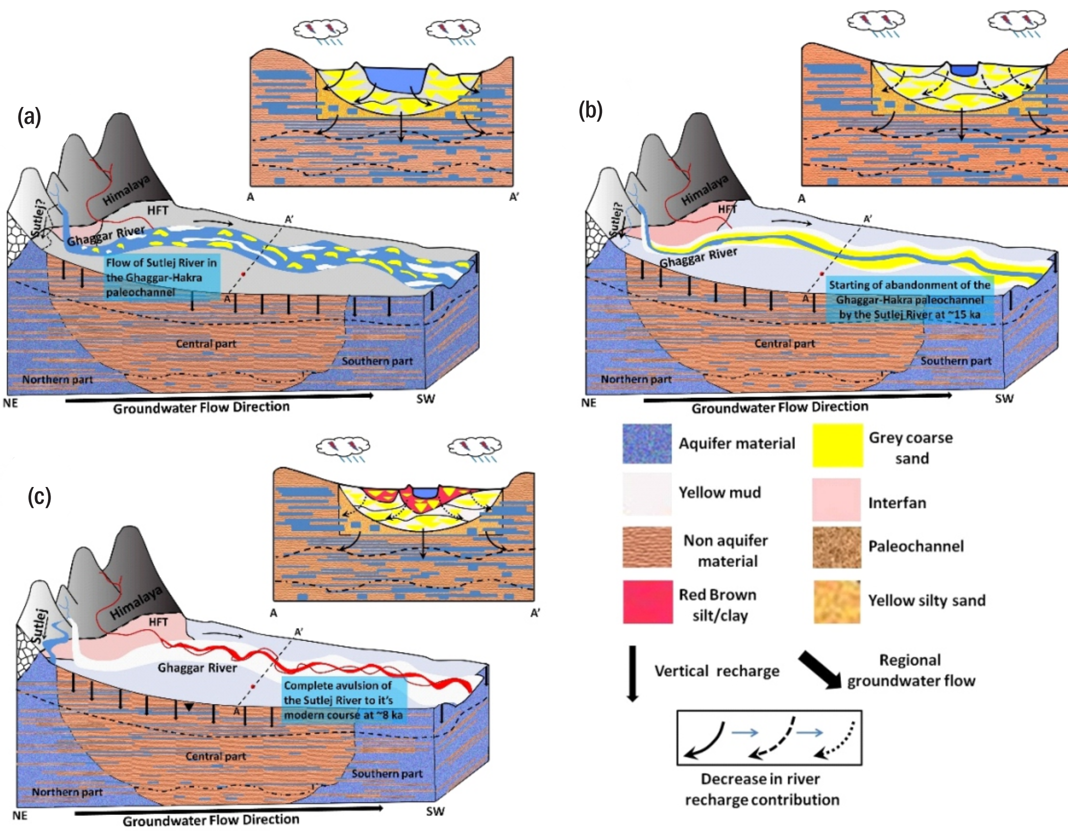

Fig.5: Conceptual models depicting hydrological scenario under varying fluvial activity of the northern Haryana region during (a) 62-30ka (b) 25-12ka and (c) 12-4.5ka (modified after [1]).

avulsions and climatic related changes, particularly due to weakening of the Indian Summer Monsoon (ISM). The final disconnection from the Sutlej River around ~4–5 ka led to the transformation of the Ghaggar into an ephemeral, rain-fed stream. The findings underscore the dynamic fluvial history of the region and its strong coupling with paleoclimate and tectonic processes.

Integrating modeled paleoprecipitation and groundwater residence values (^{14}C corrected ages) along with regional fluvial history over the past 30 ka, two distinct paleorecharge phases are identified for the northern Haryana region.

Phase I (~28.6–10.1 ka BP; Fig.5b): Groundwater $\delta^{18}O$ values during Phase I centered around –9.3‰ and the climate was characterized by weak monsoon and arid conditions. Despite enriched paleoprecipitation signatures, depleted groundwater isotopic values suggest recharge from glacial-fed rivers (probably paleo-Sutlej). It can be postulated that fault zones [16] abundant in the region may have facilitated deep aquifer recharge via fracture flow during ancient times from glacier fed river systems. A two-member mixing modeling estimated that the perennial paleoriver system contribution could be about ~48–61% during this phase.

Phase II (~12.5–0.4 ka BP; Fig.5c): During this era, $\delta^{18}O$ shifted to enriched values (–7.14 to –6.27‰) indicating dominant rainwater recharge. Early and late Holocene periods showed enriched rainfall isotopic values, while middle Holocene had transient depletion (~–9‰). Fluvial activity declined during this timeline, confined mostly to the rainfed seasonal Ghaggar River. Occasional depleted groundwater signatures during this period reflect possible residual glacial-fed recharge or vertical mixing of older (depleted) and younger (enriched) waters.

Conclusion

This study highlights that deep aquifers in the region are largely sustained by non-renewable paleowater, making their long-term use unsustainable. Moreover, unchecked overexploitation of these resources may lead to salinization and contamination, requiring advanced water treatment solutions. A strategic framework is urgently needed to limit deep aquifer exploitation and guide future interventions, which should include assessments of aquifer hydraulics, leakage, and paleowater reserves. In contrast, shallow aquifers are actively recharged and can meet current water demands. Sustainable management options include optimizing well placement, controlling pumping, enhancing recharge via infiltration structures, and promoting low-water-use crops etc.

Acknowledgements

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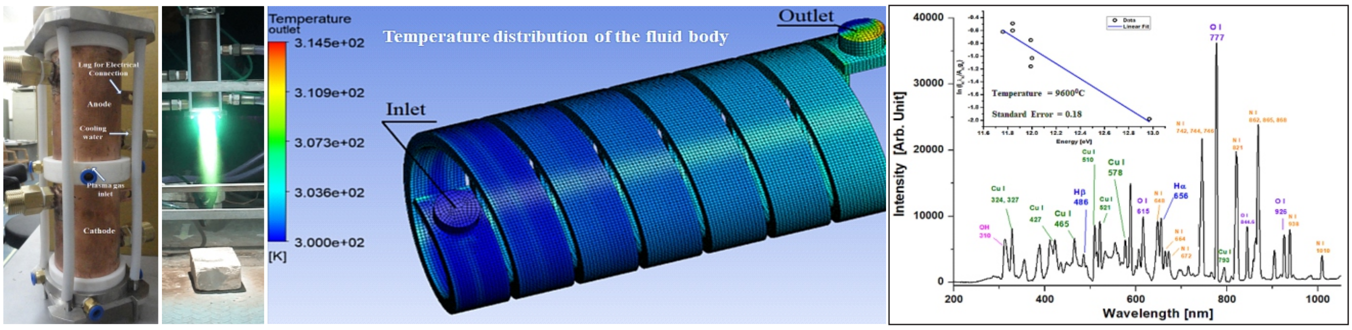
In-house Developed 100 kW Hafnium-free Cu Electrode Based Plasma Torch

Clocks Cumulative 100 hours of Operation with Potential for Further Longevity



Left to right: *The fabricated device; 100kW Thermal Plasma; Temperature distribution of the fluid body; Emission spectrum of air plasma at 100kW power (with Measured plasma temperature in the inset graph).*

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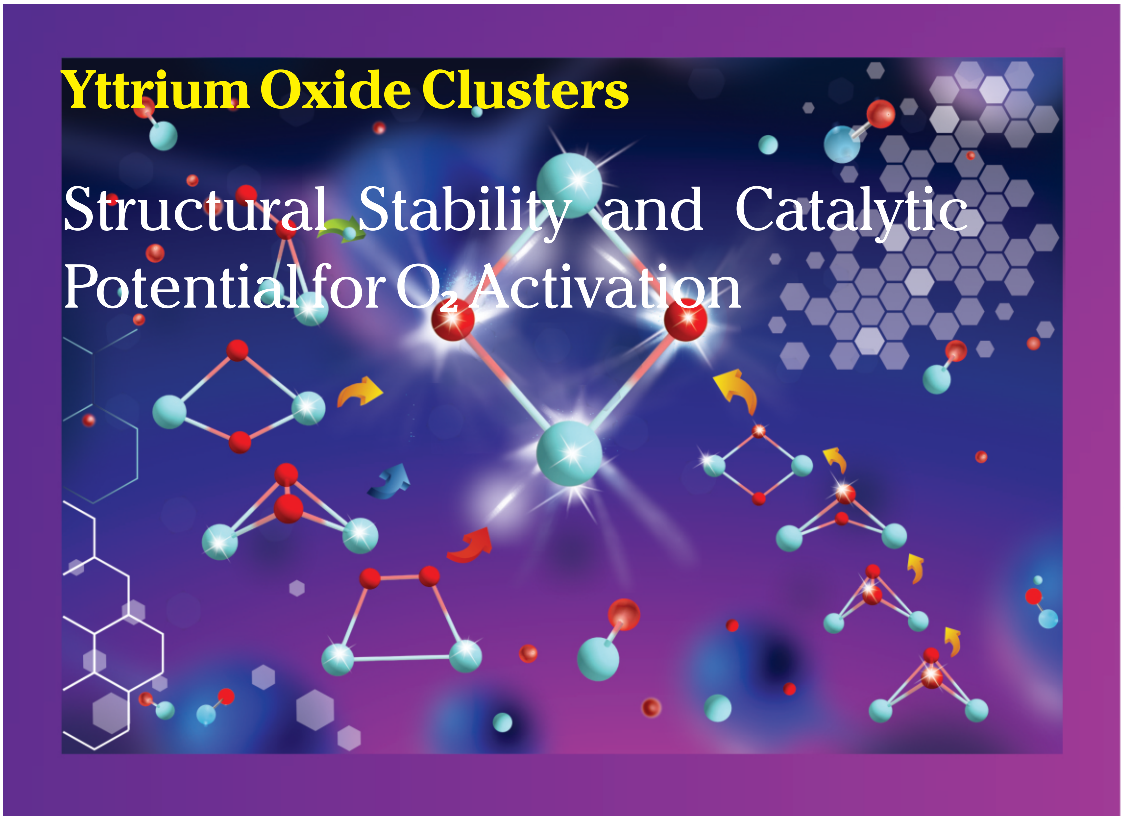
> The indigenously developed torch has operated reliably for over 100 hours without electrode replacement.

High-power (~100 kW) air thermal plasma torches are crucial for industrial processes like cutting, welding, spraying, and waste treatment, thanks to their ability to generate dense plasma at 5000–10,000°C. Air as the plasma gas makes them eco-friendly and economical. Our indigenously developed torch has operated reliably for over 100 hours without electrode replacement, enabled by several key innovations:

- Advanced Cooling Channel Design: A helical cooling water channel, developed through thermal simulations, effectively manages the torch's thermal load and ensures operational stability.
- Electrode Innovation: The torch employs a hollow, hafnium-free Cu based electrode design, improving sustainability and reducing operational costs.
- High Plasma Temperature: Spectroscopic analysis confirmed plasma temperatures approaching ~9600°C, supporting its suitability for high-performance industrial tasks.
- Novel Arc Rotation Mechanism: A unique method of utilizing the magnetic field generated by the input power cable enables arc rotation, significantly reducing localized electrode erosion. This innovation has been critical in achieving the 100-hour electrode life.

These advancements position the device as a reliable and efficient solution for industries seeking durable, high-power, and environmentally friendly thermal plasma systems.

Some part of this highlight has been published in International journal, Vacuum, titled “Increasing life & efficiency of a 100 kW hollow cathode air plasma device with helical water channel design: Operational insights through optical emission spectroscopy” [Ref: Vacuum 234 (2025) 114065].



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The study unravels the stable structures of yttrium oxide clusters through threshold photoionization spectroscopy and DFT calculations, revealing stable structures and a newly identified lowest-energy structure for Y_2O_2. These insights position Yn clusters as promising candidates for catalytic O_2 activation.

This study, conducted at the Atomic and Molecular Physics Division of BARC, explores the structure and reactivity of yttrium oxide clusters (Y_nO_m, where n = 2–8 and m = 2–4), with a focus on their potential to catalyze oxygen (O_2) dissociation. Using threshold photoionization spectroscopy and density functional theory (DFT), the research team investigated the ground-state geometries and ionization energetics of these clusters. For the stoichiometric series Y_nO_2, the authors identified the lowest-energy structures that closely match experimental spectra, including a newly predicted rhombohedral geometry for Y_2O_2. Larger clusters generally exhibit strong structural similarity between neutral and cationic forms, underscoring their resistance to oxidation.

Importantly, the study examines how O_2 interacts with these clusters. While molecular O_2 adsorption is energetically unfavorable, the dissociative adsorption is facilitated at low-coordination sites such as edges and corners. Climbing image nudged elastic band (CI-NEB) calculations reveal that O_2 dissociation proceeds via charge transfer from Y to O, accompanied by significant orbital hybridization. The process leads to the weakening of the O–O bond and formation of stable Y–O configurations, with reaction barriers increasing with cluster size.

Density of states (DOS) and Bader charge analysis further confirm enhanced electron density near the Fermi level, indicating strong Y–O reactivity. These findings position yttrium oxide clusters as promising candidates for O_2 activation and potentially catalytic applications involving oxidation processes. This comprehensive approach provides valuable insights into the design of cluster-based catalysts and advances the understanding of metal oxide reactivity at the nanoscale.

The figure displayed at the top depicts the ground state structure of Y_2O_2. Several initial structures converged to this and the reaction path after absorbing O_2 on a Y_2 dimer also leads to this stable structure. This figure has been featured as inside back cover of Dalton Trans., 2025, 54, 6402.

Reference:

Investigating the stable structures of yttrium oxide clusters: Y_n clusters as promising candidates for O_2 dissociation, Varun Vinayak Deshpande, Debashis Bandyopadhyay, Vaibhav Chauhan, Gayatri Kumari and Soumen Bhattacharyya, Dalton Trans., 2025, 54, 6402.

Radioimmunoassay Laboratory at Radiation Medicine Centre

Implementation and Impact of Liquid Handling System for Thyroid Disorder Diagnostics

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Abstract

Radiation Medicine Centre (RMC) is one of the largest centers for thyroid research and is also one of the leading referral bases for managing thyroid disorders, with a robust patient registry and an established infrastructure for diagnostic innovations. With approximately 15,000 thyroid cancer patients and over 5,000 follow-up cases annually, the center is at the forefront of thyroid disorder research, particularly thyroid cancer. A significant part of the research involves the development and validation of *in-vitro* diagnostic assays, particularly radioisotopic assays such as radioimmunoassays (RIA) and immunoradiometric assays (IRMA) which have proven instrumental in diagnosing and monitoring thyroid conditions. However, large-scale production of these assays at laboratory level has been constrained by labor-intensive manual biomolecule immobilization processes. To address this, an automated liquid handling system (ASSIST PLUS-INTEGRA) has been implemented to automate the immobilization process, thus increasing efficiency, reducing contamination, improving reproducibility, and enhancing data quality. The implementation of this system has notably advanced the production of in-house thyroglobulin (Tg) IRMA kits for routine thyroid cancer monitoring, marking a significant stride in both research and routine clinical diagnostics. This article provides an overview of the integration of this advanced liquid handling system into the RIA laboratory and discusses the benefits and impacts of its implementation.

Introduction

Thyroid disorders, including thyroid cancer, hypothyroidism, and hyperthyroidism, are among the most common endocrine disorders globally. The accurate diagnosis and monitoring of these conditions require the use of specialized diagnostic tools, particularly immunoassays [1]. Immunodiagnostic radioisotopic techniques such as RIA and IRMA play a critical role in the detection and quantification of thyroid-specific biomarkers like total T4 (TT4), Free T4 (FT4), Tg and anti-thyroid peroxidase antibodies (anti-TPOAb). These biomarkers are essential for monitoring thyroid cancer progression and recurrence, and they also aid in the management of other thyroid-related disorders [2].

The manual process of immobilizing biomolecules, such as antibodies and analytes, onto solid-phase surfaces like polystyrene tubes or plates is labor-intensive, requiring skilled personnel and a significant amount of time. In a high-throughput laboratory setting, where large-scale production of assays is necessary, this process becomes even more challenging. The need for precision, reproducibility, and cost efficiency is paramount. At RMC, TT4, FT4, anti-TPOAb, Tg and anti-Tg autoantibody (TgAb) assays have been developed and validated and some of them also found applications, as an import substitute; for routine *in-vitro* patient services [3]. In this article, we discuss how the implementation of an advanced liquid handling system has addressed these challenges and improved the efficiency of antibody immobilization in the production of Tg IRMA kits for the management of routine thyroid cancer patients.

Materials and Methods

Patient Population and Sample Collection

RMC manages a registry of approximately 15,000 thyroid cancer patients, with over 5,000 follow-up cases annually. Clinical samples, are collected from these patients for biomarker analysis using RIA and IRMA techniques. The biomarker assays developed in-house are being used for diagnostic and monitoring purposes for routine clinical care.

Radioimmunoassay Development

RIA and IRMA are essential diagnostic tools for quantifying specific biomarkers related to thyroid function and cancer. These assays rely on the binding of radiolabeled antibodies to their respective antigens (thyroid hormones, antibodies, etc.) on solid-phase surfaces. In the conventional assay production process, polyclonal antibodies are manually coated onto polystyrene tubes using manual pipetting followed by indigenously developed and fabricated equipment for aspiration and washing (Fig. 1-6). This is typically done by adding a solution containing the biomolecule to each tube and allowing it to adsorb. This step demands highly skilled personnel and is time-intensive, with the entire process taking up to a week. Until now, the immobilization of the analytes has been done manually, making the task cumbersome.

Integration of the Liquid Handling System (ASSIST PLUS-INTEGRA)

A customized (for the in-house racks) liquid handling system (ASSIST PLUS-INTEGRA) was procured to automate the biomolecule immobilization process (Fig.7). This device incorporates independent electronic pipettes into a platform to transform manual work into an automated workflow and provides precision pipetting and liquid handling capabilities, enabling the rapid and reproducible coating of biomolecules on solid-phase surfaces. The system is capable of performing a wide range of liquid handling tasks, including dilution, transfer and biomolecule immobilization; and can process large volumes in a high-throughput setting.

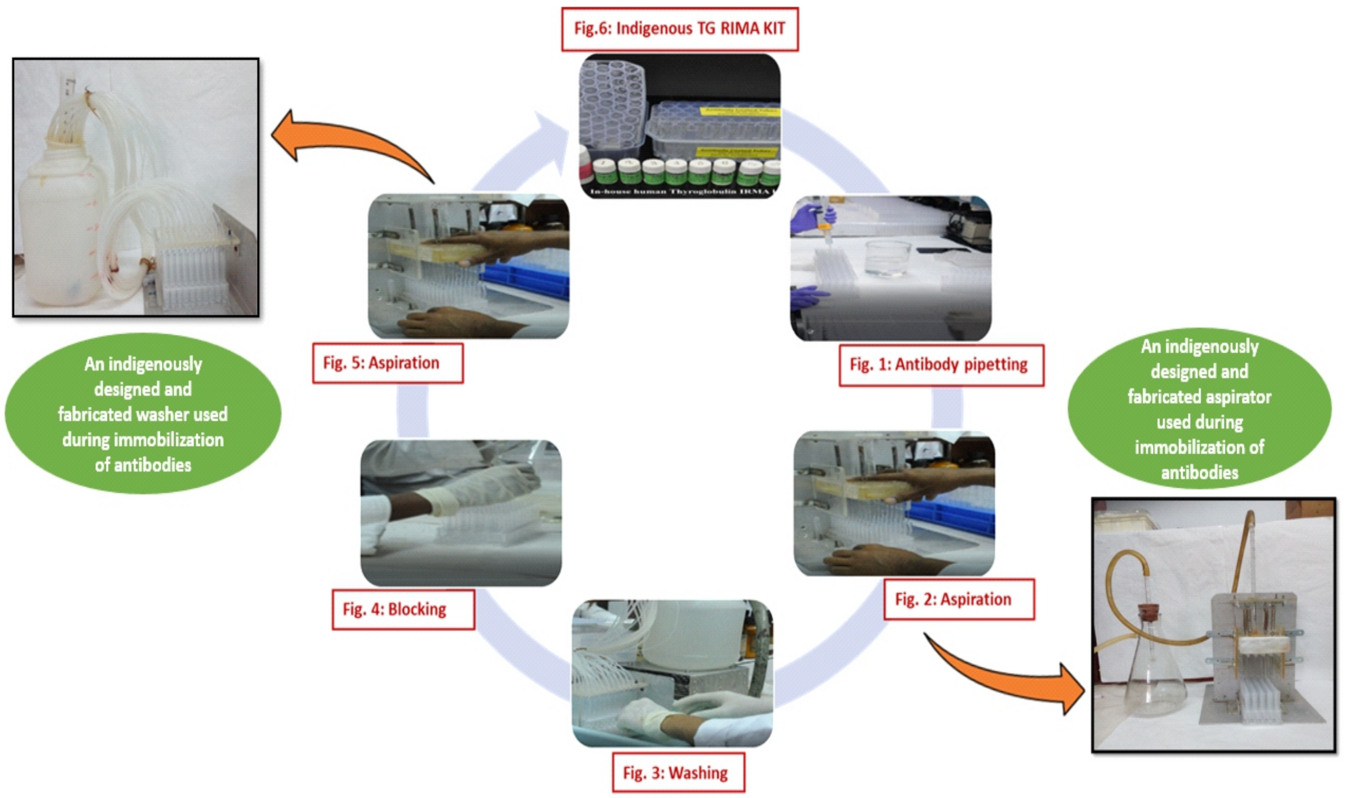

Fig.1-6: Various steps involved in the manual immobilization of antibodies at RMC for in-house Tg IRMA kit production.

In one specific instance, the liquid handling system was used to coat 10,700 tubes with polyclonal anti-thyroglobulin antibodies, which were then used for the production of in-house Tg IRMA kits. These kits are used to estimate Tg in serum for monitoring thyroid cancer patients for the detection of residual or recurrent disease.

Assay Validation

The developed Tg IRMA kits (liquid handling system used for preparing antibody coated tubes) underwent validation to ensure their performance in clinical settings. Additionally, assays for other hormones are also being developed in small batches for research and development purpose in our laboratory.

Results and Discussion

Improved Efficiency and Throughput

The integration of the liquid handling system significantly improved the efficiency of the biomolecule (antibody) immobilization process. In a single batch, the liquid handling system was able to coat 10,700 tubes, a task that would have otherwise taken a significant amount of manual labor. This customized automation not only saved time but also allowed for greater throughput, enabling the laboratory to scale its production of diagnostic kits for routine purpose without sacrificing quality [4].

Enhanced Precision and Reproducibility

One of the primary challenges in manual biomolecule immobilization is ensuring consistency across batches. Variability in antibody coating, volume dispensation, and even slight inconsistencies in technique can lead to variations in assay performance. By automating this process, the liquid handling system significantly reduced these sources of error. The system's precision pipetting capabilities ensured that each tube was coated with a desired amount of antibody, resulting in more reproducible assay performance. Sensitivity, specificity, and reproducibility were assessed using patient samples, and the performance was found to be satisfactory [5].

Reduced Contamination and Labor Costs

Manual coating processes are prone to contamination, particularly when handling large numbers of samples. The automated system minimizes the risk of cross-contamination, as the pipetting steps are performed in a controlled, enclosed environment. Additionally, by reducing the reliance on manual labor, the system has resulted in cost savings, both in terms of personnel time and the potential for errors that could lead to wasted materials or rework. Due to customization, the spare racks could be utilized for assembling the polystyrene tubes for immobilization process which further reduced the cost.

Improved Data Quality and Flexibility

The liquid handling system's ability to control the volume and precision of reagents added to each tube enhances the data quality of the final assays. Moreover, the system is highly flexible, allowing for the easy scaling up or down of assay production depending on research needs. This flexibility has been invaluable in developing assays for additional thyroid hormones and other biomarkers, as well as in customizing assays for research purposes.

Cost Efficiency and Increased Productivity

With the high throughput and reduced labor costs, the integration of the liquid handling system has made the production of radioimmunoassay more cost-effective. These improvements in productivity and cost efficiency have contributed to the sustainability of in-house assay development and production. The system can be used not only for coating the polystyrene tubes but also plates.

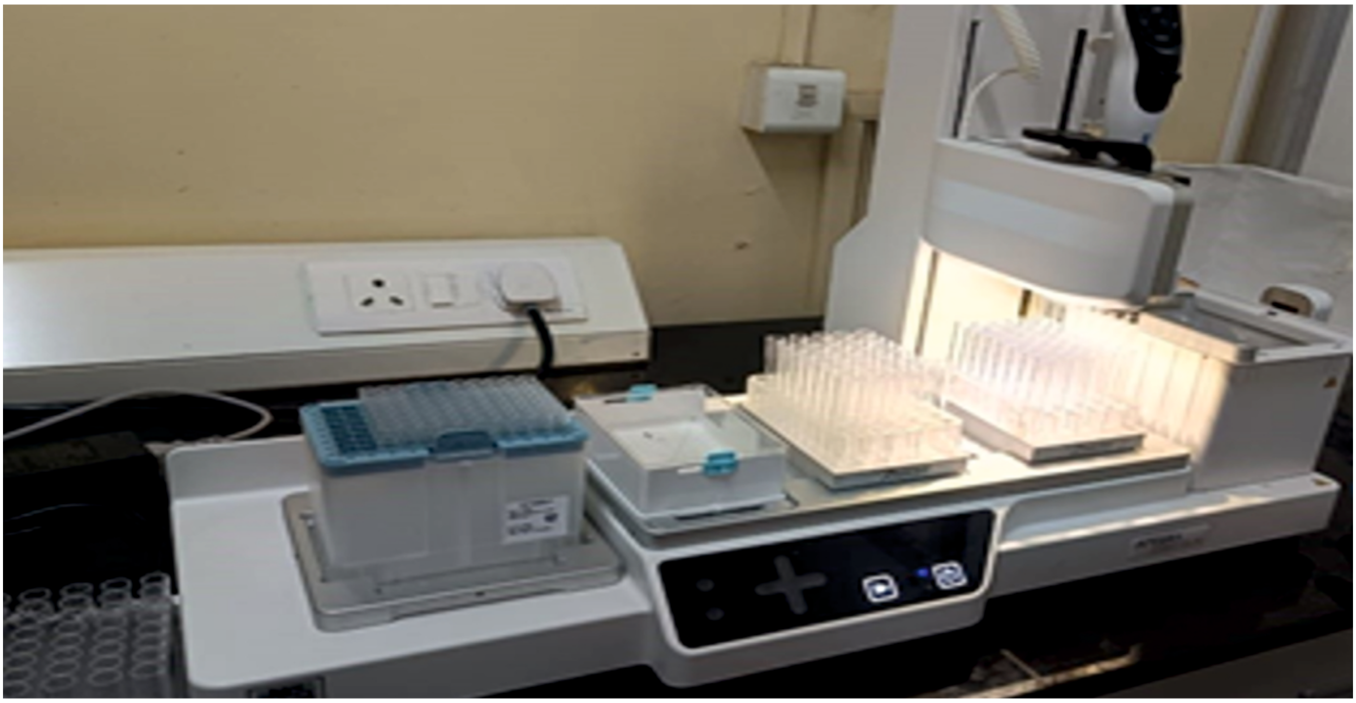

Fig.7: Customized liquid handling system at RMC: Enabling precise immobilization of biomolecules for immunodiagnostic applications.

Conclusion

The integration of the automated liquid handling system has significantly enhanced the capabilities of the radioimmunoassay laboratory in terms of efficiency, reproducibility, and productivity. By automating the biomolecule immobilization process, the system has not only streamlined the production of thyroid cancer diagnostic kits but also paved the way for future innovations in immunodiagnostic assays at the laboratory level. The benefits of this integration extend beyond increased throughput and reduced costs, improving overall laboratory performance and contributing to better patient outcomes. As the system continues to support research and development in the field of thyroid disorder diagnostics, it underscores the importance of adopting advanced technologies in the laboratory to meet the growing demands of modern healthcare.

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Managing VOC Hazards Proactively for a Safer, Healthier Workplace

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Introduction

Volatile Organic Compounds (VOCs) are carbon-containing chemicals that have a tendency to easily evaporate or "volatilize" at normal room temperature. They are present in natural products like plants, wetlands, and microorganisms, and in several man-made common products including paints, solvents, fuels, cleaning agents, building materials, etc. The VOCs can impact both environment and human health. Many VOCs react with nitrogen oxides in the presence of sunlight to produce ground-level ozone which is deleterious to crops and ecosystems. Some VOCs also act as greenhouse gases, contributing to climate change. Harmful effects of VOCs exposure on human health include short-term effects like eye and throat irritation, nausea, headaches, skin allergies, vertigo and severe long-term impacts like tissue damage, nervous system impairment, and even cancer (some are known carcinogens).

Monitoring of VOCs is crucial to understand and quantify their levels in the ambient air and indoor environments, and helps in assessment of their potential health risks. It is also needed for ensuring compliance with environmental regulations, and developing strategies to mitigate release of VOCs into the environment. Early detection of VOCs is useful in identifying sources, and preventing larger environmental impact or health related exigencies.

VOCs present a significant occupational hazard in workplace settings, particularly in the industries like manufacturing, painting, chemical processing, printing, and dry cleaning, where workers can be exposed to high levels of certain VOCs. If there is direct and chronic exposure, then it may cause respiratory irritation, nausea or chronic health problems over a period of time. This necessitates implementation of strong monitoring, and control measures, such as ventilation, and use of personal protective equipment (PPE) etc., to safeguard worker health and safety.

Workplace Sources of VOCs and Health Implications

Volatile organic compounds (VOCs) are released from a wide range of both natural and anthropogenic sources, making them inescapable in many environments. Common indoor sources such as building materials, pressed wood products (e.g., particleboard, MDF) known to emit formaldehyde, paints, varnishes, adhesives, and floor coverings, etc., contribute substantially to occupants' exposure (Salthammer et al., 2010; Yu & Crump, 1998). Common day to day use products like cleaning agents, personal care products, and electronic equipments like printers also contribute to the indoor VOC burden (Wolkoff & Nielsen, 2001). In industrial and occupational environments, VOCs emanate from solvents used in degreasing (e.g., trichloroethylene), paints and coatings (e.g., toluene, xylenes, ethylbenzene, styrene), fuels (notably benzene from gasoline), and chemical intermediates in manufacturing processes (Brugnone et al., 1994; ATSDR, 2019a). Specific industrial activities present unique VOC exposure profiles; for instance, dry cleaning industry has historically been significant sources of perchloroethylene (ATSDR, 2019b), while the automotive industry involved in the manufacture of motor vehicles, is vulnerable to exposure to a complex mixture of solvents and isocyanates (Sparer et al., 2004). Even natural sources, such as biogenic VOCs (BVOCs) like isoprene and terpenes released by vegetation contribute to atmospheric VOCs (Guenther et al., 2012). Coal mining has been identified as a significant source of anthropogenic volatile organic compound emissions with persistent health hazards and fire risks to the workers working in underground mines. The major source of these VOCs, especially methane, is the coal seam. Additionally, the hydraulic oils, fuels, and lubricants used in mining equipment often contain substances like glycol ethers, benzene, ethylbenzene, toluene, and other hydrocarbons, which also contribute to VOC emissions (Weiss et al., 2016).

The adverse health effects of occupational exposure to volatile organic compounds (VOCs) can vary in severity and nature depending on the nature of specific chemicals involved, the duration and intensity of exposure, and individual vulnerability. Prolonged or high dose exposure can manifest into more serious long-term health issues, and can damage nervous system, liver, and kidneys. Certain VOCs are known or suspected carcinogens, increasing the risk of developing cancers like leukaemia. Respiratory problems, including asthma and other chronic lung diseases, can also be exacerbated or induced by VOC exposure. Moreover, some VOCs can affect cognitive functions, coordination, and memory, while others may have reproductive or developmental

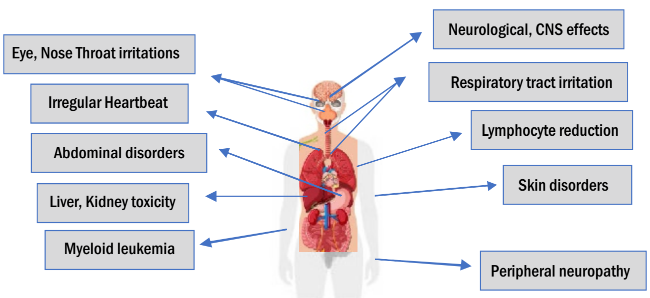

Fig.1: *Possible health implications of VOC exposure.*

***Table 1:** Workplace Sources, applications and potential health impacts of common VOCs.*

VOC Name	Common Workplace Sources	Primary Short - Term Health Effects (General) [a]	Primary Long - Term Health Effects (General & Specific) [b]	Key Industry / Application Examples [c]
Formaldehyde	Pressed wood products (particleboard, MDF), some paints, adhesives, building materials	Eye, nose, & throat irritation; headache; dizziness; respiratory distress	Known Carcinogen; organ damage; nervous system impairment; respiratory issues	Construction; Furniture manufacturing; Building materials
Benzene	Fuels (gasoline); industrial solvent	Eye, nose, & throat irritation; headache; dizziness; nausea	Known Carcinogen (leukemia); organ damage (bone marrow); nervous system impairment	Petrochemical industry; Fuel handling; Manufacturing(e.g., rubber, plastics)
Toluene	Paints, coatings, solvents, adhesives	Eye, nose, & throat irritation; headache; dizziness; confusion; nausea	Nervous system impairment (e.g., cognitive, coordination); organ damage (liver, kidney)	Painting; Printing; Manufacturing; Automotive refinishing
Xylenes (mixed)	Paints, coatings, solvents, adhesives	Eye, nose, & throat irritation; headache; dizziness; lack of coordination	Nervous system impairment; respiratory effects; potential organ damage	Painting; Printing; Manufacturing; Laboratories
Ethylbenzene	Paints, coatings, solvents; component of xylenes	Eye & throat irritation; dizziness	Possible Carcinogen; nervous system impairment; hearing damage	Manufacturing (e.g., styrene); Paints & coatings
Styrene	Paints, coatings (especially resins); manufacturing of plastics & rubber	Eye, nose, & throat irritation; headache; fatigue; dizziness	Possible Carcinogen; nervous system impairment; hearing damage	Plastics & resin manufacturing; Boat building; Paints
Trichloroethylene (TCE)	Solvents for degreasing; equipment cleaning	Headache; dizziness; confusion; nausea; facial numbness	Known Carcinogen; liver & kidney damage; nervous system impairment; immune system effects	Metal degreasing; Chemical manufacturing; Nuclear industry (cleaning)
Perchloroethylene (PCE)	Dry cleaning solvent; degreasing agent	Dizziness; headache; nausea; incoordination; eye & respiratory irritation	Probable Carcinogen; nervous system impairment; liver & kidney damage	Dry cleaning; Metal degreasing; Nuclear industry (cleaning)
Tributyl Phosphate (TBP)	Extractant in spent nuclear fuel reprocessing (PUREX process)	Eye & skin irritation; respiratory irritation	Potential for organ damage (liver, kidney); nervous system effects (less characterized in text)	Nuclear fuel reprocessing
n-Dodecane	Diluent for TBP in PUREX process; component of kerosene mixtures	Skin and respiratory irritation; dizziness;nausea (if high conc.)	Potential for organ damage; aspiration hazard (liquid)	Nuclear fuel reprocessing; Solvent manufacturing
Acetonitrile	Solvent for chromatography, sample preparation, quality control assays	Eye & respiratory irritation; headache; dizziness; nausea	Can metabolize to cyanide (high exposure); potential organ/nervous system effects	Analytical laboratories; Pharmaceutical manufacturing
Methanol	Solvent for chromatography, sample preparation; chemical intermediate	Headache; dizziness; nausea; blurred vision	Vision damage (optic nerve); nervous system damage; severe poisoning can be fatal	Analytical laboratories; Chemical manufacturing; Fuel component
Hexane (n- Hexane)	Solvent for chromatography, sample preparation; cleaning agent	Dizziness; headache; nausea; eye & throat irritation	Neurotoxicity (peripheral neuropathy-"Hexane neuropathy"); skin irritation	Analytical laboratories; Industrial cleaning; Food oil extraction
Dichloromethane (Methylene Chloride)	Solvent for chromatography, sample preparation; degreasing; paint stripping	Dizziness; fatigue; headache; nausea; eye & skin irritation	Probable Carcinogen; nervous system effects (can metabolize to carbon monoxide); liver effects	Analytical laboratories; Paint stripping; Degreasing; Pharmaceutical manufacturing
Isocyanates [3]	Automotive refinishing (paints, coatings); polyurethane manufacturing	Severe eye & respiratory irritation; chest tightness; asthmalike symptoms	Potent respiratory sensitizer (occupational asthma); skin sensitization	Automotive refinishing; Spray foam insulation; Polyurethane products mfg.

Notes:

[a,b] *Health effects listed here are generic and can vary significantly depending on the concentration, duration of exposure, individual sensitivity, and route of exposure (inhalation, skin contact).*

[c] *The "Key Industry / Application Examples" may not be exclusive.*

[d] *Isocyanates are generally considered separately from typical VOCs due to their strong sensitizing properties but are included here in the context of solvent mixtures.*

effects. The following Fig.1 illustrates the implications of VOC exposure on human health.

Within the nuclear fuel cycle, from uranium processing to spent fuel reprocessing and associated research activities, various VOCs are utilized. The most significant and well-documented use of VOCs takes place in spent nuclear fuel reprocessing, particularly in the PUREX (Plutonium Uranium Reduction Extraction) process, which employs tributyl phosphate (TBP) as an extractant, normally diluted in a hydrocarbon solvent such as n-dodecane or a refined kerosene mixture (Nash & Lumetta, 2011; IAEA, 2008). These solvents are essential for separating uranium and plutonium from fission products but can lead to worker exposure and atmospheric emissions if not meticulously managed. Beyond reprocessing, nuclear fuel production facilities and related research laboratories utilize a range of VOCs for auxiliary jobs such as equipment cleaning, degreasing, and maintenance, etc. The common examples include chlorinated solvents like trichloroethylene (TCE) or tetrachloroethylene and various alcohols or ketones. Analytical laboratories also extensively use VOCs, such as acetonitrile, methanol, hexane, and dichloromethane as solvents for chromatography, sample preparation, and quality control assays. Other VOCs, such as dioxane, formaldehyde, acetone, etc., are routinely used in radioanalytical laboratories. The presence of these compounds necessitates thorough monitoring and control, not only due to their intrinsic chemical toxicity but also because of the potential for influencing process chemistry or safety (e.g., formation of flammable gases or corrosive by-products). Table 1 lists some important VOCs, their sources at workplaces, main short-term and long-term health effects, and common industrial applications.

Challenges in the Detection and Monitoring of VOCs

Detecting and monitoring volatile organic compounds in occupational and environmental surroundings present significant analytical and logistical challenges, primarily due to their vast chemical diversity, wide, and fluctuating range of concentrations (from parts-per-trillion to percent levels), and often complex nature of their mixtures. First of all, the total number of individual VOCs (many coexisting at trace concentrations), necessitates use of highly sensitive and selective analytical techniques such as gas chromatography coupled with mass spectrometry (GC-MS) or flame ionization detection (GC-FID) for speciation and accurate quantification. However, these methods generally require discrete, and often time-consuming sampling (e.g., onto sorbent tubes followed by thermal desorption, or collection in summa canisters), and laboratory analysis (Demeestere et al., 2007; Woolfenden, 2010). Moreover, VOC concentrations display substantial spatiotemporal variability, influenced by recurrent and fluctuating source emissions, ventilation rates, and process cycles within a workplace, which make the representative sampling a difficult choice. Recording short-term peak exposures, crucial for highly toxic VOCs, generally requires real or near real-time monitoring, but many direct-reading instruments (e.g., those using photoionization detectors - PIDs, or metal-oxide sensors - MOS) may not be capable of differentiating between various VOCs or can be affected by interferences from environmental humidity or presence of other airborne compounds, providing only a total VOC (TVOC) reading, often insufficient from toxicological perspective (Fine et al., 2010). The selection of an appropriate sampling method (e.g., active vs. passive, whole air vs. sorbent-based) depends

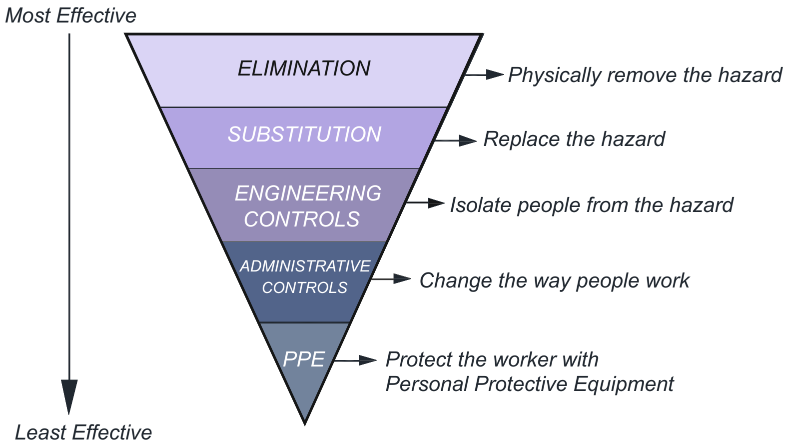

Fig.2: *Hierarchy of Controls.*

profoundly on the target VOCs' qualitative aspects (e.g., volatility, reactivity), the required detection limits, and the desired sampling duration, etc. (Brown, 2002; US EPA, 1999 - specifically Compendium Method TO-17 for sorbent tubes). Lastly, maintaining calibration accuracy for a wide range of VOCs and ensuring the integrity of samples during collection, storage, and transport can be challenging from quality assurance point of view.

Proactive management of VOC Hazards: The Hierarchy of Controls

Proactive management of the Volatile Organic Compound (VOC) hazards at workplace is vital for ensuring a healthy and safe environment for all occupants. An important and universally recognised concept in this regard is hierarchy of controls, which provides a rational framework in occupational health and safety (OHS) management to methodically eliminate or minimize workplace hazards by prioritizing control measures on the basis of their effectiveness and reliability. It outlines a categorization of desired actions, starting with the most effective and long-lasting protective measures those that remove the hazard entirely to less effective controls that depend more on human factors or provide a barrier or personal protection (Fig.1). Utilizing this hierarchy proactively for VOC management involves following and applying these principles from earliest stages of process design, material selection, and workplace layout. Instead of reacting to VOC exposures after they occur, a proactive approach uses the hierarchy as a decision-making tool to anticipate potential VOC hazards and implement the most feasible controls, ideally by designing out the need for hazardous VOCs or limiting them at their source, thereby preventing worker exposure and consequent health risks from materializing. At the most effective level, elimination involves completely removing the VOC source or process, such as by redesigning a product or not using VOC-containing adhesive/switching, or modifying a part of manufacturing technique (e.g., powder coating instead of solvent-based spraying, mechanical fastening instead of gluing) that obviates the need for VOC altogether. If elimination is not feasible, substitution is the next preferred step, which entails replacing hazardous VOCs with substances that are less volatile, less toxic, or non-hazardous while still performing the required function; examples include switching from high-VOC solvent-based paints to water-based or low-VOC formulations or replacing chlorinated solvents like trichloroethylene with less harmful aqueous cleaners or alternative organic solvents with lower toxicity (e.g., certain alcohols or esters, if suitable).

When elimination or substitution are not viable, engineering controls are implemented to isolate workers from the hazard or remove contaminants at the source. For VOCs, this often involves installing effective local exhaust ventilation (LEV) systems, such as fume hoods, paint booths with dedicated extraction, or capture hoods directly over vats of solvents, to draw vapours away from the workers' breathing zone before they can disperse into the general workplace air. Enclosing the processes that generate VOCs (e.g., closed-loop solvent recovery systems) or increasing general dilution ventilation can also decrease airborne concentrations, though LEV is generally more effective for point sources. Another engineering control measure involves the use of indoor VOC abatement technologies designed to efficiently reduce or even eliminate these airborne compounds. For example, air purifiers equipped with activated carbon filters play a crucial role in controlling VOC exposure by circulating indoor air and drawing VOC particles through the activated carbon, which then adsorbs or captures them, preventing their re-release. In addition to activated carbon systems, other progressive technologies like biofiltration, other adsorption methods, and catalytic oxidation can also be employed for comprehensive VOC removal. The deployment of these abatement systems yields significant benefits by considerably reducing VOC concentrations, thereby mitigating associated health risks for occupants. The major limitations of the adsorption process are the high cost of adsorbents and the necessity for their regeneration (Kamal et al., 2016).

Unlike adsorption, which only transfers pollutants from one phase to another, catalytic decomposition can directly convert volatile organic compounds (VOCs) into carbon dioxide and water (Yibing Mu et al., 2022). Additionally, non-thermal plasma (NTP)-assisted catalysis has emerged as an attractive alternative to conventional thermally activated catalysis. Non-thermal plasma is a highly ionized gas composed of electrons, various ions, radicals, excited species, and neutral species. Its non-equilibrium nature, low energy costs, and unique ability to initiate both physical and chemical reactions at low temperatures make it particularly beneficial. Besides, the interaction between NTP and the catalyst can enhance the selectivity in the decomposition of highly stable and corrosive chlorine-containing VOCs (Cl–VOCs) when compared to using plasma alone or thermal activation systems. In addition to the engineering controls, administrative controls can be applied to modify work practices and policies to reduce exposure. This includes developing and implementing safe work procedures (e.g., keeping lids on solvent containers, using minimal quantities, proper spill clean-up), establishing restricted access zones, scheduling high-VOC tasks during periods of low

Table 2: *Key Regulatory Frameworks and Occupational Exposure Limits (OELs) for Selected VOCs.*

Regulatory Body / Region	Key Regulatory	Key Provisions / Requirements related to VOCs	Example VOC	Occupational Exposure Limit (OEL) & Type	Notes / Source for OEL Examples
International Labour Organization (ILO)	C155 - Occupational Safety and Health Convention, 1981; C170 - Chemicals Convention, 1990; ILO Code of Practice "Safety in the use of chemicals at work."	Provides foundational principles for national legislation. Emphasizes risk assessment, prevention, control of chemical hazards (including VOCs), right to information, training. Promotes hierarchy of controls.	N/A	ILO does not typically set internationally binding OELs but provides guidance, compiles international OEL lists, and promotes the establishment of national OELs.	ILO Conventions & Recommendations.
European Union (EU)	Chemical Agents Directive (98/24/EC) & subsequent amending Directives establishing OELs; REACH Regulation (EC No 1907/2006); CLP Regulation (EC No 1272/2008).	Employers must assess risks from hazardous chemical agents, implement preventive measures (hierarchy of controls), adhere to binding OELVs (BOELVs) and indicative OELVs (IOELVs). REACH: Registration, Evaluation, Authorisation & Restriction of Chemicals. CLP: Classification, Labelling and Packaging.	Benzene	0.2 ppm (0.66 mg/m³) (8-hr TWA) - BOELV (Directive (EU) 2022/431). Skin notation. Carcinogen Category 1A.	ECHA (European Chemicals Agency); Official Journal of the EU. OELs are subject to change.
			Toluene	50 ppm (192 mg/m³) (8-hr TWA); 100 ppm (384 mg/m³) (STEL) - IOELV. Skin notation.	ECHA; SCOEL (Scientific Committee on Occupational Exposure Limits) recommendations.
			Formaldehyde	0.3 ppm (0.37 mg/m³) (8-hr TWA); 0.6 ppm (0.74 mg/m³) (STEL) for healthcare, funeral, embalming sectors until July 2024, then general limit. Skin notation. Carcinogen Category 1B, Sensitizer. (Directive (EU) 2019/983).	ECHA; Official Journal of the EU.
United States (OSHA)	29 CFR 1910.1000 (Air Contaminants - Tables Z-1, Z-2); Specific substance standards (e.g., Benzene: 29 CFR 1910.1028, Formaldehyde: 29 CFR 1910.1048); 29 CFR 1910.1200 (Hazard Communication Standard - HCS).	Sets Permissible Exposure Limits (PELs). Mandates hazard communication (Safety Data Sheets, labels, training). Requires engineering controls, work practices, and PPE. Specific standards often include medical surveillance and exposure monitoring.	Benzene	1 ppm (8-hr TWA); 5 ppm (STEL) - OSHA PEL (29 CFR 1910.1028). Action Level: 0.5 ppm.	OSHA website (www.osha.gov). PELs may differ from other recommended limits (e.g., NIOSH RELs, ACGIH TLVs).
			Xylene (mixed isomers)	100 ppm (435 mg/m³) (8-hr TWA) - OSHA PEL (Table Z-1).	OSHA website.
			Trichloroethyl-ene (TCE)	100 ppm (8-hr TWA); 200 ppm (Ceiling); 300 ppm (5-min Peak in any 2 hrs) - OSHA PEL (Table Z-2). OSHA is considering lowering this PEL.	OSHA website. Note: TCE is a known carcinogen.
India	The Factories Act, 1948 (and associated State Factories Rules). The Manufacture, Storage and Import of Hazardous Chemical Rules, 1989 (MSIHC Rules).	Sec 41F (general duties of occupier for health), Sch II of Factories Act (permissible levels of exposure), Sec 13 (ventilation), Sec 36 (dangerous fumes), Sec 35 (PPE). MSIHC rules mandate safety reports, on-site emergency plans.	Benzene	5 ppm (16 mg/m³) (8-hr TWA) - Schedule II, The Factories Act. Carcinogen.	The Factories Act, 1948,

occupancy or at the end of shifts, providing comprehensive worker training on VOC hazards and safe handling, and implementing job rotation to limit individual exposure durations. Finally, as the last line of defence, Personal Protective Equipment (PPE) is used when other controls cannot sufficiently reduce exposure. For VOCs, it is crucial to select appropriate respiratory protection, e.g., air-purifying respirators with organic vapor cartridges specific to the VOCs present or supplied-air respirators for high concentrations or oxygen-deficient environments. For selecting other PPEs such as chemical-resistant gloves, aprons, and eye protection (e.g., goggles, face shields) one must ensure that these are made from materials impervious to the specific VOCs being handled. The effectiveness of PPEs relies heavily on proper selection, fit, maintenance, and consistent, correct use by employees, underscoring why it is the last rung control measure in the hierarchy of control framework.

Legal and Regulatory Obligations Related to Occupational VOC Exposure

Internationally, organizations like the International Labour Organization (ILO) establish conventions (e.g., ILO, 1981, C155 -Occupational Safety and Health Convention) and recommendations outlining fundamental principles for national legislations, and emphasizing risk assessment, prevention, and control of chemical hazards, including VOCs. Highly industrialized countries, in general, have strong regulatory frameworks. European Union's Chemical Agents Directive (Council Directive 98/24/EC) mandates assessment of risks from hazardous chemical agents, implementation of preventive measures based on the hierarchy of controls, and compliance with obligatory occupational exposure limit values (OELVs) for specific VOCs. Similarly, the U.S. Occupational Safety and Health Administration (OSHA) provides Permissible Exposure Limits (PELs) for numerous airborne contaminants, many of which are VOCs (e.g., under 29 CFR 1910.1000), and mandates hazard communication (29 CFR 1910.1200). In India, the primary legislation governing OHS, including chemical exposure, is The Factories Act, 1948, along with the accompanying State Factories Rules, which may vary, to some extent, from state to state. Section 41F of the Factories Act outlines the general duties of the occupier to ensure the health of workers, which implicitly includes protection from harmful chemical exposures. More explicitly, Schedule II of The Factories Act, 1948 lists permissible levels of exposure for various toxic substances, many of which are common VOCs (e.g., benzene, toluene, xylene, trichloroethylene), serving as India's OELs. The Act also mandates provisions for effective ventilation measures for protection against dangerous fumes and gases (Section 13, Section 36), the supply of suitable personal protective equipment (Section 35) when hazards cannot be otherwise controlled, and administrative controls such as health monitoring of workers. Therefore, both globally and within India, the regulatory system expects the establishment to identify VOC hazards, assess risks, implement controls, monitor exposure levels, and train workers to ensure a safe working environment. The table 2 provides a summary of important regulatory frameworks and occupational exposure limits thereof.

Conclusion

Volatile Organic Compounds, emanating from diverse sources, ranging from industrial processes to everyday workplace products may present significant implications for both human health and the environment. Occupational exposure to VOCs can affect the health adversely and thus a comprehensive understanding and assessment of the potential VOC hazards is necessary for the implementation of proactive OHS management strategies. In accordance with the hierarchy of controls strategies, prioritizing elimination and substitution over other measures, wherever feasible, and diligently employing engineering and administrative measures can contribute to significant reduction in the workplace VOC exposure. Various national and international level legal and regulatory frameworks provide the standards and guidelines for monitoring, control, and worker protection vis-à-vis VOC exposure. Effective management of VOCs is not only a regulatory compliance but a commitment for workplace safety and well-being of occupational workers.

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Measuring Isotope Fingerprints of Water through Mass and Laser Spectrometry

Tools and Techniques for Stable Isotope Measurements in Hydrology

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Isotope hydrology is a powerful tool to understand source and movement of water in environment, which is essential for water resources management. Measurement of stable isotopic ratios is the primary requirement of isotope hydrology. Stable isotopic ratios ($^{2}H/^{1}H$, & $^{18}O/^{16}O$) undergo predictable fractionation/modification during environmental processes (evaporation & condensation) and provides basis for tracing the water molecules in hydrological cycle. Since these modifications are very small, advanced analytical instruments such as mass spectrometers and laser-based isotope analyzers are required for precise measurements. This article provides a brief summary of isotope measurement techniques pertaining to stable isotopes of water molecule.

The combined constituents of water molecule (^{1}H & ^{2}H and ^{16}O, ^{17}O & ^{18}O) can form nine isotopologues of water. Among these only $^{1}H_2{}^{16}O$ (99.76%), $^{1}H_2H^{16}O$ (320 ppm) and $^{1}H_2{}^{18}O$ (2040 ppm) have practical importance due to their measurable abundance. During evaporation and condensation processes these natural isotopic ratios change owing to mass differentiation and these changes allow labelling of different reservoirs of water with different isotopic signatures. Stable isotope ratio measurement can distinguish among different water reservoirs (i.e. rainwater, snowmelt, surface water & groundwater) and help in deducing the dynamics. The natural isotopic ratios are indeed very small and changes due to fractionation are still smaller, therefore measuring the absolute values of these isotopic ratios on a routine basis for a large number of samples is challenging. In addition, comparing the dataset from different laboratories would be difficult. Also, in hydrology, the change in the isotope ratio is more relevant than its absolute isotope ratio. Hence a normalized ratio is reported where relative deviation of the isotopic ratio of sample with respect to a standard is calculated and expressed by δ notation ($\delta = (R_{sample}/R_{standard} - 1) \times 1000$). The δ values are reported as per mil (per thousand, ‰) instead of percent since for better readability (McKinney et al., 1950).

Isotope Ratio Mass Spectrometer

Measurement of stable isotope dates back to early 20th century when Sir J. J. Thomson and Fransis William Aston developed a mass spectrograph and separated isotopes of Ne (^{20}Ne

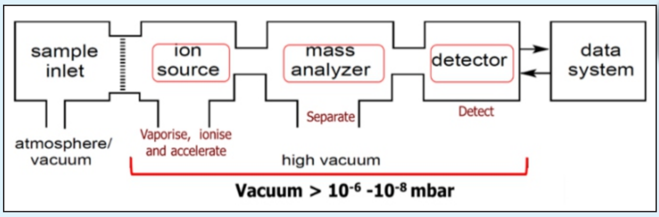

Fig. 1: A block diagram of conventional mass spectrometer.

and ^{22}Ne) (Griffiths, 2008). Subsequently several advancements were made including online sample preparation, automated data analysis, micro-sized sample analysis, enhanced precision & sensitivity and simultaneous multi-isotope measurements. These developments shaped the currently used Isotope Ratio Mass Spectrometer (IRMS), which still has the same basic design of mass spectrometer comprising an inlet system, an ion source, an analyzer for ion separation, and a detector for ion quantification (Fig.1). The ions are separated in the mass analyser based on their mass to charge ratio (m/z) utilising combined magnetic and electric fields. The samples are introduced into the mass analyser as gases; hence it is required to convert the samples into gaseous form.

Sample Preparation

There are several methods of sample preparation including gas-equilibration, pyrolysis and reduction. In gas-equilibration method, the water sample is equilibrated with H_2 and CO_2 for $^{2}H/^{1}H$ and $^{18}O/^{16}O$ measurements respectively. For deuterium measurement, samples are equilibrated for 7 hr at $40^{0}C$ in presence of Pt catalyst and for ^{18}O measurement, equilibration is done at $40^{0}C$ for 2.5 hr (Horita et al., 1989). The headspace gases are then dehydrated by passing through cold finger and finally introduced into the ionization chamber. Another method for conversion of water into H_2 gas is reduction by metallic zinc in a sealed tube at very high temperature (at $450^{0}C$) (Coleman et al., 1982). The reaction completion times are typically 30 minutes, after which the reaction tube is directly attached to mass spectrometer inlet. In pyrolysis mode, the water samples are pyrolyzed over glassy carbon at high temperature (>$1400^{0}C$) to produce H_2 and CO gases, which are then introduced into ionization chamber (Gehre et al., 2003).

Advancements of sample preparation methods have further opened the scope of isotope measurement of individual compounds/species in water sample (compound specific isotope analysis–CSIA) by interfacing the gas or liquid chromatographic setup with sample preparation unit. In the gas chromatography (GC)–IRMS, the dissolved volatile compounds in water can be analysed. Here, the sample mixture is introduced into GC column, which allows separation of the compounds based on their volatility and affinity toward stationary phase. The separated moieties are oxidised to corresponding gases and fed to ionization chamber. In liquid chromatography (LC)–IRMS, isotope ratios of dissolved compounds are measured. Here, the samples are injected to a stream of mobile phase maintained at high temperature (~$2000^{0}C$), which moves through a densely packed column of stationary phase by means of a pump. The compounds are separated based on their polarity, which are then combusted to generate gases such as CO_2, NO_x, SO_2. Some gasses are reduced using Cu turnings to convert (NO_x to N_2, & CO_2 into CO) and finally introduced into ionisation chamber.

In ionisation chamber, gaseous samples are converted to a beam of positive ions, which is focused and accelerated through a potential difference (V) so that all ions acquire same kinetic energy. Subsequently ions are subjected to a magnetic field applied perpendicular to the electrical field. Because of Lorentz force, ions take a circular path inside magnetic field and the monoenergetic ions are dispersed and separated based on their mass to charge ratio (m/z). The lighter masses follow a path with smaller radii while heavier masses have larger radii. Faraday cups are placed along the path of ion beams, which measure the ion currents and subsequently the isotope ratios are computed. Based on the inlet system IRMS are divided into (i) Dual inlet and (ii) continuous flow.

Dual Inlet – Isotope Ratio Mass Spectrometer

In this system the sample and reference gases are introduced into the ionisation chamber alternately. The heart of dual inlet system is the changeover valve that allows alternate introduction of sample and reference gases from two different reservoirs to ionisation chamber (Fig.2). The gases are fed to changeover valve by

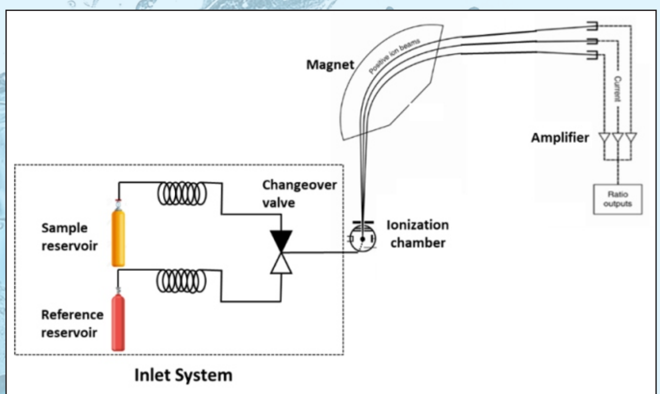

Fig.2: Schematic diagram of Dual Inlet Isotope Ratio Mass Spectrometer.

means of capillaries of around 0.1 mm diameter and about l m in length with crimps for adjusting gas flows at their ends. When either gas flows to ionisation chamber the other one is directed to vacuum waste chamber so that uninterrupted gas flows through capillaries. As sample and reference gases are measured under identical conditions, dual inlet systems are highly accurate and precise (Ghosh et al., 2003).

Continuous Flow- Isotope Ratio Mass Spectrometer

In continuous flow system the gases are introduced sequentially to the ionisation chamber along with He as carrier gas (Brenna, J. T. et al., 1997). The reference gas is introduced by a separate interface and pneumatic actuators quickly toggle between sample and reference gases to introduce the gases into ion analyser (Fig.3).

Laser based optical Techniques

Most molecules have absorption spectra in visible to near IR zone containing sharp peaks corresponding to roto-vibronic transition. Analysing the intensity of these characteristic IR peaks allows measurement of concentration of isotopologues. However, due to low natural abundance of isotopologues of water, the absorption peaks are too weak and precise quantification is difficult. However, the recent advancement in laser techniques has allowed the measurement of isotopic ratios of water precisely. This is achieved by increasing the path-length of the laser beam during absorption. The laser-based techniques are non-destructive, very fast and cost-effective. Two types of laser isotope analysers are widely used for hydrological investigations.

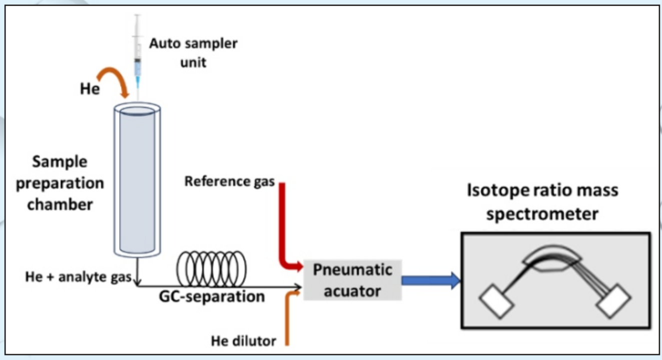

Fig.3: Schematic representation of a continuous flow IRMS system.

Cavity Ring Down Spectroscopy (CRDS)

Here a particular wavelength of light is allowed to resonate with a cavity filled with analyte gas. The cavity comprises two or more highly reflective mirrors (reflectance > 99.99%), where photons can propagate for prolonged time. Optical length of the cavity is typically few kilometres. When laser enters the cavity, resonance between laser light and ring down cavity is achieved by constructive interferences as light reflects back and forth between the mirrors (Fig.4). At this point, a sudden increase in intensity is detected by photo detectors that senses small amount of light leaking via either of the mirrors. As soon as the increase in intensity is detected, the incoming laser source is cut off and the light intensity is measured outside the cavity. Theoretically, intensity of light pulse decreases after each cycle due to absorption and scattering by medium and reflective losses. A CRDS spectroscopy measures the time taken to reduce the intensity to $1/e^{th}$ of its initial value. The measured time (ring down time) is then used to calculate the concentration of absorbing substance inside the cavity (Wahl et al., 2006; Santos et al., 2019). For measuring isotopologues of water molecule, the measurements are carried out separately at three different wavelengths, 1392 nm for $^{1}H_2{}^{16}O$, 1395 nm for $^{1}H_2{}^{18}O$, and 1403 nm for $^{1}H^{2}H^{16}O$. Despite of high sensitivity, CRDS has some limitations, which

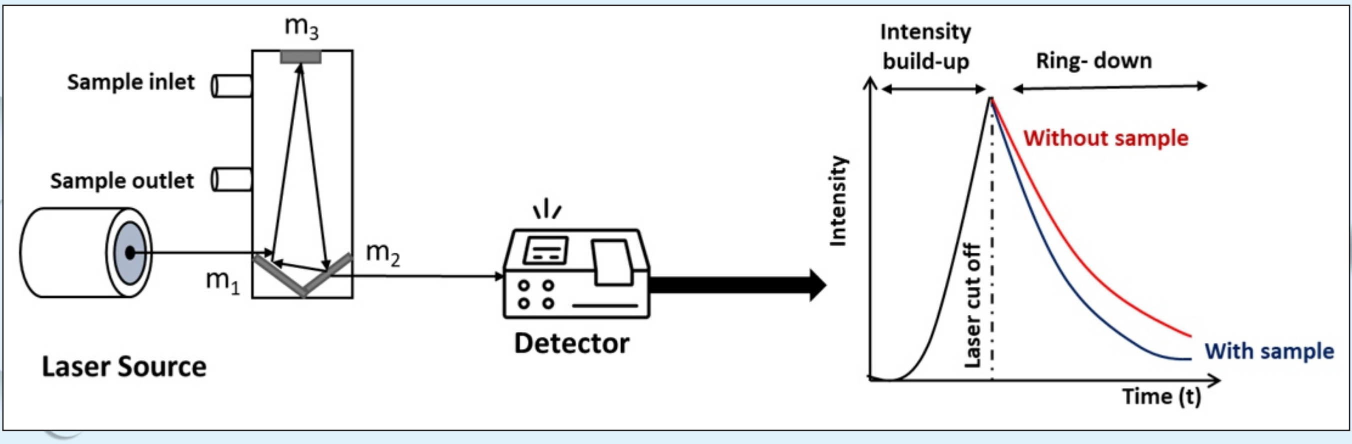

Fig.4: Instrumentation of a cavity ring down spectrometer with detector output.

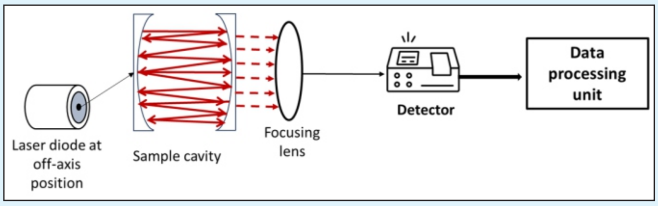

Fig.5: Schematic representation of OA-ICOS instrumentation.

includes requirement of sub-nanometre optomechanical precision, and stability of laser beam for wavelength resonance.

Off Axis - Integrated Cavity Output Spectroscopy (OA-ICOS)

In OA-ICOS, continuous scanning of laser wavelength is done to achieve a highly resolved spectrum (Fig.5). A tuneable diode laser is allowed to pass through a high-finesse cavity at an off-axis angle. Specific wavelengths are absorbed by water vapour present in the optical cavity. The intensity of transmitted light is measured by a photodiode and the difference between incident and transmitted light is utilised to calculate the concentration of each isotopologues. As wavelength scanning is possible from UV region to IR, the instrument focuses on the strongest absorption lines and this process enhances the sensitivity several times compared to CRDS. For stable isotope measurement in water sample a diode laser is used having wavelength cantered at 1390 nm (Gupta., 2023).

In OA-ICOS, multiple isotope ratios (e.g. δ^2H, δ^{18}O) can be measured simultaneously with a single scan, while in case of CRDS measurements need multiple wavelength scanning. Though IRMS remains the gold standard for stable isotope ratio measurement in water, laser-based techniques are getting more popularised due to the advantages in providing fast results, minimal sample preparation and cost effectiveness.

Conclusions

The advancements in isotope measurement systems are broadening the role of isotopes in hydrological systems, ecological sciences, climate studies. Many new methods are being developed using laser techniques for the measurement of different isotopes, which is allowing comprehensive understanding of the complex hydrological processes.

References for this article have been consolidated and are available upon request.

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Isotope Hydrology in India

In search of untouched frontiers and actionable inputs for water resource management

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Isotope hydrology was initiated in India concurrently with the beginning of the International Hydrological Decade (IHD) in 1964 by UNESCO, and its close collaboration with International Atomic Energy Agency (IAEA) for scientific and methodological developments for water resources. Indian isotope hydrology community also quickly picked up the nuances, and succeeded in keeping pace with the latest developments in this field so far. However, in the emergent scenario, it is urgently required to build an ecosystem favoring and facilitating exchange of ideas and collaboration among expert groups in isotope hydrology and other research domains if we have to trailblaze towards untouched frontiers of hydrology research rather than replicating the global trends. Such an interdisciplinary and multipronged approach in isotope hydrology is even more necessary to be able to provide actionable inputs for water resource management in India, and provide solutions to practical hydrological problems. A snippet of admirable achievements in isotope hydrology is presented in this review, followed by the limitations of missing links, and some of the most important research problems of scientific and societal relevance.

Isotope hydrology originated concurrently with the world-wide programme of the International Hydrological Decade (IHD), during 1965–1974, launched by the 13th session of the General Conference of United Nations Educational, Scientific and Cultural Organization (UNESCO) in 1964. IHD was the first concerted international endeavor to address the problems concerning freshwater worldwide and to promote international cooperation in research, studies, and the training of specialists and technicians in scientific hydrology. The IAEA and UNESCO established a close cooperation within the framework of IHD for scientific and methodological developments related to water resources. It was during this phase that the applications of stable and radioactive isotopes for hydrology were developed, including low level counting methods (Oeschgar, 1963); dating of groundwater with tritium and radiocarbon (Munnich et al., 1967); oxygen and hydrogen isotopes for studying soil water movement and evapotranspiration (Zimmermann et al., 1967); and infiltration and recharge through sand dunes in arid zones using stable isotopes and thermonuclear tritium (Dincer et al., 1974).

Initiation of Isotope Hydrology in India and the achievements hitherto

India was quick enough to learn the nuances, and pick up the pace with these latest developments in the world, and began use of environmental tritium to evaluate the groundwater recharge in the Semi-arid region of India (Sukhija and Rama, 1973), and in Western Uttar Pradesh (Datta et al 1973). This was followed by several other studies (Sukhija and Shah 1976; Gupta and Sharma, 1984; Athavale and Rangarajan 1988; Sukhija et al. 1996a, 1996b) in which environmental or injected tritium was used to estimate groundwater recharge and to understand recharge processes in arid and semi-arid regions of India.

In addition to use of environmental and injected tritium to understand groundwater recharge processes, the uranium series isotopes and radiocarbon were also used to understand river-groundwater interaction, groundwater age determination, and estimating horizontal flow velocities (Borole et al., 1979; Bhandari, et al., 1986). For estimating vertical leakage across semi-permeable aquitard layers, a dual tracer (^{32}Si and ^{14}C) dating method was also used (Gupta et al., 1981).

In addition to radiocarbon and uranium series methods, helium accumulation and $^4He/^{222}Rn$, methods have also been used for groundwater age determination and to understand the hydrothermal circulation along the major fault systems (Gupta and Deshpande, 2003a, b; Agrawal et al., 2006; Deshpande, 2006, Deshpande and Gupta, 2013).

The isotope tracers have also been used to understand origin, movement and mixing of natural contaminants like Fluoride (Gupta and Deshpande, 2003; Gupta et al., 2004), and Arsenic (Mukherjee et al., 2007). Isotopic composition in conjunction with geochemical properties have also been used to understand climatic signatures in the ground waters and to understand climatic controls on observed geochemical properties of groundwater (Sukhija et al., 1998, Gupta et al., 2005).

Among all isotopes, the stable isotopes of oxygen and hydrogen have been used most extensively in India due to its relative ease of sampling and analyses. What has been learnt from stable isotope applications in India by the turn of twentieth century, has been exhaustively compiled and reviewed earlier (Gupta and Deshpande, 2005a).

A DST sponsored National Programme on Isotope Fingerprinting of Waters of India (IWIN) launched in 2008 provided a massive impetus to application of oxygen and hydrogen isotopes for hydrology in India. This was achieved through wide spread sampling of water from different components of hydrological cycle (rainwater, groundwater, river water, surface waters of Arabian Sea and Bay of Bengal), and isotopic analyses of these samples. This was possible through a collaboration between 14 research and academic institutes, and central agencies of India (PRL, NIH, BARC, NRL-IARI, NIO, IIT-Kgp, Anna University, CWRDM, CRIDA, CGWB, CWC, CPCB and IMD), with Physical Research Laboratory (PRL) as the nodal agency for its coordination and implementation. Details about the IWIN National Programme are published (Gupta and Deshpande 2005b; Deshpande and Gupta, 2008; 2012).

The coordinated research under the aegis of IWIN National Programme has substantially revised and upgraded the fundamental understanding about many hydrological processes including kinetic fractionation under super-saturated environment, melt contribution to Ganga River, rain-vapour interaction, ground level vapour dynamics, magnitude of evaporation from falling raindrops, percentage of continental recycling, variation in vapour sources, surface water - groundwater interaction, megacryometeors, groundwater recharge and submarine groundwater discharge (Achyuthan et al. 2013; Deshpande et al., 2010, 2013 a and b, 2015; Ganguly et al., 2022, 2023; Hameed et al., 2014, 2015, 2016; Jeelani and Deshpande, 2017; Krishan

ISOTOPE HYDROLOGY research in India is at par with the latest trends and developments at international level. Very few laboratories in India are capable for analyzing radioactive isotopes for hydrological applications, hence these capabilities need to be rekindled, expanded and newly developed at multiple places.

et al., 2015, 2024; Maurya et al., 2011; Oza et al., 2020a,b, 2022; Pandey et al., 2022, 2023a,b; Purushothaman et al., 2012; Saranya et al., 2018; Warrier et al., 2015). This programme also contributed in capacity building in isotope hydrology through hand-holding of research institutions not equipped with isotope analytical facilities (University of Kashmir, Srinagar). The research findings from this sustained and targeted initiative are published in a series of research papers (Jeelani et al., 2017 a,b,c; 2018 a,b,c,d; 2021 a,b; Lone et al., 2017; 2019 a,b; 2021 a,b; 2022; 2023).

Besides the above mentioned coordinated and multi-institutional collaborative research programmes of larger magnitude, researchers from various academic and research institutes across India (IITs, IISER, NITs, JNU, MAHE, CWRDM, NCESS, and several others) have also carried out important hydrology research using stable and radioactive isotopes, in conjunction with other parameters. These numerous research studies led to important findings related to different aspects of hydrological cycle encompassing sub-surface, surface and atmospheric components. Some of the important results from these studies are related to lakes (Ramesh et al., 1993, Yadav 1997, Kumar & Nachiappan, 1999) stable isotopes in Yamuna and its tributaries (Dalai et al., 2002); evidence of dual (Arabian Sea and Bay of Bengal) vapour sources in monsoonal precipitation over north India (Sengupta and Sarkar 2006); positive amount effect in rainfall in western Ghats (Yadava et al., 2007); contribution of southwest monsoon rain to Bhagirathi River near Gaumukh, western Himalayas (Rai et al., 2009); submarine groundwater discharge in the coastal regions (Chakrabarti et al., 2028; Muthukumar et al., 2022); isotope characteristics of Indian Precipitation (Kumar et al., 2010); water vapour dynamics over Bay of Bengal during monsoon and monsoon circulation (Midhun et al., 2013; 2018); DIC and its $\delta^{13}C$ in Ganga River (Samanta et al., 2015); spatial variation in amount effect over peninsular India (Lekshmy et al., 2015); Intra-event isotope and raindrop size data of tropical rain (Managave et al., 2015); residence time of karst groundwater in mountainous catchment in western Himalayas (Shah et al., 2017); estimation of fraction of recycled moisture in rainwater over Indian sector of Southern Ocean (Rahul et al., 2018); water and carbon cycles in monsoon driven humid tropics of the Western Ghats (Tripti et al., 2018); contribution of snowmelt and glacier melt to the Bhagirathi River (Rai et al., 2019); Hydrological processes in Ganga River (Kumar et al., 2019); monsoon intra-seasonal oscillation and stratiform process in northern Bay of Bengal (Sengupta et al., 2020); tracing groundwater sources in Indian alluvial plains (Joshi et al., 2018) groundwater recharge processes in a semi-arid region of southern India (Gopinath et al., 2021); surface runoff in high mountain catchments (Dasgupta et al., 2021); source and transportation of water vapour in the western Himalayan region using triple water vapour isotopes (Ranjan et al., 2021); interaction between precipitation isotopes and biosphere-atmosphere interaction (Chakraborty et al., 2022); diverse rain forming processes revealed from isotope data of rain from three different geomorphic regions (Rajaveni et al., 2024); monsoon dynamics in the core monsoon zone in India (Chakraborty et al., 2025).

Review and Introspection

A large number of research publications and impressive scientific knowledge generated collectively by isotope hydrology researchers from India, as showcased above, may give an impression that isotope hydrology research in India is at par with the latest trends and developments at international level. However, a careful review of the Indian studies and comparison with some of the recent developments in isotopes hydrology at international level (Birkel et al., 2025; Jasechko, 2019; Ehleringer et al., 2016; Bowen et al., 2011) reveals that: (1) We are hardly able to keep pace with the multi-disciplinary, multi-pronged and radically novel approaches in isotope hydrology invented and adopted by the trailblazers from time to time. (2) Directly actionable input for water resource development and management is not arising from most of the isotope hydrology studies in India. (3) Water resource managers and planner in India are not directly involved in the isotope applications in hydrology. (4) Most of the isotope hydrology laboratories in India are set up by academic and research institutes where researchers undertake isotope-based hydrology research, but are not specifically mandated to work for solutions to a particular water resource problem of a given area. (5) Even those agencies which are specifically mandated to address the water resource related issues and manage the water resources have not adopted isotope approach as part of their standard methodologies. (6) There is greater appreciation, recognition and reward for publication of scientific research in high impact journal, compared to that for undertaking a study to provide possible solutions to a water resource problem of societal relevance, which can yield technical report but not necessarily a high impact publication.

ACCURATE UNDERSTANDING of spatio-temporal variation in vapour sources (Arabian Sea, Bay of Bengal, Mediterranean region, and terrestrial recycling) for rain in different parts of India is very important and can be studied accurately only by isotopic characterization of rain for identifying the source.

Missing Links

In the backdrop of the above scenario in India, following missing links are prominently identified: (1) The inter-disciplinary (hydrology, geology, geophysics, geomorphology, climatology, oceanography, atmospheric science, environmental science) and multi-pronged (mathematical and statistical remote sensing, isotope embedded modelling, Artificial Intelligence) approach adopted in the globally leading research is not so commonly adopted in isotope hydrology in India. (2) A specific information gateway (school, consortia, workshop, conference) for isotope hydrology, meant to facilitate the inter-disciplinary dialogues and cross pollination of ideas is urgently needed. (3) Isotope applications in hydrology are presently dominated by conveniently analyzed isotopes such as stable isotopes of oxygen and hydrogen, and the radioactive isotope of Radon. These measurements are possible through table-top or transportable equipment. However, the application of the radioactive isotopes (^{14}C, ^{3}H, ^{36}Cl), and noble gases (^{39}Ar, ^{81}Kr, and ^{85}Kr), which is more important for groundwater age determination, assessment, development and management, has diminished over the past few decades. This could be due to cumbersome laboratory procedures, which are both cost and labor intensive. Very few laboratories in India are capable of analyzing these and other radioactive isotopes for hydrological applications, hence these capabilities need to be rekindled, expanded and newly developed at multiple places.

Pending Research Problems

Specific research problems in hydrology which needs to be addressed urgently with the multi-pronged and multi-disciplinary isotope applications are summarized in the following: (1) India has a vast coastline of more than 7500 km, through which an estimated ~155 km^3 of submarine groundwater discharge (SGD) is being lost into the oceans, although exact volume of SGD is not ascertained. If the SGD locations, volumes and feasibility of extracting it can be ascertained, it will be a big boost for the water resource potential of the country. (2) The terrestrially recycled water vapor is a significant proportion of annual water budget of India, but not uniform across the country. Estimating regionally varying terrestrial recycling is important for accurate assessment of water budget and also for evaluating the most feasible agricultural practices in the wake of imminent climate change. (3) The glaciers feeding the eastern Rivers in the Indus system are retreating faster compared to glaciers in the Karakoram, feeding western rivers. It is very important to estimate time varying contribution of glacial and snowmelt to stream discharge of the six rivers of Indus system draining out of India. This is important for revisiting annual average and seasonal flows in six rivers of the Indus system, particularly because climate change response of cryosphere is highly variable geographically. (4) The deeper confined groundwater extracted and applied for irrigation in several parts of the country effectively transfers static groundwater from passive stagnation in sub-surface domain into active atmospheric circulation. It is important to quantitatively estimate this transfer of water mass because it has implications to static groundwater reserves and increasing water flux through hydrological cycle. (5) Interaction between the rainwater – Intermittent Rivers and Ephemeral Streams (IRES) and groundwater in dryland regions can be studied only with application of isotopes in conjunction with remote sensing and modeling. Studying this is important because arid regions, mainly in the northwestern India, are the most water stressed regions but there are also reports of westward shifting of monsoonal rainfall belts. (6) Accurate understanding of spatio-temporal variation in vapour sources (Arabian Sea, Bay of Bengal, Mediterranean region, and terrestrial recycling) for rain in different parts of the country is very important and can be studied accurately only by isotopic characterization of rain for identifying the source. This is particularly more important in Himalayas because the dynamical structure, evolution-decay, and interaction of WDs with the Himalayas is very different for western and central Himalayas. (7) Use of isotopes in managing urban water resources has not been initiated yet in India though spatial and vertical understanding of water supporting urban systems derived from the stable isotopes has been successfully used as a management tool in other countries.

Epilogue

If the isotope tracer application in hydrology research has to play a prominent role in deriving new knowledge for academic interest and providing effective solutions for societal problems, it is essential to address the organizational aspects, and improve understanding on the identified missing links, discussed here. It is also necessary to disruptively initiate major coordinated research on the pending problems identified herein.

References for this article have been consolidated and are available upon request.

Professor R. D. Deshpande is a hydrology researcher well-known for his research contributions in addressing fundamental scientific questions concerning subsurface, surface and atmospheric components of hydrology. He is affiliated with Physical Research Laboratory (PRL), a unit of Dept. of Space, Govt. of India, Ahmedabad, from where he superannuated as a Senior Professor and Chairman, Geosciences Division. His research over more than three decades at PRL, based on applications of stable and radioactive isotopes as tracers, in conjunction with other geohydrological and hydro-meteorological parameters and geochemical tracers has provided important new insights about fundamental hydrological processes.
Prof. Deshpande was the Principal Co-ordinator of the National Programme on Isotope Fingerprinting of Waters of India (IWIN). He has mentored several isotope hydrology research groups in different academic and research institutes within India. He has served several Ministries and Departments in Government of India, and the State Governments as an expert member in advisory, monitoring and review committees, Senate and Board of Studies. He is the Fellow of the Geological Society of India and the Gujarat Science Academy. He has more than 100 research publications to his credit, with over 3000 citations.

Heaping dividends for Isotope Hydrology

Through Global Partnerships

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Two-thirds of the Earth's geographical surface is covered by water, however, most of it is not ideal for drinking purposes and the resources used by mankind comes mainly from underground aquifers. Usually, such aquifers remain connected to rivers and surface water bodies and hence have inflows during dry seasons and feed the associated lakes and rivers during wet seasons. Despite the voluminous occurrences of waterbodies, still we are not certain about the sustainability of these waterbodies for our future generations. Climate change, over-extraction and anthropogenic pollutions (due to mining, textile industries, livestock farming) are some of the key factors altering the rates of feeding and replenishment of a given 'hydrological cycle' (evaporation, precipitation, infiltration, runoff, returning to ocean/atmosphere).

The recently published United Nations data (WHO/UNICEF Joint Monitoring Program Report 2023) pertaining to SDG-6 (Sustainable Development Goal – Clean Water and Sanitation) suggests that of the current over 8 billion population, 2.2 billion (~1 in 4) live without safely managed drinking water, and approximately 1.8 billion people still lack access to drinking water on-premises. As per the World Meteorological Organization (WMO) Report 2021, there are about 2 billion people living in countries under 'water stress' and ~3.6 billion face 'inadequate access to water' at least a month. As per the World Health Organization (WHO) 2023 report, nearly 1000 children, below 5 years, die every day due to consumption of unsafe water, sanitation and hygiene. Rough assessments suggest that at least 6 times faster improvements are needed in the domains of safely managed drinking water to achieve SDG-6. Achieving this goal NOW is crucial, as any delay will make the future challenge exponentially more difficult.

As per the World Population Prospectus (2024) shared by Department of Economic and Social Affairs Population Division (UN DESA/POP/2024/TR/NO.9), 'the world's population is expected to continue growing over the coming 5-6 decades, reaching a peak around 10.3 billion people in the mid-2080s. Following this, it will decline marginally to 10.2 billion by the end of this century. This population growth curve is expected to shape up differently among the SDG regional groupings e.g. Sub-Saharan Africa, Northern Africa and Western Asia, Central and Southern Asia, Eastern and South-Eastern Asia, Latin America and the Caribbean, Australia and New Zealand, Oceania, Europe and Northern America, including 'Least Developed Countries (LDC)', 'Landlocked Developing Countries (LLDC)' and 'Small Island Developing States (SIDS)'.

Overcoming Challenges

The only way out to address these challenges is through effective and sustainable water resource management. Respective Governments along with their responsible laboratories and organizations should invest its resources to develop robust and effective strategies, which should integrate real-time feedback mechanisms, at regional, interregional levels and national levels, responding to the changing demands and futuristic needs efficiently. In such efforts key roles are to be played by

- *Isotope Hydrology techniques for sustainable water management* for drinking water, irrigation and industrial sectors by tracking the movement of water through respective hydrological domains, tracing the original source of groundwater, and examining possible mixing processes.

- *Continuously upgrading the methodologies* for water resources evaluation, both its quantity & quality.

Capacity building will be another important aspect to address the water security issues in future. Training and state of the art infrastructure for isotope hydrology laboratories are absolutely necessary to prepare young professionals for data acquisitions, monitoring and interpretations. On the whole we require concerted global efforts to safeguard the water resources for future use.

International Concerted Efforts

The International Atomic Energy Agency (IAEA) is playing crucial roles in all the domains mentioned above through application of '**isotope hydrological techniques**' (oxygen-18, deuterium and tritium of water molecule) as promising tools. In recent times naturally occurring tracers e.g. hydrogen (tritium), carbon (carbon-14) and noble gases (helium-3, helium-4 and krypton-81); and other isotopes like boron-11, nitrogen-15, and sulfur-34, etc. are being explored for identifying the pollutant sources.

The Agency is also maintaining international platforms like ***Global Network of Isotopes in Precipitation (GNIP), Global Network of Isotope Rivers (GNIR)*** and ***Global Water Analysis Laboratory (GloWAL) Network*** for empowering the Member States to generate their own chemical, biological and isotopic water data and for providing basic data for the use of isotopes in hydrological investigations within the scope of water resources inventory, planning and development. IAEA and WMO jointly established the GNIP in 1960 to track temporal and spatial variations in oxygen-18 and deuterium in the context of precipitation. GNIR is relatively younger initiative (2002) focused on worldwide data collection, compilation and dissemination of isotopic assays of Earth's river waters. A couple of years ago the 'GloWAL' initiative was launched at the UN 2023 Water Conference, with the aim of establishing global collaboration and communication among Hydrological laboratories for sharing knowledge and promoting capacity building through running training programs. IAEA also encourages its Member States to participate in its technical cooperation program, bilateral cooperation and collaboration with other international organizations, for better understanding the challenges and address them collectively. Needless to say, such multidimensional global approaches are absolutely necessary for strategic planning and holistic management of water resources.

AMONG ALL OTHER INTERVENTIONS, Isotope techniques in hydrology enhances our understanding of the water cycle at local, regional, and global scales—providing the knowledge needed to meet the targets of SDG 6 and ensure water sustainability for future generations.

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Groundwater Resource Assessment of India

A scientific approach towards making the invisible visible

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Groundwater has become a fundamental resource for meeting the freshwater needs of various sectors in India. The sustainable development and efficient management of this limited resource is challenging, esp. in Indian context which has a unique and very diverse hydrogeological and geological setup. For quantification and prioritizing the areas for groundwater management interventions, the annual assessment is carried out jointly by Central Ground Water Board (CGWB) and State Ground Water Departments. The current assessment of 2024 estimates total annual groundwater recharge at 446.90 billion cubic meter (bcm) and extraction at 245.64 bcm, with an overall stage of extraction 60.47%. Out of 6,746 assessment units (Blocks/ Mandals/ Taluks etc.) 751 (11.13%) are 'Over-exploited', 206 (3.05%) are 'Critical', 711 (10.54%) are 'Semi-critical', and 4,951 (73.39%) are 'Safe'. Additionally, 127 (1.88%) units have saline groundwater resources. Compared to 2017, groundwater recharge has increased by 15 bcm, while extraction declined by 3 bcm. The assessment results are being utilized for regulation for groundwater extraction, planning, policy making and implementation of groundwater management strategies of the country.

It is rightly said that we can manage only what we can measure. This statement assumes even more relevance for resources that are invisible in nature and its quantum cannot be witnessed (World Bank, 2012). Groundwater, stored within the aquifers beneath the surface, is the backbone of India's agriculture and drinking water security, contributing nearly 62% to irrigation, 85% to rural water supply, and 50% to urban water supply (World Bank 2012; Foster and Willetts 2019). Groundwater extraction from aquifers to meet various requirements of the growing population has raised concerns about overexploitation of the resources, decline in water level and deterioration in groundwater quality in several parts of the country (Bhanja et al. 2017; Saha & Ray 2018). The adverse effect has caused tragedy for the people, with some areas facing not only reduced access to groundwater but also compromised water quality. Considering these, scientific and judicious management of the country's groundwater resources is the need of the hour, which fundamentally requires accurate assessment.

The National Water Policy of 2012 emphasizes periodic, scientifically-based assessments of groundwater resources, including evaluating trends in water availability due to factors such as climate change during water resource planning. Following that, Groundwater Resource Assessment is carried out at periodical intervals jointly by Central Ground Water Board and State Ground Water Departments and under the guidance of the respective State Level Committee (SLC) on Groundwater Assessment at State Levels and under the overall supervision of the Central Level Expert Group (CLEG). Such joint exercises have been taken up earlier in 1980, 1995, 2004, 2009, 2011, 2013, 2017, 2020 and 2022. From 2022, the exercise is being carried out annually (CGWB Achieve, 2022).

The dynamic groundwater resource assessment in India is carried out using a mass balance approach based on the lumped model framework, as defined in the Groundwater Estimation Committee (GEC), 2015 methodology. The methodology defines the approach: i) Estimation of Annual Groundwater Recharge by accounting for contributions from various sources such as rainfall, surface water bodies, return flow from irrigation, and recharge from water conservation structures, ii) from this total recharge, a provision is made for natural discharge, and the remaining component is considered as the Annual Extractable Groundwater Resource, iii) the Annual Groundwater Extraction is estimated based on groundwater usage across sectors, including agriculture, industry, and domestic, iv) Stage of Groundwater Extraction is then calculated as the ratio of annual extraction to extractable resource, expressed in percentage, v) finally, assessment units (AUs) are categorized into four classes Safe (≤70%), Semi-Critical (>70%–≤90%), Critical (>90%–≤100%), and Over-Exploited (>100%)—based on the stage of extraction (GEC, CGWB 2015).

As per Groundwater Resource Assessment of the Country for the year 2024, the total annual groundwater recharge in India has been estimated as 446.90 bcm, with an extractable resource of 406.19 bcm after accounting for natural discharge. Rainfall recharge during monsoon and non-monsoon periods is the primary contributor to total annual groundwater recharge, accounting for 270.91 bcm (61%) of the total recharge (Monsoon: 55%, Non-monsoon: 6%). The remaining 39% (175.68 bcm) comes from other sources like canal seepage, irrigation return flow, and recharge from tanks, ponds, and

Scientific collaborations have been initiated with BARC for investigating the role of paleochannels in reviving the groundwater resources in northwestern part of India, aquifer mapping studies in Central Ganga Plains, groundwater recharge rate estimation using injected radiotracer techniques and evaluating sustainability of deep aquifers.

water conservation structures. Rainfall contributes over 70% of annual groundwater recharge in the Indian States/UTs: Assam, Goa, Gujarat, Jharkhand, Kerala, Madhya Pradesh, Manipur, Meghalaya, Mizoram, Rajasthan, Daman & Diu, and Lakshadweep. The total annual recharge into depth units (m), is highest (>0.20 m) in the Indus-Ganga-Brahmaputra alluvial belt covering States Punjab, Haryana, Uttar Pradesh, Bihar, West Bengal, and North-Eastern valleys, where abundant rainfall and alluvial formations support replenishment (Fig.1). The eastern coastal belt also has high groundwater recharge (>0.20 m). In contrast, arid regions like Rajasthan and northern Gujarat experience very low recharge (<0.075 m), while hard rock terrains in Southern and Central India have moderate recharge (0.075–0.20 m) due to lower infiltration and limited storage capacity (GEC, CGWB 2022).

The Total Annual Groundwater Extraction of the

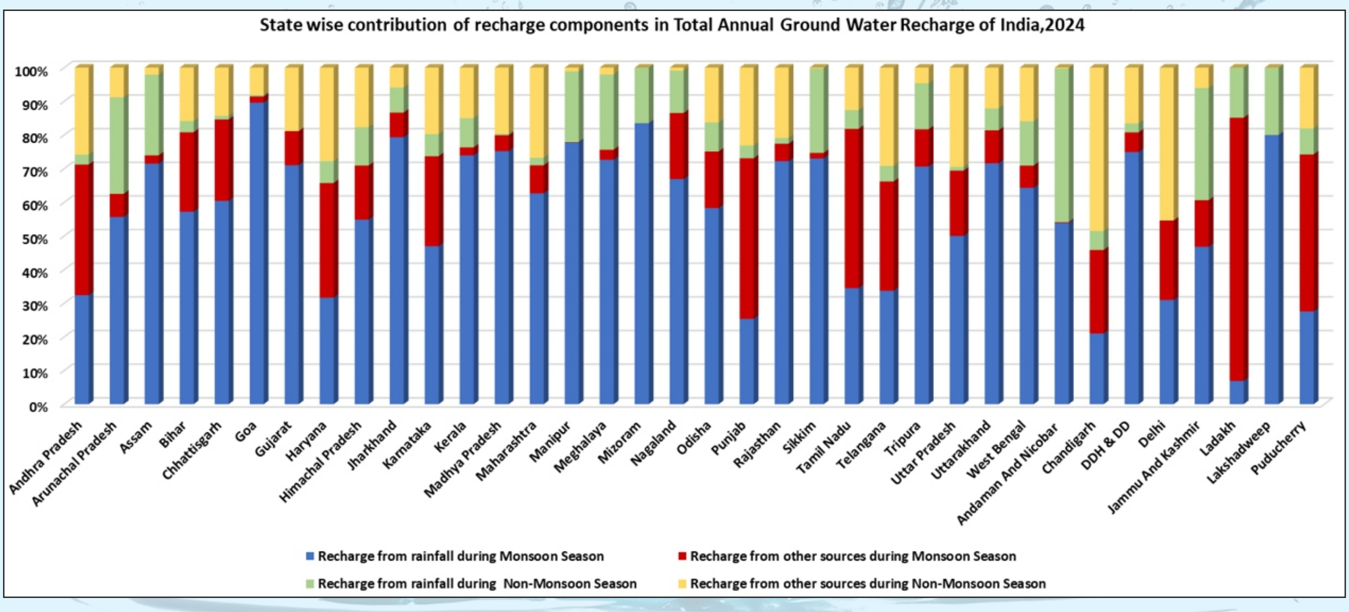

Fig.1: State wise contribution of recharge components in Total Annual Groundwater Recharge of India, 2024.

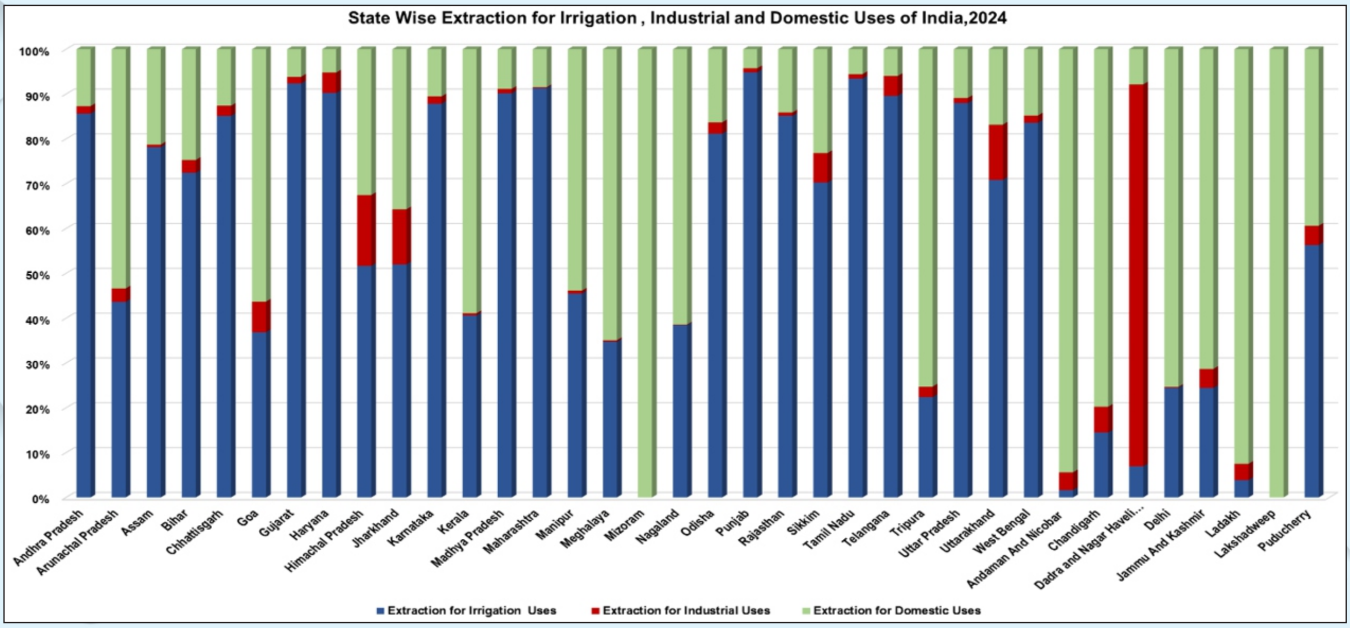

Fig.2: State wise % of Groundwater extraction for Irrigation, Industrial and Domestic Purposes, 2024.

The efforts otowards artificial recharge of groundwater and water conservation, along with the impact of various schemes and initiatives, are bringing about transformative changes in the country's groundwater resources.

entire country for the year 2024 has been estimated as 245.64 bcm (Fig.2). The agriculture sector is the largest consumer of groundwater accounting for 87% of the total annual groundwater extraction, which amounts to 213.29 bcm. The domestic consumption accounts for 11% (28.07 bcm), while industrial use represents 2% (4.28 bcm) of total annual groundwater extraction of the country. In the states/UTs of, Arunachal Pradesh, Delhi, Goa, Kerala, Manipur, Meghalaya, Mizoram, Nagaland, Tripura, Andaman and Nicobar, Chandigarh, Jammu and Kashmir, Ladakh, Lakshadweep the groundwater extraction for domestic uses is more than 40 % (GEC, CGWB 2022).

The overall stage of groundwater extraction in the country is 60.47 %. The State/UT wise distribution of Stage of Groundwater Extraction is as follows (Fig.3):

- **Stage of Groundwater Extraction >100%:** Punjab, Rajasthan, Dadra and Nagar Haveli and Daman and Diu, Haryana, and Delhi.
- **Stage of Groundwater Extraction >90% to 100%:** Nil
- **Stage of Groundwater Extraction >70% to 90%:** Tamil Nadu, Uttar Pradesh, Puducherry and Chandigarh.
- **Stage of Groundwater Extraction <70%:** Andhra Pradesh, Arunachal Pradesh, Assam, Bihar, Chhattisgarh, Goa, Gujarat, Himachal Pradesh, Jharkhand, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Manipur, Meghalaya, Mizoram, Nagaland, Odisha, Sikkim, Telangana, Tripura, Uttarakhand, West Bengal, Andaman and Nicobar, Jammu and Kashmir, Ladakh, Lakshadweep.

Out of 6,746 assessment units (Blocks/ Mandals/ Taluks etc.), 751 (11.13%) are 'Over-exploited', where groundwater extraction exceeds recharge. 206 (3.05%) are 'Critical' (90-100% stage of extraction), 711 (10.54%) are 'Semi-critical' (70-90% SoE), and 4,951 (73.39%) are 'Safe' (<70% SoE) (Fig.4). Additionally, 127 (1.88%) units have saline groundwater. States with over 25% Over-exploited and Critical units include Delhi, Haryana, Punjab, Rajasthan, Tamil Nadu, Dadra & Nagar Haveli, and Daman & Diu. Of India's 2.48 million sq. km recharge-worthy area, 16.93% is Over-exploited, 3.55% is Critical, 11.40% is Semi-Critical, 66.57% is Safe, and 1.55% is Saline. Regarding total extractable resources (406.19 bcm), 46.02 bcm (11.33%) is Over-exploited, 13.23 bcm (3.26%) is Critical, 45.76 bcm (11.27%) is Semi-Critical, and 301.17 bcm (74.14%) is Safe (GEC, CGWB 2022).

Artificial recharge and water conservation initiatives are being actively implemented through various schemes and programmes by both the Central and State Governments (Satapathy,

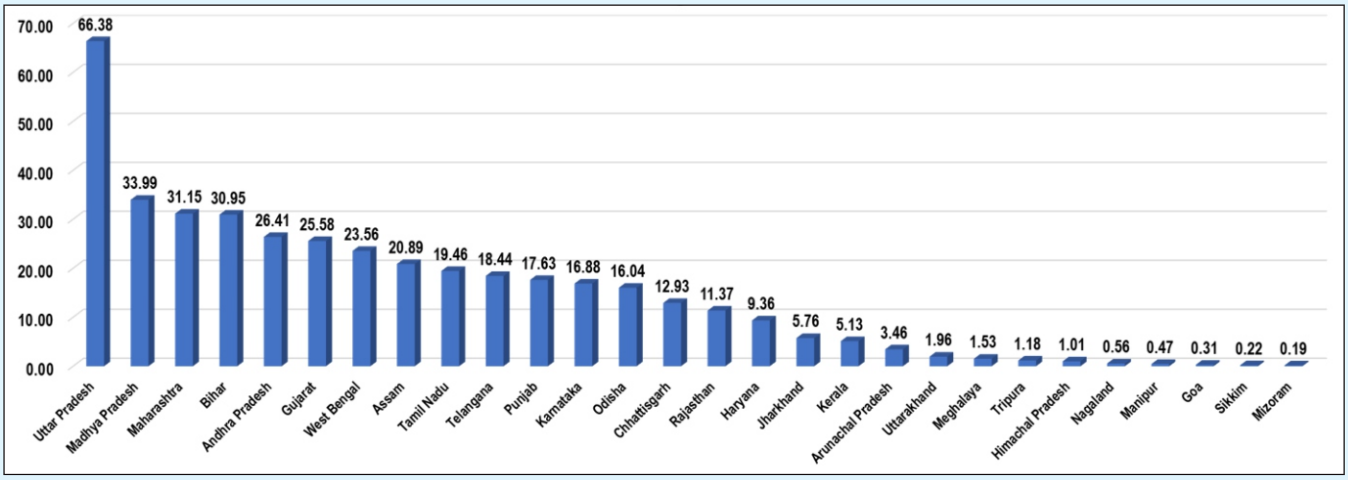

Fig.3: Stage of Groundwater Extraction of Major States.

2023). In recent years, the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA), 2005, has emerged as a key driver of water conservation efforts across rural India. The Jal Shakti Abhiyan launched in 2019 with the motto "Catch the Rain, where it falls, when it falls" has further accelerated the implementation of decentralized water resource management practices. Atal Bhujal Yojana (ATAL JAL) with focus on community participation and demand side interventions for sustainable groundwater management in identified water stressed areas in 7 States has been taken up by Government of India. The Mission Amrit Sarovar was launched by the Central Government in 2022 to rejuvenate 75 water bodies in each district of the country. Ministry of Jal Shakti, Govt of India has circulated a Model Bill to all the States/UTs to enable them to enact suitable groundwater legislation for regulation of its development, which also includes provision of rainwater harvesting. So far, 19 States/UTs have adopted and implemented the groundwater legislation. Other Government interventions include the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), Atal Mission for Rejuvenation and Urban Transformation (AMRUT), the Model Building Bye-Laws (2016), and the Urban and Regional Development Plan Formulation and Implementation Guidelines (2014), which intends to integrate water conservation across both urban and rural planning frameworks. The efforts towards artificial recharge of groundwater and water conservation, along with the impact of various schemes and initiatives, are bringing about transformative changes in the country's groundwater resources. These positive outcomes are also reflected in the results of resource assessments. In comparison to 2017, the groundwater recharge has increased from 431.86 bcm in 2017 to 446.90 bcm in 2024, with an increase of 15.04 bcm. Recharge from tanks, ponds and water conservation structures has increased by 11.36 bcm during this period (GEC, CGWB, 2017).

Similar efforts have been made in demand-side management by the government. The Bureau of Water Use Efficiency has been established under the National Water Mission to plan and implement a nationwide programme for promoting efficient water use across irrigation, domestic water supply, municipal, and industrial sectors. Considering the substantial extraction of

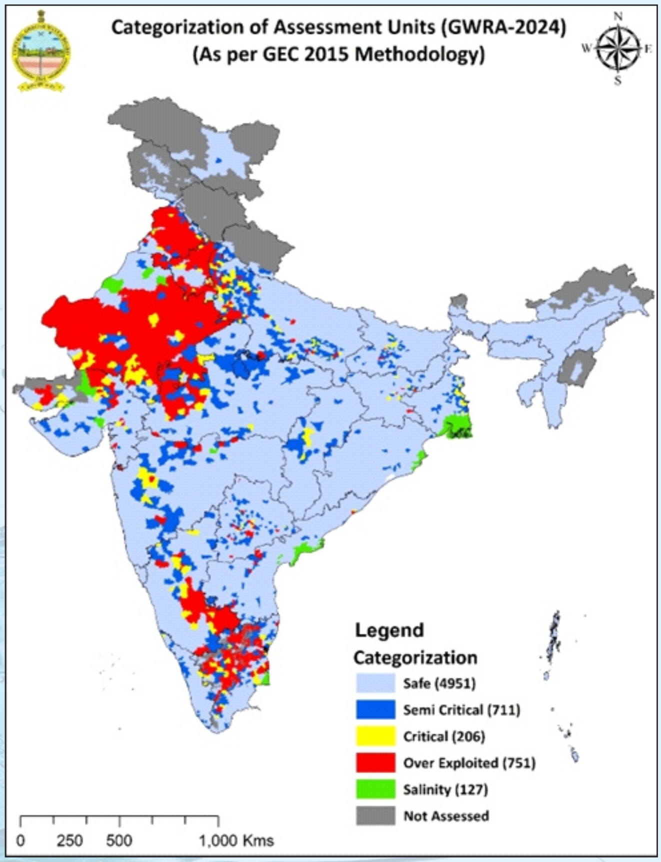

Fig.4: Categorization of Assessment Units, 2024.

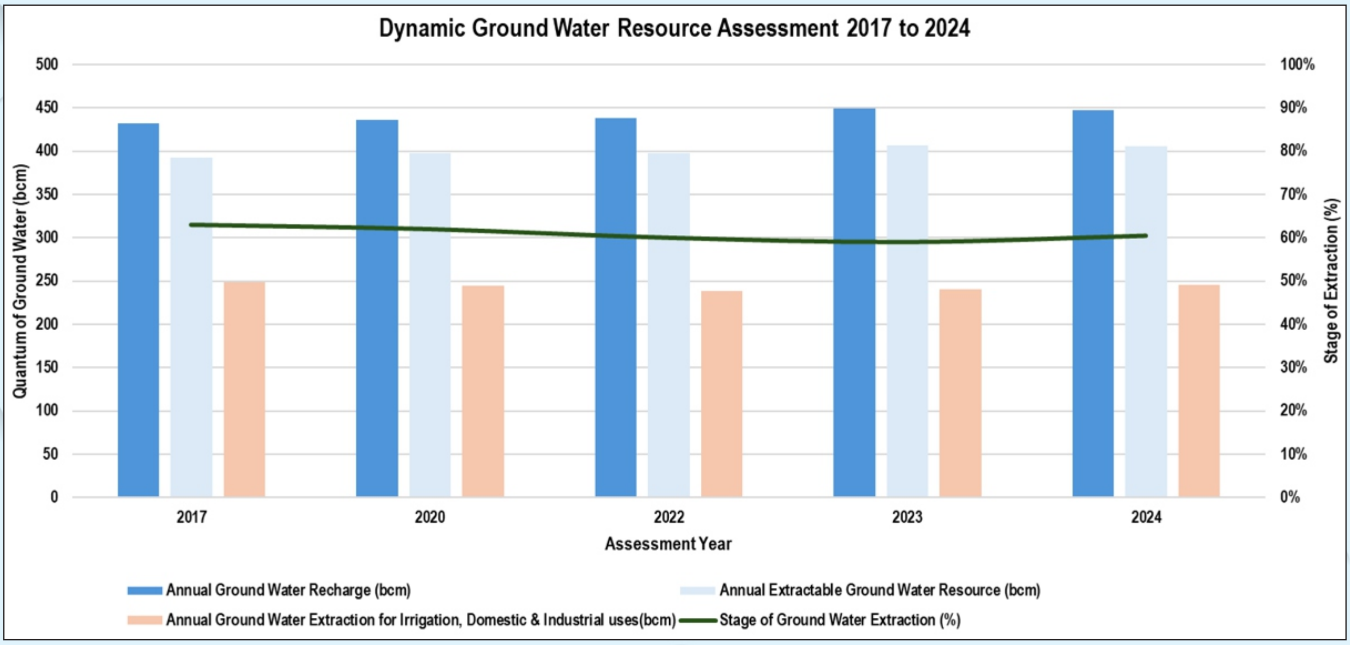

Fig.5: Dynamic Groundwater Resource Assessment, 2017 to 2024.

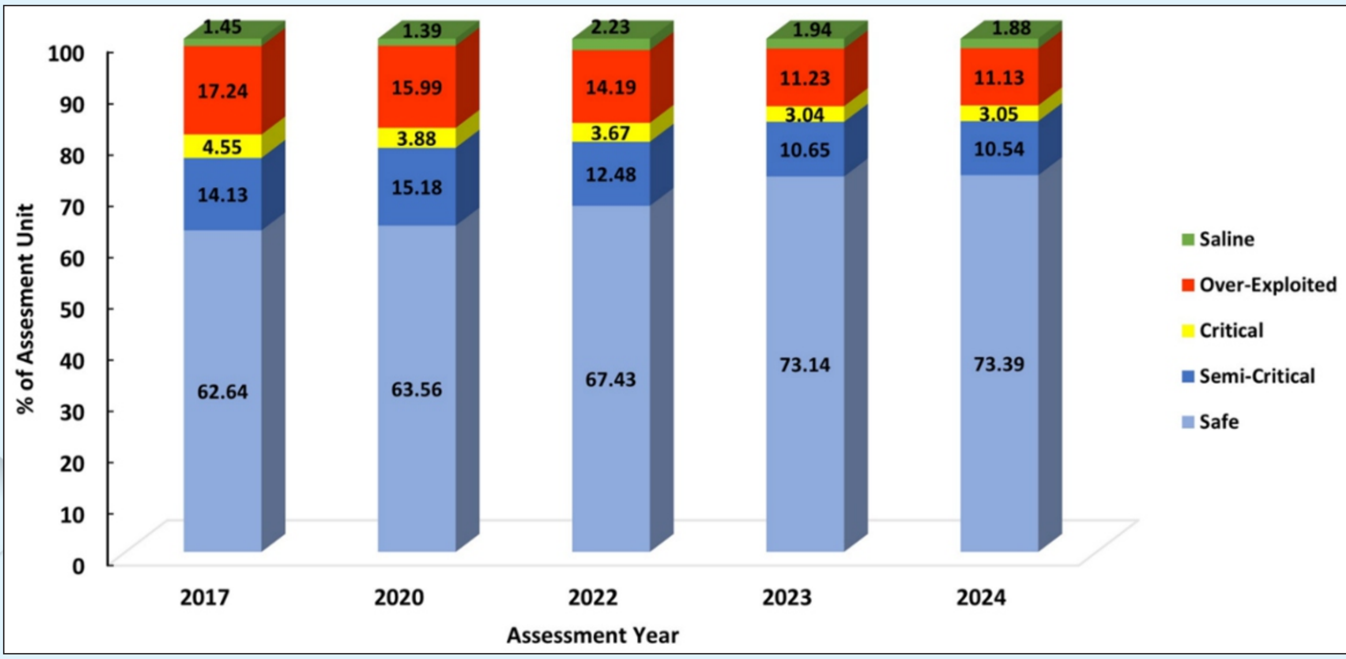

Fig.6: Categorization of % of Assessment Units (2017 to 2024).

groundwater for irrigation, significant emphasis has been placed on adopting advanced irrigation practices and expanding the coverage of micro-irrigation to reduce groundwater dependence. The Per Drop More Crop (PDMC) and accelerated irrigation benefit programme component are being implemented under PMKSY scheme with focuses on micro irrigation, and faster completion of major/medium irrigation projects. The Micro Irrigation Fund (MIF) has been launched by National Bank for Agriculture and Rural Development (NABARD) in 2018, to provide financial assistance to States/UTs for expanding micro-irrigation coverage, offering top-up subsidies, and incentivizing farmer adoption. The Rashtriya Krishi Vikas Yojana (RKVY), which grants flexibility and autonomy to states in planning and implementing agriculture development schemes, and the National Mission on Sustainable Agriculture (NMSA), under the National Action Plan on Climate Change (NAPCC), are being implemented for on-farm water management. In addition to Central Government efforts, several states such as Gujarat, Andhra Pradesh, Maharashtra, and Tamil Nadu have launched their own State Micro Irrigation Missions (Sujalam Sufalam), providing subsidies and support for micro-irrigation systems. As a result of these collective efforts, a noticeable change in groundwater extraction has been observed. The annual groundwater extraction for industrial, domestic, and irrigation purposes combined has decreased from 248.69 billion cubic meters (bcm) in 2017 to 245.64 bcm in 2024, reflecting a reduction of 3.05 bcm (Fig.5) (GEC, CGWB, 2017). The efforts for better irrigation practices and increase water efficiency has also been reflected in food grain production. India has been able to increase the food grain production from 196.81 million metric tons (mmt) to 323.55 mmt during 2000-01 to 2022-23 (an increase of 64%) without significant increase in groundwater extraction. The country wide stage of groundwater extraction has also reduced by 2.86%, in 2024 (60.47%) compared to 63.33% in 2017. The percentage of Over-Exploited, Critical, and Semi-Critical assessment units in the country has decreased from 35.8% in 2017 to 24.72% in 2024. Similarly, the percentage of Safe assessment units has increased from 62.6% in 2017 to 73.39% in 2024 (Fig. 6).

The findings from the Dynamic Groundwater Resource Assessments have been instrumental in planning and implementing groundwater regulation and management strategies across the country. The assessment results have guided policymakers in formulating several large-scale schemes, such as the Atal Bhujal Yojana, the PMKSY–Groundwater Component, and the Jal Shakti Abhiyan. Categorization of assessment units forms a basis for preparation of policies and implementation of regulatory measures by Central Ground Water Authority (CGWA) and State Ground Water authorities for groundwater extraction. Several scientific initiatives have also been planned in accordance with the results of resource assessment. Central Ground Water Board (CGWB) has taken up National Aquifer Mapping & Management Programme (NAQUIM), and high-resolution mapping of the aquifers through the state-of-the-art heli-borne geophysical surveys for mapping of aquifers, their characterization and formulation of management plans to ensure sustainability of the groundwater resources, with a focus on Over-exploited, Critical, and Semi-critical areas of the country.

Scientific collaborations have been initiated with premier institutions like, Bhabha Atomic Research Centre, Department of Atomic Energy for investigating the role of paleochannels in reviving the groundwater resources in northwestern part of India, aquifer mapping studies in Central Ganga Plains, groundwater recharge rate estimation using injected radiotracer techniques and evaluating sustainability of deep aquifers. All these projects have been implemented using advanced isotope hydrological techniques being developed by BARC and successful completion of these projects is encouraging further expansion of isotope techniques to other regions of India, capacity building, mutual collaborations and technical cooperation. The annual assessment of the groundwater resources using advanced techniques and integrating scientific data into planning, policy making and implementation has significantly improved the efficiency and sustainability of groundwater resources Nationwide.

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A Comprehensive Look at India's Water Pollution Landscape

Examining the Status and Sources of Groundwater Pollution

Abhijit Mukherjee

An estimated 100-300 million people across India have been exposed to health concerns such as arsenicosis, fluorosis, carcinogenicity, and death due to ingestion of non-point-source geogenic contaminants. The prevalence, extent, variability, and environmental impact of these groundwater-borne contaminants have been extensively examined and discussed by water and health researchers over the past four decades. However, as of the date, a full understanding the provenance/sources, natural fate and transport of these contaminants in various geological media and consequent aquifers are not very well discerned. This article highlights types of groundwater pollutants and their status in Indian context and also highlights the role of isotope tracers in deducing source and mechanism of groundwater pollution.

A

In both pre- and post-independence India, the use of untreated waters has led to frequent outbreaks of water-borne illnesses. In order to meet the drinking and household water needs, various urban and rural communities of the country have been increasingly depending on groundwater sources since the 1970s. Currently, groundwater provides more than 70% of the nation's residential water supply. However, the presence of natural pollutants in many regions has raised concerns regarding the supply of safe water (Mukherjee et al., 2015; Mukherjee, 2018a).

According to recent estimates, around one-fourth of the 300 billion m^3 of groundwater in the Indus Ganga and Brahmaputra (IGB) aquifer is brackish and unfit for human use. Additionally, naturally occurring, elevated concentrations of non-point sourced pollutants contaminate about 40% of groundwater, putting the public health of over 100 million people at risk (Fig. 1, Mukherjee et al., 2015). As a result, approximately 60% of the groundwater in the IGB aquifers is classified as unsafe and unusable (MacDonald et al., 2016). It has not yet been determined the amount and impact of other newly discovered and unidentified groundwater contaminants (such as pesticides, radiogens, antibiotics, etc.). According to Saha and Alam (2014), intensive agriculture is linked to a significant amount of chemical and synthetic pesticide input that seeps into groundwater systems. A more pervasive and acute, but less documented groundwater contamination can be linked to sanitation-sourced pollution, causing larger public health concerns.

Natural groundwater pollutants

In certain parts of India, elevated levels of naturally occurring, geogenic contaminants, like arsenic (As) and fluoride (F), are frequently found in groundwater. The geological formations of the aquifers, where As and F are present as trace elements in rocks, are the source of these toxins. There have been reports of As contamination of groundwater in 86 districts across 10 Indian states (Mukherjee et al., 2015; Bhattacharya et al., 2014), and it has exposed over 50 million people in the Bengal Basin alone, causing “the largest mass poisoning in human history” (Smith

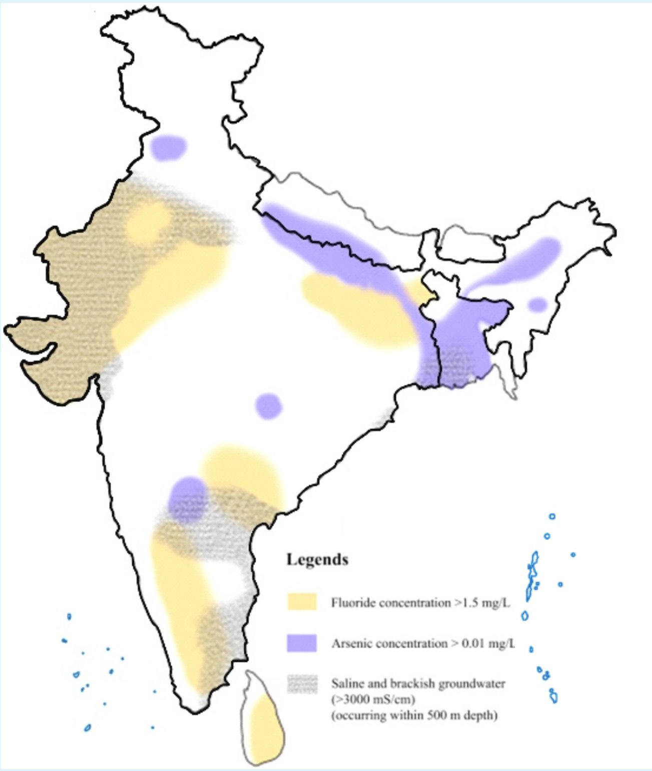

Fig.1: A pictorial representation of extent of major geogenic groundwater contaminants across India (Mukherjee et al., 2015)

et al., 2000). The Ganges-Brahmaputra river basin aquifers in the Indian states of West Bengal, Assam, Bihar, and Uttar Pradesh are reported to have arsenic in groundwater. The contaminant has been proposed to be associated with the Siwalik deposits from the eastern Himalayas. Although it hasn't been verified, widespread pollution from Punjab's Indus basin has also been proposed recently. According to Bhattacharya et al. (2011), the anoxic groundwater of these IGB aquifers supports redox-dominated metal cycling mechanisms. According to Mukherjee et al. (2011), widespread groundwater abstraction may have contributed to the pollution's worsening. The first occurrences of health problems linked to contaminated water were noted in West Bengal and Bangladesh in the early 1980s, and they were documented in the medical literature by Garai et al (1984).

Long-term exposure to water containing high amounts of As can cause severe health problems, such as melanosis, hyperkeratosis, skin lesions, and cancer in several organs, some of which can be lethal. Although the health implications of drinking As-contaminated water are widely known, it is still unclear how it may affect the food chain, particularly crops that are irrigated with polluted water. Numerous factors, such as the soil's redox potential, pH, organic matter content, soil microorganisms, and the amounts of iron (Fe), manganese (Mn), phosphorus (P), and calcium carbonate ($CaCO_3$), affect the bioavailability of As for crops. Furthermore, the majority of As absorbed by plants tends to build up in the roots, with progressively less accumulation in the stems, leaves, and grains.

There have also been reports of high levels of F in groundwater, primarily in crystalline aquifers in portions of 19 states (Maheshwari, 2006). In India, it is estimated that over 66 million people are exposed to excessive levels of F in their groundwater (Mumtaz et al. 2017). The states of Rajasthan, Gujarat, and Andhra Pradesh are the most severely impacted. Higher amounts (1.5-2 mg/L) can cause dental fluorosis, however a dosage of 0.8-1.0 mg/L is necessary for the calcification of tooth enamel. Even greater concentrations (3-6 mg F/L) cause skeletal fluorosis, which damages ligaments and bones.

Many aquifers across the nation have also been found to contain high levels of groundwater nitrate (NO_3-) and iron (Fe) (CGWB, 2014b). While highly saline groundwater is also common in the inland aquifers of various states, sea water intrusion that causes aquifer salinization has also been reported in several of the aquifers that border the coastal regions of the Arabian Sea and Bay of Bengal (CGWB, 2014a, MacDonald et al., 2016). Such inland salinization may be associated with agricultural pollution and/or mineral dissolution.

Human sourced groundwater pollution

Agricultural and Industrial pollution

The "Green Revolution" in the 1960s and 1970s saw the introduction of agricultural practices that heavily relied on agrochemicals to boost crop yields. These practises led to overuse of croplands and application of excess pesticides and fertilisers, which seep through subsurface and contaminate groundwater sources (Saha and Alam, 2004). Due to the increased prevalence of nitrogen and phosphate fertilisers in groundwater, the redox condition and the chemistry of aquifers were altered, producing a powerful feedback effect. Due to their slow rate of degradation, many agricultural pesticides remain in groundwater for extended periods of time. The pesticide residues tend to both bioaccumulate and become biomagnified in creatures that consume contaminated groundwater.

Further, India has experienced rapid industrial and agricultural growth in recent decades, exposing people to a wide variety of chemical contaminants that are progressively contaminating groundwater and surface water (ITT, 2018). Since the adoption of best practices for cleaner industrial processes is not keeping pace with the growth of overall industrial production in a wide variety of industrial facilities, industrial pollution is generally on the rise. Large amounts of industrial effluent pollutants are produced during the processing of industrial chemicals for food production as well. Agricultural runoff is diffuse non-point source pollution that originates from wide areas, whereas industrial effluent is usually concentrated through "point source" contamination from discrete facilities (Mukherjee et al., 2011, 2018b). The chemical and biological contaminants found in these effluents, such as antibiotics, polycyclic aromatic hydrocarbons (PAH), persistent organic pollutants (PoPs), are highly poisonous, flammable, corrosive, and reactive, and they can have detrimental impacts on human health. Moreover, endocrine disruptors and heavy metals are two particularly alarming categories of pollutants released into groundwater through industrial effluents (Mondal et al., 2012). Lead (Pb), mercury (Hg), cadmium (Cd), and chromium (Cr) are among the heavy elements that is frequently found in these effluents. These contaminants bioaccumulate in the body over time and are not biodegradable. Numerous human systems are impacted by Pb exposure. Young children are especially susceptible to the harmful effects of Pb, which can disrupt the body's normal hormone balance and result in irreversible harm to the brain and nervous system (Sorensen et al., 2016).

Sanitation sourced pollution

India's social and economic development is very complex with wide variations across the regions and communities. Limited access to safe drinking water sources or/and inadequate sanitation pushed a vast majority of the Indian population particularly vulnerable to widespread outbreaks of water-borne illnesses. According to ITT (2018), there were six cholera pandemics in the IGB region and discovered that cholera during some of the past episodes was caused by the usage of contaminated water and poor hygiene. Global estimates show that till about 2016, over 500 million Indians (about 40%) likely still defecate in the open, accounting for more than half of the approximately 1 billion people worldwide who lack access to adequate sanitation and engage in this behaviour (Sorensen et al., 2016). However, as India's economy expands, a concerted effort has been made in the past ten years, particularly in the last few years, to end open defecation. The ambitious plans aim to provide all residents with access to adequate household sanitation, which will lower water-borne pathogens and improve public health. However, quantitative analyses show that since the 1990s, there has been a significant decline in the prevalence of water-borne illnesses including diarrhoea. The proportion of children under five who are under-developed has also decreased. Between 1990 and 2010, India's total number of cases of diarrhoea in children under five years old dropped from 320 million to 280 million (UNICEF, 2017). According to recent research, Indian administrative policies have been encouraging the construction of basic sanitation infrastructure over the past few years, which has helped to advance the country's attempts to meet UN Sustainable Development Goal 6 (clean water and sanitation). Water quality has improved because of a considerable drop in groundwater microbiological pollution (faecal coliform), according to studies conducted throughout the IGB basin. Even though areas with poorer water quality and improper human practices were found to outweigh economic development patterns in these areas indicated a clear inverse relationship with faecal coliform concentrations in groundwater in the majority of areas (Mukherjee et al., 2019).

Isotope tracers for pollutant source identification

Isotope techniques are instrumental in tracking how pollutants move and change within water systems (Keesari, 2024). By examining the ratios of isotopes of boron ($^{11}B/^{10}B$), nitrogen ($^{15}N/^{14}N$), sulphur ($^{34}S/^{32}S$), etc., researchers can distinguish among different pollutant sources. For contaminant sources with overlapping signatures of one isotope and dual isotopic signatures can be used to identify different contaminant sources that are chemically similar. Examples of dual isotopes are; for NO_3- ($\delta^{15}N$-$\delta^{18}O$), for SO_4^{2-} ($\delta^{34}S$-$\delta^{18}O$). Isotope of trace metals such as $^{53}Cr/^{52}Cr$, $^{66}Zn/^{64}Zn$, $^{56}Fe/^{54}Fe$, $^{60}Ni/^{58}Ni$, $^{65}Cu/^{63}Cu$, $^{80}Se/^{78}Se$, $^{114}Cd/^{110}Cd$, $^{199}Hg/^{198}Hg$ and $^{206}Pb/^{204}Pb$ are used for a variety of water quality related issues. Isotopic methods contribute to the detection of specific sources and pathways of pollution, assessment of remediation effectiveness by monitoring the isotopic changes over time. These insights are essential to plan development of targeted interventions, evaluate the success of pollution mitigation strategies, ultimately leading to access to clean drinking water for all.

Summary and Way Forward

Public health impacts due to emerging, human-sourced contaminants are still palpable and on rise. It is reasonably well documented that the individuals who are most affected by health impacts of contaminated water are primarily from lower-income groups. Further, contaminant distribution and fate can be influenced by human activities such as vigorous pumping and land use-land cover alterations. As a result, some of these contaminants, mostly the non-point sourced ones, may affect millions of people by contaminating their food crops and drinking water. Mitigation strategies are developed in response to contamination through detection, monitoring, prediction, and interventions using in-situ and ex-situ remediation techniques as well as the exploration of natural solutions, such as drilling to safer aquifers and changing water sources, for the supply of uncontaminated water. Isotope techniques offer a powerful suite of tools for addressing water pollution challenges. By providing detailed insights into the sources, movement, and transformation of contaminants, these methods enable more effective monitoring, detection, and informed decision-making for water resource protection and pollution mitigation.

References for this article have been consolidated and are available upon request.

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Prof. Mukherjee's main research areas are physical, chemical and isotope hydrogeology, including water policy applications to society. He has published more than 150 International journal articles. He serves /has served in an Editorial role in several leading International geoscience and environmental science journals.

He is a Fellow to the Geological Society of America (GSA), Royal Society of Chemistry (RSC), and the American Geophysical Union(AGU). For his work, among several accolades, Prof. Mukherjee has been conferred the National Geoscience Award 2014, Kharaka Award in 2020 by International Association of Geochemist, the Shanti Swarup Bhatnagar Prize in 2020, AGU D.L. Memorial Union Medal in 2023, and GSA G.B. Maxey Award 2024.

He is presently also serving in the Council of the Geological Society of America.

Human–Climate Interactions and the Changing Water Cycle

Monitoring and modeling the water cycle using isotope tracers

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The climate system comprises the coupled dynamics of the atmosphere, hydrosphere, geosphere, and biosphere. These systems interact through the energy, water, and carbon cycles, enabling the Earth to maintain a thermodynamic state far from equilibrium (Kleidon, 2010). Anthropogenic activities—including greenhouse gas emissions, deforestation, and large-scale water abstractions—have drastically altered this balance. As global temperatures rise, these interconnected cycles face systemic disruptions, with the water cycle being especially sensitive to climate perturbations.

Recent assessments from the Inter-Governmental Panel on Climate Change (IPCC AR6) report an unequivocal intensification of the global hydrological cycle. This includes heightened frequency and severity of both droughts and floods due to greater variability in precipitation (IPCC, 2021a). Glaciers in the Himalayas, which supply water to over a billion people across Asia, are melting at accelerated rates, contributing to shifting seasonal flows and downstream water uncertainty (IPCC, 2021b). These changes present direct threats to disaster preparedness, the water-food-energy nexus, and long-term urban resilience strategies. Vulnerable regions in the Global South, particularly South Asia, are disproportionately affected due to high population densities and limited adaptive infrastructure. Moreover, because carbon dioxide has a centennial-scale atmospheric lifetime, adaptation in the water sector becomes crucial for resilience even if mitigation efforts succeed.

The water cycle does not operate in isolation from human activity. Human interventions—such as dam construction, irrigation, inter-basin transfers, and groundwater extraction—have profoundly modified the water cycle, often surpassing the impacts of climatic variability at regional scales (Wada et al., 2014). Yet, this anthropogenic component remains difficult to monitor and even harder to predict. A core challenge in understanding human impacts on the hydrological cycle lies in the spatial and temporal heterogeneity of water usage patterns. Unlike atmospheric processes, human water use is driven by a confluence of economic, cultural, and political factors, which vary from village to village and season to season. Data on irrigation, particularly in countries like India, is sparse, outdated, or politically contested. In India, unmonitored irrigation and groundwater abstraction are especially problematic to understand their impacts on water cycle. According to Jha et al. (2022), human water management activities like irrigation show limited influence on mitigating pre-monsoon heat stress in the Indo-Gangetic Plain, challenging previous literature that irrigation alone buffers climatic extremes in pre-monsoon summer, which is not a major crop season. However, irrigation has impacts on monsoon as found by Devanand et al. (2019), revealing a feedback loop: irrigation practices affect land-atmosphere coupling, thereby distorting regional rainfall patterns.

Controversy persists in literature over the extent of groundwater extraction, particularly due to inconsistencies in satellite-derived versus in-situ measurements. Disagreements also stem from the political sensitivity of declaring groundwater “over-exploited,” which has economic ramifications for agricultural subsidies and resource access. Recent studies have attempted to reconcile this gap through high-resolution modeling and remote sensing techniques (Jha et al., 2022; Famiglietti et al., 2011). Literature also emphasizes the limitations of current irrigation datasets.

The findings expose the blind spots in India's irrigation governance, where state-level water usage is either unreported or not correctly estimated. This inadequacy impedes regional modeling efforts and leads to miscalibrated climate adaptation strategies. Moreover, the dynamic nature of human decisions—e.g., switching crops, sudden abstraction during heatwaves, or farmer-led water-sharing—introduces non-stationarity into water demand models. This makes the modeling of water flows as difficult as weather prediction itself. Unlike precipitation or temperature, which follow physical laws, water use decisions are socio-politically governed, making them inherently unpredictable and poorly captured in Earth system models. In sum, the “human component” of the water cycle is both vital and opaque. Without adequate monitoring and modeling of irrigation practices, abstraction trends, and infrastructure impacts, any climate adaptation strategy risks being both incomplete and ineffective, especially in South Asia’s rapidly changing hydrosocial landscapes.

Water management practices, though essential for sustaining human society, do not merely respond to climate variability—they actively reshape it. In regions like India, large-scale water diversions, inter-basin transfers, and intensive irrigation systems generate land-atmosphere feedbacks that alter precipitation patterns, soil moisture dynamics, and monsoon variability (Chauhan et al., 2023). This anthropogenic modification of hydroclimatology represents a secondary, human-driven layer of climate forcing. One of the most profound illustrations of this comes from India's proposed river interlinking projects. According to Chauhan et al. (2023), simulations using Earth system models demonstrate that the interlinking of river basins leads to major changes in the spatial structure of Indian Summer Monsoon (ISM) rainfall (in September).

The altered water availability and evapotranspiration patterns from irrigation expansion generate regional imbalances in heat fluxes, suppressing rainfall in some areas while enhancing it in others. Devanand et al. (2019) earlier emphasized that such irrigation-induced modifications in surface energy fluxes influence the intensity of the monsoon in September. Their work shows that irrigation shifts regional soil moisture availability, which acts as a boundary condition for atmospheric circulation. Overall, irrigation introduces large uncertainty into seasonal forecasts, complicating both water planning and agricultural decisions. Joseph et al. (2021) adds another dimension to this understanding by examining how water management interfaces with the water-food-energy nexus.

In some of the water-stressed regions of India, groundwater extraction for irrigation has surged, supported often by subsidized electricity (Joseph et al., 2021). This coupling of energy and water sectors creates feedback loops where excessive water abstraction necessitates more energy input, leading to greater emissions—ironically reinforcing the climate change problem. These findings point to the importance of integrating hydrological feedbacks into infrastructure planning to ensure that short-term adaptation does not undermine long-term resilience. Taken together, these studies underscore the complex, bidirectional relationship between water management and the climate system. Instead of viewing human activity as merely reactive to climate signals, these insights compel us to consider humans as active geomorphic agents whose decisions reshape the climate-water landscape.

The Indian monsoon system is a product of complex feedbacks among oceanic, atmospheric, and terrestrial systems. While global models offer broad projections, regional monsoon dynamics often diverge due to localized land–atmosphere interactions, land use changes, and soil moisture variability. The critical challenge lies in accurately modeling these regional processes, which govern a significant portion of water availability in South Asia. Roxy et al. (2017) have shown that the frequency of extreme rainfall events over Central India has tripled over the past six decades, largely due to intensified moisture flux convergence from the Arabian Sea (Roxy et al., 2017). Their work identifies the weakening of large-scale monsoon circulation coupled with increased mid-tropospheric humidity—both consequences of warming oceans—as primary drivers.

More importantly, the study underscores that regional land surface processes, including precipitation recycling and vegetation feedback, modulate the spatial extent and intensity of monsoon rainfall, a feature not well captured in coarser global models. These findings reflect a shift in the understanding of monsoons—not merely as ocean-driven phenomena but as tightly coupled land-ocean systems. Recent work by Chandel et al. (2024) further expands this understanding by exploring the role of land-to-land water transport within India. The model, based on Lagrangian moisture source tracking, identifies that during monsoon breaks, recycled moisture from the Indo-Gangetic Plains and central Indian forests contributes significantly to rainfall in downwind regions such as Odisha and Telangana. This intra-continental moisture recycling is sensitive to soil moisture anomalies and irrigation intensity, reinforcing the importance of regional land management in shaping rainfall.

Chandel et al.(2020) also examined the uncertainty associated with Himalayan glacier melt and downstream runoff in the context of warming scenarios. His results highlight that poorly constrained subsurface hydrology and sparse glacier monitoring contribute to wide uncertainty bands in runoff projections. Since a significant portion of India's dry season flow comes from snow and ice melt, this gap in data poses a serious challenge to water resource planning in northern India. Together, these studies highlight the importance of integrating regional land-ocean interactions into hydroclimatic models. Failure to do so risks missing critical tipping points in rainfall patterns, particularly in monsoon-dependent regions like South Asia.

Despite significant advances in climate modeling, gaps in hydrological data—especially concerning groundwater abstraction, recharge rates, and regional runoff—continue to hinder water-related climate adaptation. Conventional observational systems fall short in characterizing sub-surface and atmospheric moisture fluxes, particularly in complex terrains like the Himalayas and semi-arid agricultural zones. In this context, water isotope analysis offers a powerful and increasingly indispensable approach for monitoring and modeling the water cycle at multiple scales. Stable water isotopes act as natural tracers within the hydrological cycle. Since isotope ratios in precipitation, runoff, soil water, and groundwater vary with evaporation, altitude, and moisture source, they provide a fingerprint of water's history. This makes isotopes uniquely suited for quantifying partitioning processes such as evapotranspiration vs. percolation, snowmelt vs. rainfall runoff, and natural recharge vs. artificial irrigation (Gat, 1996). A study by Wen et al. (2024) highlights how isotope-enabled modeling can resolve key ambiguities in Asian monsoon hydrology.

Using isotope records in conjunction with general circulation models, they reconstructed moisture pathways and rainfall intensities with high spatial fidelity, capturing previously unresolved dipole responses in South Asia. Their results also reveal how past climate changes manifest in isotope signals, helping to validate projections under future warming. Water isotope studies have also proven vital in glacier-fed systems. Zhao et al. (2025) used isotopic tracing to determine the contribution of snow, glacier, and groundwater sources to river flow in the Tibetan Plateau. Their findings confirmed that groundwater-fed baseflows, long thought to be negligible in alpine systems, are actually critical during dry seasons—particularly when glacial melt alone cannot sustain discharge. These insights call for better integration of isotopic data into river basin management and climate resilience strategies.

In India, such methods can directly address uncertainties around unmonitored irrigation and groundwater dynamics. For example, isotopic mapping can differentiate between canal-fed and groundwater-fed irrigation, offering insights into human water management even in data-scarce regions. This approach is particularly valuable where socio-political constraints limit access to abstraction records. From a modeling perspective, isotope-enabled hydrological models offer a more nuanced understanding of water residence time, flow paths, and recharge-discharge dynamics. When paired with remote sensing (e.g., GRACE satellite mass anomalies) and machine learning, these models can inform early warning systems for floods, droughts, and aquifer depletion. Critically, isotopic data also offer a common calibration metric for integrating disparate hydrological datasets—such as rainfall, river discharge, and groundwater levels—into coherent models. This synthesis is essential for operational climate adaptation, where decisions rely on predictive reliability. In summary, water isotope science bridges critical data gaps in the hydrological cycle. By enabling better monitoring, enhancing model accuracy, and uncovering hidden water pathways, isotopes support robust design of early warning systems and long-term adaptation strategies in South Asia and beyond.

References for this article have been consolidated and are available upon request.

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Securing Safe Drinking Water for Future

Challenges and Scientific Imperatives

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India's Jal Jeevan Mission represents a transformative endeavor to provide functional household tap connections to every rural home. While its public health implications are significant, its potential to liberate millions of women and girls from water-collection burdens cannot be overstated. However, as we approach the midpoint of this initiative, fundamental challenges to its sustainability have emerged, including institutional capacity for infrastructure maintenance, water supply reliability, and drinking water safety.

Nearly two-thirds of Jal Jeevan schemes rely on groundwater sources, many of which face depletion during summer months. This decline stems primarily from anthropogenic pressures, with agricultural irrigation representing the dominant factor. While the Mission functions as a supply-side intervention, its success necessitates complementary demand-side approaches and additional supply augmentation strategies.

Demand reduction requires improved agricultural water efficiency, adoption of less water-intensive crops, or alternative freshwater replacement mechanisms. Supply augmentation demands comprehensive watershed management: rainwater harvesting, aquifer recharge, and revival of traditional water bodies.

Scientific Gap in Aquifer Management

Presently, aquifer recharge efforts are constrained due to insufficient hydrogeological knowledge. The assumption that surface water conservation automatically recharges shallow aquifers often proves unfounded. Without understanding localized hydrogeology and identifying specific recharge zones, interventions may prove both inefficient and costly.

The potential for shallow aquifer recharge through dug-wells remains less utilized due to contamination concerns. Implementing water quality testing and filtration systems prior to recharge is essential to prevent aquifer contamination — an approach that requires scientific expertise currently lacking at scale.

Water Quality Crisis

Water quality represents perhaps the most significant challenge. The growing trend of households purchasing bottled water or installing purification systems — 15% of urban and 6% of rural households according to the 79th National Sample Survey—reveals declining public confidence in government-supplied water safety.

The World Bank's 2019 report "Quality Unknown: The Invisible Water Crisis" highlights global challenges from nitrogen compounds, salinity, and biological oxygen demand, demonstrating substantial health impacts and economic losses. As societies grow, the range of contaminants expands beyond fecal matter to include nutrients, plastics among others.

India's water quality testing infrastructure remains inadequate, with limited data availability and poor inter-agency coordination. Rural areas face particular challenges from microbiological contaminants, fluoride, arsenic, iron, salinity, and nitrates — requiring both scientific solutions and community engagement.

Bridging Science and Society

To address the aforesaid challenges, we must mobilize citizens, strengthen local institutions, and generate demand for improved services. The scientific community can contribute through:

1. Demystifying the "invisible" nature of groundwater depletion and water contamination through effective science communication.

2. Developing a cadre of "barefoot hydrogeologists" who can identify recharge zones and guide local planning.

3. Improving field testing methodologies, particularly for microbiological contamination.

4. Evaluating purification technologies based on scientific efficacy, capital requirements, and maintenance feasibility.

5. Creating scientific advisory mechanisms to support governments and community organizations.

The sustainability of rural water supply ultimately depends on bridging the gap between scientific expertise and community action. Without this holistic integration, the goal of safe, reliable household water connections for all rural households remains an unfinished task.

THE SUSTAINABILITY of rural water supply ultimately depends on bridging the gap between scientific expertise and community action.

Mr. V.K. Madhavan has spent over three decades working in the voluntary sector. Fifteen of these have been spent living and working in rural India on an integrated development approach. First, in desert districts of North-Western Rajasthan with the Urmul Rural Health Research and Development Trust till 1998, and then in the Kumaun region of Uttarakhand with the Central Himalayan Rural Action Group (CHIRAG) (2004 – 2012). In the interim, Madhavan worked on policy related issues with ActionAid, as an independent consultant and then on women's leadership and governance with the Hunger Project. For a three-year stint between 2013 and 2016, Madhavan headed a skill development company that sought to provide unemployed young people with access to jobs in the organized sector. Since May 2016, Madhavan has been the Chief Executive of WaterAid India.
Madhavan has a Master's in Politics (International Studies) from the Jawaharlal Nehru University.

Empowering Local Decisions with Isotope Hydrology

A New Frontier for India's Water Strategy

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This article explores some of the pertinent challenges being faced by rural and urban communities in India. Impact of fertilizers, canal seepages, salinization of fresh water, surface water contamination, urban hydrology and spring-shed development are some of the key issues brought out in this article which can be addressed through isotope hydrological techniques. A work plan for upscaling the isotope applications in water resources management through government policies is also discussed.

Isotope hydrology has made tremendous strides in addressing "big hydrology" questions and has revolutionized our understanding of the water cycle by using stable and radioactive isotopes to trace the origin, age, and movement of water. It has improved our understanding of the Indian monsoon and allowed scientists to identify recharge zones, the residence time of groundwater and quantify groundwater-surface water interactions. In fact, the government of India has since launched a major effort to develop new isotope methodologies and monitor isotopic fingerprints of major water sources in spatial and temporal domains through various departments and R&D centers.

India faces a complex water crisis marked by seasonal scarcity, overexploited groundwater, polluted surface water, and growing demand across sectors, all exacerbated by climate change. These challenges are underpinned by lack of scientific data and efficient technological innovations. It is in this respect; Isotope hydrology can play a more direct and effective role in water resources management. There have been some studies, mainly region-specific and issue-based, but not enough to address the scale of India's water challenges. These research studies often end up as peer reviewed publications, but have the tremendous potential to provide solutions to pertinent water issues through providing deeper insights into the causes of the problem. With the advent of new-age instruments, the throughput and accuracy of isotope measurements has drastically improved with reduced costs, allowing isotope hydrology readily accessible for water resource management and research.

There is a need to identify questions that could be answered by isotope hydrology where the knowledge could inform specific decisions at the local level (ULB, Panchayat). Below are some questions that could be tackled through isotope techniques.

Impact of fertilizers and inadequate sanitation on drinking water sources

Multiple studies have shown nitrate in drinking water supplies is particularly high in rural areas, where average levels have been reported to range from 46 mg/L to 100 mg/L (Ward et al., 2018). CGWB (2023) data suggests that about 56% of India's districts have excessive nitrates defined as more than 45 mg/L in their groundwater. This widespread contamination poses significant health impacts. For instance, a recent World Bank study showed that continuous exposure to nitrate levels exceeding ~50 mg/l in early childhood can lead to "decreased height as an adult, a well-known indicator of overall health and productivity in adulthood" (Zaveri et al., 2020).

The primary sources of nitrate contamination in India's groundwater are:

- Agricultural runoff: Excessive use of nitrogen-based fertilizers leads to leaching of nitrates into the groundwater.
- Improper human/animal waste disposal: Inadequate management of animal waste and sewage contributes to nitrate levels in water sources.
- Urbanization: Rapid urban development without proper solid waste management systems exacerbates the problem.

Isotope studies can discriminate between sources of nitrate contamination in groundwater by analyzing the isotopic composition of nitrogen and oxygen atoms within the nitrate ($\delta^{15}N-NO_3^-$) molecule. For instance, high $\delta^{15}N$ (e.g. >10%) traces a sewage/manure source whereas low $\delta^{15}N$ (e.g. <5‰) points to a synthetic fertilizer. Although the studies in the global north point to fertilizer as the primary source of nitrate, studies from the global south are more varied. Attribution studies can help to establish whether efforts should focus on sanitation or a gradual shift towards more agro-ecological agricultural practices. Understanding the causal pathways is important, because nitrate is challenging and expensive to remove from well water, once contaminated.

Groundwater quantity and quality issues in canal command areas

Canals are built for surface irrigation yet the seepage from unlined or poorly maintained canals can significantly recharge underlying aquifers and provide a crucial back-up water source, especially in the dry season. Many canal command areas are seeing a sharp increase in "conjunctive use" (use of both canal and groundwater). This is helpful because access to groundwater helps farmers irrigate their crops even after the canal flows stop, allowing them to grow higher value crops. Accurately estimating recharge from canals is essential for building robust water budgets at the distributary level by "water user cooperatives (WUCs)".

Increasingly governments are promoting "pipe to the field" projects and canal lining to improve efficiency. At the same time, they are promoting crop diversification that requires reliable irrigation. Thus, it becomes doubly important to accurately assess water availability at the distributary level. So, an accurate estimation of recharge from canals is essential for building robust water budgets.

WITH THE ADVENT OF NEW-AGE instruments, the throughput and accuracy of isotope measurements has drastically improved with reduced costs, allowing isotope hydrology readily accessible for water resource management and research

Rainfall and canal water often have distinct isotopic signatures (in $\delta^{18}O$ and $\delta^{2}H$ values), especially if canal water originates from a distant reservoir or river (Keesari et al., 2017). Groundwater that recharges from canal seepage retains the isotopic fingerprint of the canal water whereas recharge from rainfall reflects local precipitation isotopes. By sampling and comparing isotopic compositions of canal water, rainfall, and local groundwater, researchers can use mixing models to estimate the proportional contribution of each recharge source.

Many canal command areas in India are beginning to experience soil and groundwater salinity. For instance, salinity in the Tungabhadra Left Bank Canal (TLBC) region, in Karnataka's Raichur and Koppal districts, has emerged as a significant agricultural concern. There are many reports on soil and water salinity in Indira Gandhi Nahar Project (IGNP), western India and other places (Tewari et al. 1997, Sinha and Navada 2008). This issue ostensibly stems from prolonged irrigation without adequate drainage, leading to waterlogging and the accumulation of salts in the soil. If the causal pathway is established with the support of isotopic data, it could be part of a communications campaign to persuade farmers and irrigation departments in newer canal command areas to avoid getting trapped into an intensive paddy cultivation system right from the beginning.

Identifying the source of contamination in surface water bodies

Phosphate and organic contamination in water bodies leads to excessive algal growth (eutrophication), which depletes oxygen, harms aquatic life, and degrades water quality. Many lakes in India are hypereutrophic. With Jal Jeevan Mission, and piped water to every home, there is likely to be an increase in greywater flows as well. It is likely that many water bodies will see higher domestic wastewater inflows containing phosphates from detergents. Raw sewage flows are also increasing as people switch to flush toilets. Further agricultural runoff, increasingly laden with fertilizers is also contributing to deterioration of surface water bodies.

Once polluted, these water sources will be lost to the community for livelihood and domestic in-situ uses. This is especially important to prevent eutrophication of existing drinking water reservoirs. Water may need to be imported from distant sources at considerable cost, even spurring conflicts over the resource.

Different sources (e.g., fertilizers, manure, detergents) often have characteristic phosphate ($\delta^{18}O$), nitrate ($\delta^{15}N$, $\delta^{18}O$) or sulphate ($\delta^{34}S$) values and can be used to trace whether contamination is from sewage, fertilizer, or industrial sources, helping link surface water bodies to pollution sources (Pillai et al., 2024, Keesari 2023, IAEA 2013). Again, source apportionment studies on these nutrient sources can help inform management. For instance, the specific composition of nutrients will determine the course of action – whether catchment level management on non-point source pollution is needed or investments in sewerage and STPs would be useful.

Factors leading to salinization of freshwater coastal aquifers

There is evidence that indicates increasing salinity in coastal aquifers across India - primarily due to seawater intrusion, exacerbated by over-extraction of groundwater, climate change, and sea-level rise. In deltaic areas, changing river discharge regimes as consequence of human interventions and climate change, which amplifies seasonality and inter-annual variations, are also driving intrusion along distributaries, particularly in the east coast. Approximately 7% of India's coastal areas are affected by seawater intrusion, with some regions experiencing intrusion up to 14 km inland.

But many of these coastal regions (such as the Cauvery Delta) have practiced intensive irrigation for decades, even centuries. It would be useful to distinguish the source of salinity among seawater intrusion, irrigation, modern agricultural chemicals or past (ancient) marine transgressions.

BARC CONDUCTED EXTENSIVE research on spring rejuvenation employing advanced isotope techniques. These studies have successfully demonstrated the critical role and applicability of isotope technology in understanding the hydrodynamics of spring sheds, assessing recharge mechanisms, and guiding effective management strategies.

A range of isotopes can help detect the causes of salinity in coastal aquifers by distinguishing between different sources and processes that contribute to salinization. For instance, stable isotope ratios of B, S and Cl have been used to distinguish between seawater intrusion and anthropogenic sources like fertilizers or wastewater. Stable water isotopes of O and H ($\delta^{18}O$ and $\delta^{2}H$) along with environmental tritium (^{3}H) can be used to identify whether saline water is from modern seawater intrusion, evaporated irrigation return flows, or paleowaters as seawater has a distinct isotopic signature compared to local meteoric water (Rao et al. 1998).

Urban hydrology and groundwater balance

City water balances are important because they provide a comprehensive picture of how water enters, moves through, and exits an urban system, enabling informed decisions on sustainable water management. Traditionally city water balances have tended to include piped supply and demand. They are used to highlight mismatches between available water and demand (domestic, industrial, institutional) and to plan new infrastructure investments or retrofits.

In recent years, it is becoming common to develop water balances that link water resources and water supply to inform integrated urban water management (Kulranjan et al., 2023). These connect surface water, groundwater, wastewater, and stormwater, encouraging cities to shift from siloed approaches to circular urban water systems. Groundwater, however, tends to be a “black box”, as both recharge and extraction are poorly quantified. Isotope techniques can help differentiate recharge from rainfall, lakes, and leaking water supply systems (Brauns et al., 2022). Artificial radioisotopes are also being employed quantify the groundwater recharge from rain (Rangarajan and Athavale 2000), which can help in preparing the water budget models and recommend effective plans for sustainable development of groundwater resources.

Promoting spring-shed management in Himalayan states

IAn important contribution of isotope hydrology is to spring protection, which requires identification of source areas and timing of recharge to springs (e.g., intake of a drinking water well). Springs are the main source of supply for many hill communities. As quality deteriorates, water treatment becomes more expensive. Springs in valleys often derive from higher-elevation recharge (Sharma and Mandal, 1999).

The altitude effect on stable isotope ratios of O and H in precipitation refers to how the stable isotope composition of precipitation—and therefore groundwater recharge—systematically changes with elevation. This is a fundamental concept in isotope hydrology that can help identify recharge zones and track water movement (Mook, 2000). Tracing the origins of spring discharges is valuable as it averts polluting industries or sewage contamination in recharge zones of springs supplying large populations.

The Bhabha Atomic Research Centre (BARC), under the Department of Atomic Energy (DAE), has conducted extensive research on spring rejuvenation employing advanced isotope techniques. These studies have successfully demonstrated the critical role and applicability of isotope technology in understanding the hydrodynamics of spring sheds, assessing recharge mechanisms, and guiding effective management strategies. The insights gained from these investigations provide robust scientific evidence that can significantly enhance the sustainable management of spring ecosystems. It is imperative that these scientific findings be integrated into water resource policy frameworks and decision-making processes to ensure the long-term preservation and rejuvenation of springs, which are vital freshwater sources for many communities (Keesari et al., 2025).

Maximizing the benefits of isotope technology through upscaling

Grounded isotope hydrology requires local field-based studies. Importantly, many empirical studies are needed to discern patterns and perform meaningful meta-analyses. The Government of India has prepared a very accessible handbook on interpretation of stable isotopes and the Oasis-G Tool. Although it focuses mainly on rainfall and recharge ($\delta^{18}O$ and $\delta^{2}H$ values) similar handbooks may be prepared for other common isotopic tracers.

A strong case might then be made to train post-graduates and research scholars in these isotope techniques with the object of answering more directly and locally water resources management problems. This will require starting with a “user validated” research question, then rigorously designing a simple study to answer the question. The study would entail carefully designed local sampling, designed to answer a management question at the appropriate level. Ideally, the study would be done in partnership with the decision-making agency.

To answer these questions well, there is a need for strong, robust research design (sampling methodology, sample collection protocols, timing and frequency of sample collection etc.). Hypothesis testing, which is central to grounded stable-isotope hydrology, is also a good way of developing research capacity in students of the scientific process while also addressing critical societal problems.

Dr Veena Srinivasan is leading WELL Labs' mission to transform scientific research into real-world impact. In 2022, she was listed as one of the top-cited scientists in the world. Her research has focused on understanding anthropogenic and climatic influences in urbanising watersheds and identifying appropriate policies and adaptation measures. Dr Veena Srinivasan has won several awards for her work, including the 2015 Jim Dooge Award for best paper in the journal Hydrology and Earth System Science from the European Geophysical Union and the 2012 Water Resources Research Editor's Choice Award from the American Geophysical Union. Veena chairs the Strategic Advisory Group for the Integrated Monitoring Initiative for UN SDG6. She was the Prins Claus Chair at Utrecht University, Netherlands from 2018 to 2020. She received the International Water Association Award for research in 2023. She joined the board of the International Water Management Institute (IWMI) in January 2024.

Dr. (Prof.) Richard Taylor's research at University College London (UCL) focused on the development and interrogation of observations to advance understanding of the impact of climate change and human development on groundwater systems. His research seeks to inform solutions to sustain equitable access to water for drinking and irrigation in low-income countries in the tropics most affected by global change.

For over a decade (2008-2018), he led the International Association of Hydrogeologists' Commission on Groundwater and Climate Change. He has been a Contributing Author to two chapters (Water Cycle Changes, Africa) of the 6th Assessment Report of the Intergovernmental Panel on Climate Change, and Lead Author of a chapter of the UN World Water Development Report 2022: Groundwater, Aquifers and Climate Change. Prof Taylor is the recipient of a Senior Fellowship from The Royal Society and he is currently a Fellow of the Earth 4D programme of the Canadian Institute For Advanced Research (CIFAR).

From Waste to Resource

Addressing India's Water Problem through Wastewater Reuse

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India is confronting a deepening water crisis, driven by rapid urbanization, population growth, and unsustainable water use practices. Especially, the urban centers are under growing stress, exacerbated by inefficient distribution, inadequate pricing, and mounting wastewater generation. While wastewater reuse presents a sustainable solution, its potential remains vastly underutilized in India. This article explores the scale of India's water challenges and highlights the urgent need to integrate treated wastewater into urban and agricultural water management strategies. Drawing from global best practices and scientific evidence, it outlines the benefits of wastewater reuse, particularly for agriculture, and emphasizes the role of nutrient-rich effluents in improving soil health and crop productivity. The article also examines policy, regulatory, and economic barriers impeding large-scale adoption and argues for a more enabling framework to promote safe and affordable waste water reuse. With rising water demand and increasing environmental stress, treated wastewater must be repositioned not as waste, but as a vital resource for building water resilience in India.

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India accounts for around 17% of the world population. However, the country has been endowed with just 4% of the world's freshwater resources. More than half of the twenty river basins in the country face water scarcity conditions, with availability of less than 1000 cubic meters (cbm) per capita per annum. According to a report by the Union Water Resources Ministry, total water demand in the country is estimated to increase by 34% by 2025 and over 78% by 2050, indicating a major gap of around 30% with respect to the replenishment capacity, signalling a serious water crisis in the nation.

Further, the crisis is compounded by a growing population. According to the Water and Related Statistics (WRS) published by the Central Water Commission (CWC, 2011), per capita annual availability of water in the country has decreased from 1,816 cbm in 2001 to 1,545 cbm in 2011 and is likely to further fall to 1,174 cbm by 2025. As per the Falkenmark Index (1989), one of the most commonly used indices of water scarcity, if per capita water availability falls below 1,700 cbm per annum, the condition is termed as water stress. If it further decreases and falls below 1,000 cbm per annum, the condition is termed as water scarcity.

India is urbanising at an unprecedented rate. it is estimated that at present about 540 million Indians live in towns and cities. A UN Habitat report estimates that India's urban population will grow to 675 million by 2035, making it the second largest in the world after China ((UN-Habitat, 2022). It is also projected that by 2050, around 50% of the Indian population (about 877 million) will reside in urban cities.

Indian cities are already reeling from inadequate water provisioning and sub-optimal distribution. Many large cities are dependent on private water tankers, with the poor and marginalised facing the brunt of water insecurity. Bangalore experienced a major water crisis last year, and most large Indian cities report water rationing during summer months.

> **The fundamental** principle for any resource management, including water, comprises the 3Rs-Reduce Consumption-Reduce Losses & Inefficiencies-Reuse and Recycle Water.

The fundamental principle for any resource management, including water, comprises the 3Rs: a) reduce consumption, b) reduce losses and inefficiencies and c) reuse and recycle water. At the core of water insecurity is the underpricing of water in urban areas, wherein high demand chases an under- price resource. Water security must be ensured for basic human needs and essential services. However, there is an urgent need to correctly price water for recreational and commercial use.

It is important to note that water availability is limited. Most easily harvestable surface water has already been dammed in most parts of India (excluding some eco-fragile zones), and much of the irrigation and domestic demand has shifted to groundwater. As in other large countries like China, households and industries rely more on surface water, while irrigation needs are largely met through groundwater. Overexploitation of groundwater has led to aquifer shrinkage and plummeting water tables across large parts of India. Since water availability is unlikely to increase in the near future, there is an urgent need to reduce distribution losses and improve the efficiency of water utilities. Non-revenue water is estimated at 20 to 50% of total supplied water in Indian cities, an avoidable loss that could substantially increase water availability. As urban populations grow, so do urban wastewater generation too. However, India still has a long way to go to ensure safely managed sanitation for its citizens. According to the Central Pollution Control Board (CPCB), about 70% of sewage generated in Indian cities is discharged untreated into the environment, polluting many rivers and water bodies.

On one hand, while India faces a massive water stress, on the other hand there is a significant gap in used water treatment. According to a 2050 projection report (Amerasinghe, P., et al., 2013), India will require approximately 1,447 cubic kilometres of water, with 74% needed for irrigation. However as mentioned, about 70% of used water is released untreated, causing environmental degradation and health hazards. Hence, effective reuse and recycling of wastewater is essential to meet this demand-supply gap. Treated wastewater is already a critical resource in many countries. Israel, for example, uses it extensively for irrigation, and some treatment plants in Singapore produce water of higher-than-drinking water quality, which is primarily used in high-end industries. In addition, Sustainable Development Goal 6 (UN 2015), also aims to halve the untreated wastewater and substantially increase recycling and reuse by 2030.

Contrary to popular belief, technology to treat sewage to potable standards has existed for decades. While international goals emphasize the need for reuse, some countries have already implemented pioneering solutions. Windhoek, Namibia, has been treating and reusing wastewater for drinking since 1968, currently meeting about 35% of its potable water needs this way, with no reported outbreaks of waterborne diseases (Lahnsteiner & Lempert, 2007). Of course, as the end use of the treated water is directed away from agriculture to high-end industries, recreational, and potable usages, the cost of treating wastewater increase exponentially.

Agriculture is the largest water-consuming sector in India. Farmers in peri-urban areas have used wastewater for irrigation for decades. It is reported that 5 billion cbm of wastewater released annually by Indian cities could irrigate 3 million hectares, nearly double the command area of the Sardar Sarovar project, and could contribute about one million tons of nutrients and 130 million man-days of employment (Tushar et al., 2014, Minhas et al., 2004).

Used water is rich in nutrients such as nitrogen and phosphorus. Studies report higher crop yields from wastewater irrigation compared to freshwater, which results in financial savings and environmental benefits (Kaur et al., 2012). Despite increased use of chemical fertilizers, India faces stagnant agricultural productivity and soil degradation (Patra et al., 2016). With adequate organic content, wastewater reuse offers a sustainable solution to enhance soil productivity. Agricultural reuse of treated wastewater is cost-effective and can shield farmers from erratic rainfall, especially in a changing climate. It can also reduce farmers' dependence on chemical fertilizers and improve soil health.

A key challenge in establishing a business case for non-agricultural reuse of treated wastewater is India's rainfall pattern. Monsoon rains adequately recharge aquifers and surface sources during certain months, reducing market demand for treated water. Thus, innovations in pricing, distribution, and management are essential for making treated water viable for non-agricultural purposes. However, untreated wastewater used for irrigation also poses health risks, including helminth infections, viral diseases, and heavy metal toxicity (Qadir et al., 2010). Long-term application without safeguards can degrade soil properties and crop quality (Ghosh et al., 2012). Therefore, comprehensive treatment and management protocols are essential for reuse.

Many countries have established standards for treated water reuse in agriculture, industry, recreation, and potable use. WHO and FAO (2006) have also issued reuse guidelines. As water scarcity worsens, more nations will adopt treated wastewater reuse. Under the Environment Protection Act (1986), the Government of India can set quality standards for water use. CPCB (2024) has issued a draft guideline on reuse, advocating some of the world's strictest standards as recommended by Central Public Health and Environmental Engineering Organization (CPHHEO). These CPHHEO recommendations on reuse are even more stringent than those of the US EPA (2012). The rationale behind these stringent benchmarks is unclear. Tougher standards entail higher capital and operational costs and may hinder rather than promote safe reuse.

CPCB’s draft also claims that wastewater treatment plants above 40 MLD can be self-sufficient and generate revenue (CPCB, 2022). These cost and revenue projections warrant deeper scrutiny. If correct, wastewater treatment and reuse could turn out to be a revenue source for governments and urban local bodies, instead of a huge public finance burden. However, these assertions do not reflect the current ground reality and hence, these need further examination and contextualisation.

Isotopic techniques play a vital role in assuring the quality of treated wastewater, especially as reuse becomes increasingly important in water-scarce regions like India. They offer a scientific and non-intrusive method to trace contaminants, assess treatment efficiency, and verify the safety of water intended for reuse.

Isotopic techniques play a crucial role in assuring the quality of treated wastewater, especially as reuse becomes increasingly important in water-scarce regions like India. Isotopes offer a scientific and non- intrusive method to trace contaminants, assess treatment efficiency, and verify the safety of water intended for reuse. Stable isotopes such as nitrogen-15 ($\delta^{15}N$) and oxygen-18 ($\delta^{18}O$) in nitrates are particularly useful in identifying the sources of nitrogen pollution, distinguishing between human sewage, agricultural runoff, and industrial effluents. Similarly, hydrogen ($\delta^{2}H$) and oxygen ($\delta^{18}O$) isotopes in water molecules can trace the mixing of treated wastewater with natural water bodies, helping to monitor the extent of dilution or potential contamination.

During wastewater treatment, isotopic shifts in carbon ($\delta^{13}C$) and nitrogen signatures can be used to evaluate the effectiveness of biological processes like nitrification, denitrification, and organic carbon degradation. These changes provide insights into whether treatment units are functioning optimally or require adjustments. In urban areas, where wastewater may inadvertently mix with stormwater or leak into groundwater systems, isotopes serve as sensitive tracers, capable of detecting even low levels of contamination. Additionally, the isotopes of heavy metals such as chromium (Cr) and cadmium (Cd) are gaining prominence in wastewater studies, particularly for tracing and monitoring industrial pollution. Chromium isotopes, especially the ratio of $^{53}Cr/^{52}Cr$, can indicate redox transformations of chromium, distinguishing between toxic hexavalent Cr(VI) and the less harmful trivalent Cr(III). Monitoring such transformations is vital in determining the effectiveness of treatment processes in removing toxic metal species. Cadmium isotopes, on the other hand, help trace industrial discharges into water bodies and can reveal sources of contamination linked to battery manufacturing, plating industries, or phosphate fertilizers. Isotopic fingerprinting of these metals not only identifies pollution sources but also aids in evaluating long-term accumulation risks in soil and crops when treated wastewater is reused in agriculture. Furthermore, compound-specific isotope analysis (CSIA) is used to identify residual pharmaceuticals, industrial chemicals, and other micropollutants, ensuring that treated water meets quality standards for agricultural or industrial application (Keesari et al., 2024).

Conclusions

Treated wastewater should be integrated into urban water management strategies with proper monitoring. This can mitigate environmental and health risks and meet agricultural water demands. Adoption of Industrial and portable applications of treated wastewater may be adopted based on strong business cases and context-specific planning. India also needs a functional regulatory framework to encourage, not hinder, safe and affordable wastewater reuse. With India at a critical crossroads of urban growth and environmental stress, safe and strategic reuse of treated wastewater is not merely an option, but a necessity for water resilience.

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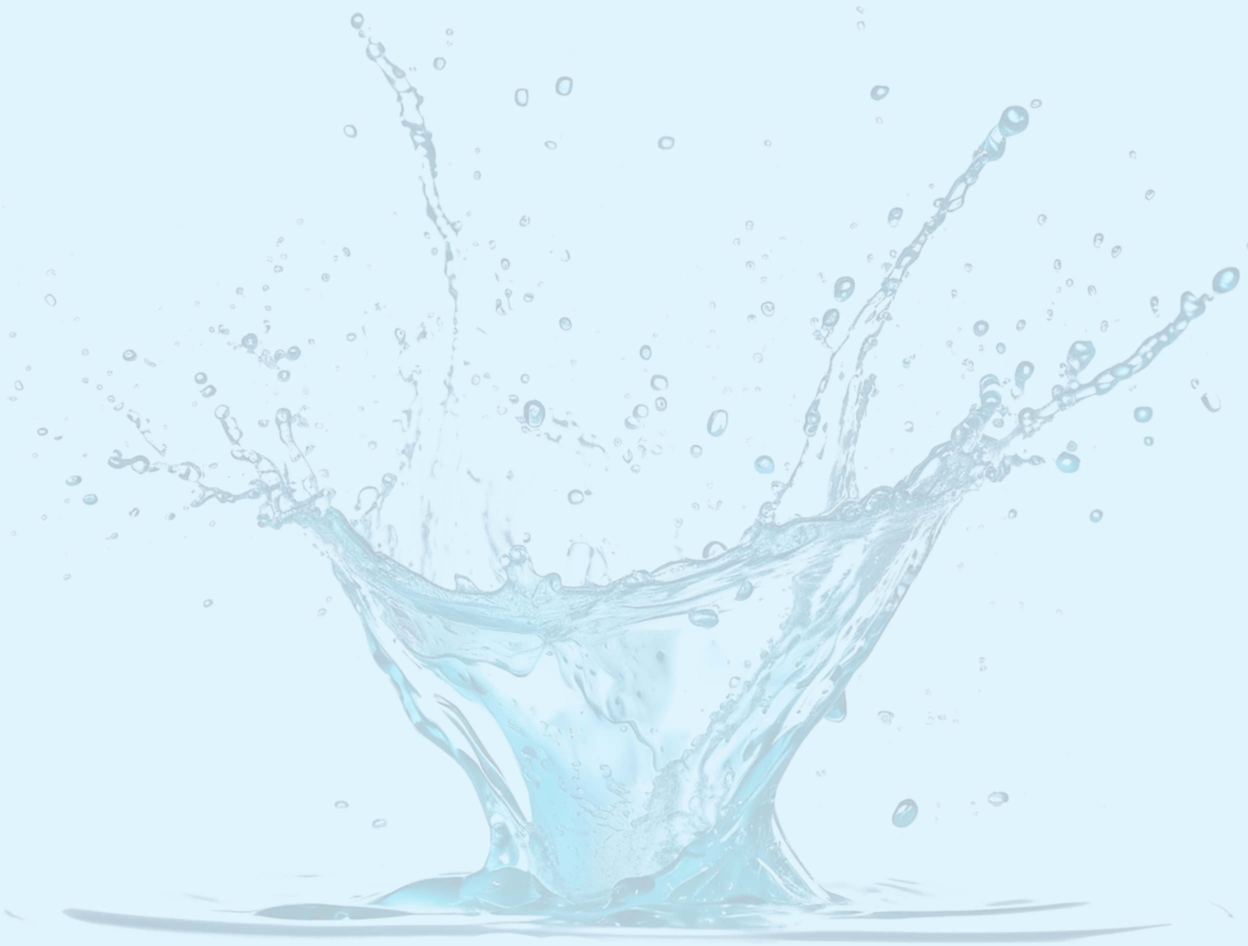

Deep and strategic groundwater resources in the Gangetic Plains

Can environmental isotopes be effective assessment tools?

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The Gangetic Plains, occupying the central part of the 1.1 million km^2 spread Ganga Basin, holds some of the rich aquifer systems of the world. At places, the aquifers are very deep and hold immense groundwater resources recharged hundreds/thousands of years ago. This component, lying below the replenishable resource recharged every year, is termed as a static groundwater resource. In case of emergency such as successive drought years, the static resource can be used in a planned and coordinated manner. Application of environmental isotopes of water (2H & 18O) and radioisotopes (3H & 14C) can play a critical role in understanding and assessing this static resource.

The Ganga Basin, with catchment spread over 1.1 million km^2 , is the most populated and intensively cultivated area in the world. The basin spreads across India, Nepal, Bangladesh and China. The major part of the basin lies in India, receiving good rainfall and drained by perennial rivers, fed both by the glaciers in higher Himalayas as well as by the rainfall. In a hydrological year, the basin receives about 1200 Billion Cubic Meter (BCM) of precipitation of which about 500 BCM is stream flow. A part of the remaining 1000 BCM infiltrates to recharge groundwater, while the remaining returns to atmosphere through evaporation or evapotranspiration (Jain et al 2016). The hydrology of the basin is monsoon driven where 85% of the rainfall occurs during May to September, causing excess water in monsoon and scarcity in dry season. The potential of the hilly area in terms of water resources utilization has not developed fully. The water infrastructure to store runoff during monsoon is yet to be fully developed. On the other hand, the Plain areas are marked with considerable groundwater resource development. The Ganga basin may be divided into three major groups based upon the broad hydrogeological characters (Fig.1):

a] Himalayan terrain: hilly and rugged terrain, rocks are consolidated to semi-consolidated in Nepal, India and China. Low groundwater potential

b] Gangetic Plains: underlain by unconsolidated sediments of variable thickness. Moderate to high groundwater potential. This unit may be further subdivided into the following units;

i) Bhabar belt-along the base of Himalaya, 10-30 km wide in general

ii) Terai belt- along the southern part of the Bhabar belt 10-50 km wide

iii) Central Alluvial Plain- vast stretches along the both side of the Ganga River.

iv) Marginal Alluvial Plain- along the base of the hard rock upland of peninsular India.

v) Deltaic Region- at the southern part of the basin, where the Ganga River meets the Bay of Bengal.

C] Southern Peninsular region: hilly and undulating terrain underlain by consolidated to semi consolidated variety of rocks with moderate to low groundwater potential.

The Central Alluvial Plain covers the major part of the Ganga Basin in India, that spans over 2,50,000 km (Singh, 1996). Unconsolidated thick Quaternary deposits (even more than 2000 m at places) hold rich aquifers at various depths. Immense groundwater resource has made this unit as one of the most extensively exploited regions of the world. The Quaternary alluvial deposits grade to semiconsolidated Upper Tertiary deposits at depth. The sand layers, with occasional mix of pebble & gravel, form highly potential multi-layered aquifer systems. The detailed aquifer configurations could be made available up to 300 m below ground, through National Aquifer Mapping (NAQUIM) Programme, carried out by Central Ground Water Board (CGWB). In the Middle Ganga Plain, lying between the Munger-Saharsa ridge in the east & the Faizabad ridge in the west, is particularly rich with multi-tiered aquifer systems. Very high transmissivity(5163-6974 m^2/day) was reported from these aquifers (Saha et al., 2010). The replenishable groundwater resource, which is rejuvenated every year is estimated in 2011 as 164.4 BCM for the Indian part of the Ganga Basin (Saha et al 2016). No accurate data is available for the Gangetic Plains underlain by unconsolidated deposits holding good aquifers. However, safely it can be assumed that about 80% of the resource, i.e., 132 BCM is confined in this part. The overall stage of exploitation of groundwater resource for the Indian part of the Ganga Basin is around 66%. However, considering large scale exploitation of the groundwater in the Plains through millions of borewells, we can assume that the stage of exploitation would be much high. In fact, in the western part of the Gangetic Plains, falling in the state of Uttar Pradesh, significant number of blocks are classified as over-exploited, indicates groundwater extraction exceeds the recharge in an annual scale. The replenishable resource represents volume lying between the pre- and post-monsoon groundwater levels and it is only a small fraction of the total groundwater resource trapped in the entire column of the sediments. The resource available below the premonsoon water level, till the hard rock basement, is termed as Static Resource. This resource remains untapped if the stage of groundwater exploitation is <100%. No estimation is available on the static resource available in the Gangetic Plains. However, it can be safely assumed that volumetrically this component of groundwater resources would exceed even 50 times of the replenishable resource. It can be even more in the Central Alluvial Plains, where aquifers are thicker and the basement lies at greater depths.

WITH AN annual extraction around 240 billion cubic meters, India is the largest extractor of groundwater in the world. Because of various reasons, including the uncertainty imposed on availability of surface water due to climate change, dependence on groundwater resources will rise in the future.

There are two major concerns on sustainable groundwater management of the Gangetic Plains:

a) Rising exploitation to meet up the drinking and irrigation demands

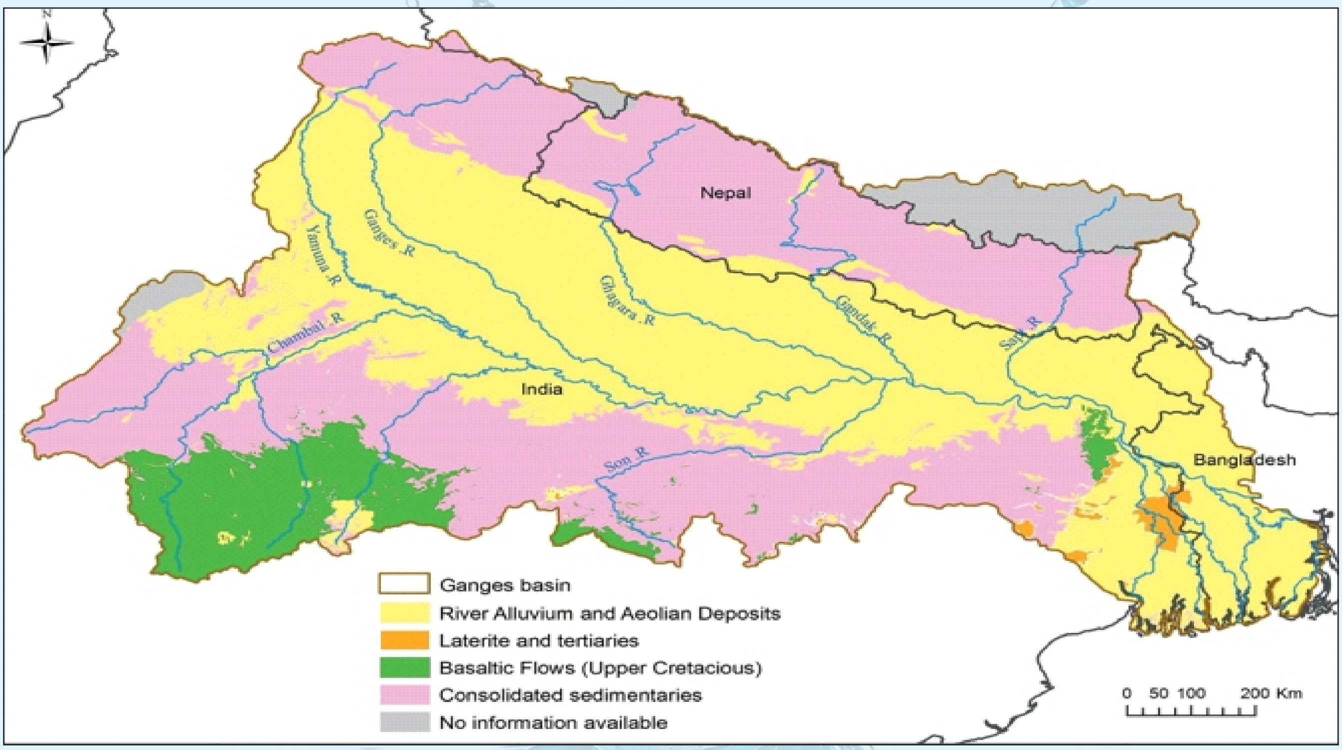

Fig.1: The figure showing the River Alluvium which holds all the five sub units. The Himalayan Terrain is located in the north and the Peninsular Region borders the south. In both the regions the major rock types viz., consolidated sediments, basaltic flows and laterites are also shown.

b) Possible adverse impact because of uncertainties in rainfall and rising temp imposed by climate change

As a country, with an annual extraction around 240 BCM, India is the largest extractor of groundwater in the world. Because of various reasons, including the uncertainty imposed on availability of surface water due to climate change, dependence on groundwater resources will keep on increasing in future. Under such a scenario in large areas, the extraction would exceed replenishable resource and mining of static resource will increase. We must have an accurate assessment of static resource for developing a comprehensive plan to exploit it judiously, as this component of groundwater resource takes much more time to recharge. In first stage, this assessment can be made up to the depth of 300 m below ground, which has been considered as depth of investigation under NAQUIM. In next stage the assessment could take forward till 600 m depth.

> ENVIRONMENTAL ISOTOPE techniques can play a significant role in assessment of static water resource from depths of 300m to 600m. It would aid efforts of researchers to understand better the recharge path mechanism for different aquifers, the age of the groundwater and the hydraulic interaction between aquifers.

Environmental isotope techniques can play a significant role in assessment of the deeper concealed static resource. Isotopes such as hydrogen-2, oxygen-18, tritium and radiocarbon are helpful in understanding the following complexities of the static resource: a) Recharge path a mechanism for different aquifers at depths holding static resource. b) Age of groundwater from different aquifers, which would further elaborate recharge mechanism c) Hydraulic interaction between different aquifers, vertically and laterally. Significant research has been carried out in this direction in the Gangetic Plains by CGWB and other agencies in collaboration with BARC. Keesari et al. (2021) revealed a three-tiered aquifer system, till the depth of 600 m, along a section, between the river Ganga and the southern basin margin ending with the hard rock upland. A 3-tiered aquifer system is identified representing unique groundwater flow regime, aquifer conditions and geometry. The dominant recharge in the shallow unconfined Aquifer-I was found to be from rainfall with mean transit time of about 20 to 23 years. This aquifer system is extensively exploited for irrigation and domestic purposes. Aquifer-I is rejuvenated through river inflows and rainwater percolation through paleo-channels (Fig.2). The semi-confined to confined Aquifer-II holds fresh groundwater with a modelled age of around 400 years. This aquifer system is less tapped for irrigation but intensively exploited in the urban areas through heavy duty deep tubewells. Recharge takes place along the basin margin, where this aquifer is exposed to surface. A part of the recharge to Aquifer-II is contributed by leakage from aquifer-I. The deep confined Aquifer-III (>220 m depth) holds fresh groundwater and is characterised by 3.5 to 4.7 ka ages. Any extraction from Aquifer-III needs a long-term and aquifer-specific recharge plan. In another study, radiocarbon evidence from a network of multilevel monitoring wells in the Bengal Aquifer System showed residence times of between 1000 and 10000 years for groundwater at depths >150 m (Lapworth et al., 2018). The regional security of deep groundwater from the ingress of shallow contaminated groundwater is

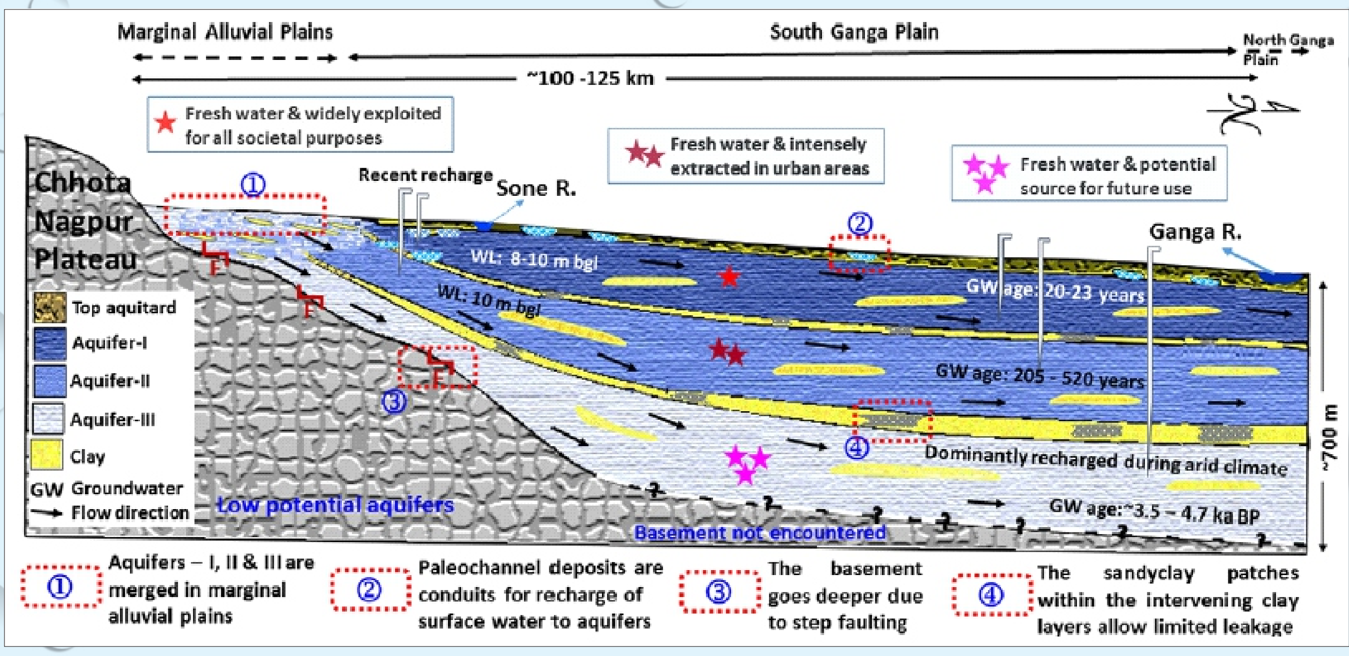

Fig.2: Three tier aquifer system shown as north-south transect in the Middle Ganga Plain in the south of the River Ganga (Keesari et al., 2021).

confirmed by age vs.depth profiles. Sikdar and Sahu (2009) reported high tritium content in shallow groundwater in the shallow aquifers in the Gangetic Plains of West Bengal, suggesting local recharge. While the deep groundwater was found to contain very low tritium implying distant recharge. Authors also observed mixing of groundwater of between shallow and deep aquifers at places. Khanna (1992) has reported four-tiered aquifer system within 425 m depth in the region made up of western part of the Middle Ganga Plain and eastern part of the the Upper Ganga Plain in the state of Uttar Pradesh.

Conclusions

As per the policy adapted in India, groundwater utilization should not exceed the replenishable resource available so that the stage of overexploitation is not reached. However, the factors like rising water demand and the adverse impact of climate change are gravitating the society to rely more on groundwater resources. This is particularly true for the Gangetic Plains, particularly the Central Alluvial Plain - a thickly populated and intensively cultivated region underlain by thick alluvial and deltaic deposits. The replenishable groundwater resource, which is recharged every year is only a fraction of the total groundwater resource available within the thick unconsolidated sediments. At present the groundwater wells are mostly confined within 150 m depth and the average extraction is within the safe limit, though number of overexploited blocks is emerging in the western part because of unsustainable groundwater extraction. In future groundwater extraction is likely to increase further in the central and eastern parts also, which is presently marked with lower stage of development, to meet up rising demand from irrigation. As the groundwater demand increases in the Gangetic Plains, the Static resource, occurring at deeper levels, can be used in a limited scale and under a planned manner, if the replenishable resource is under pressure. In-case of emergency like, successive years of drought or rain failure Static resource can be a huge support. This component of resource can be used strategically with proper planning and supporting interventions for its recharge and replenishment. Given the importance of this resource, and expected future demand, all-out precaution should be taken to avoid vertical leakage of contaminated shallow groundwater to deeper zones due to leakage through intervening aquitards or faulty well construction. Applications of environmental isotopes can play a pivotal role in understanding the recharge paths and mechanisms and also estimating the volume of Static resource, trapped within a complex web of multi-tired aquifer system in the Gangetic Plains.

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From Source to Solution

Isotopic Tools in Arid Land Water Management

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Isotopic signatures in all components of the hydrological cycle provide valuable insights into their source, origin, and migratory history, especially in water-scarce & arid regions. Furthermore, radioactive isotopes aid in dating groundwater, enabling the determination of recently recharged groundwater, quantifying the mixing proportions and water dynamics. Of late, isotopes have been used in conjunction with hydrological, statistical, meteorological, remote sensing, and GIS techniques for providing better information on climate change impacts on water resources.

In arid zones, groundwater often exists in deep, fossil aquifers that recharge very slowly. This makes understanding the hydrogeological context essential before any extraction begins. Middle East and North Africa (MENA) regions are characterised by arid climate and rely heavily on non-renewable groundwater for agriculture. The outcome of the isotope studies in MENA regions demonstrate that water management plan must be based on robust scientific data including recharge rates, aquifer capacity, and water quality. By learning from each other and from past mistakes, countries can safeguard their groundwater resources for future generations. Despite the challenges, a wealth of experience from MENA regions provides valuable lessons for sustainable groundwater governance. This article provides key findings of the isotope studies conducted towards groundwater management in this MENA and other arid regions, which are relevant to arid and semi-arid areas of India.

A

Arid regions face significant water resource challenges due to extreme temperatures, low rainfall, high evaporation, and limited surface water availability. The arid (representing 16% globally) and hyper-arid (8%) regions cover nearly about 28 million km^2 of the world. Population growth and climate change further exacerbate these issues, necessitating innovative solutions for sustainable water management. The main source of freshwater in the region is obtained through desalination. Advanced technologies such as remote sensing (El-Bagoury et al., 2025), GIS (Dharmavarapu et al., 2025), geochemical studies (De Windt et al., 2025), and groundwater modeling (Gan et al., 2025) help in assessing and managing the water resources. However, models often fail to accurately represent extreme hydrological behaviours such as monsoons and droughts (Ali et al., 2015), highlighting the need for uncertainty assessments in decision-making. Recently, machine learning (Aicha et al., 2025), big data analysis (Keesari et al., 2021), and artificial intelligence (Wederni et al., 2024) have been used to provide a deeper understanding on groundwater occurrence, movement and sustainability.

Isotopes serve as vital tools for understanding the origin, movement, and age of water sources in arid regions (Ali et al., 2015). They provide insights into hydrological processes, groundwater recharge, pollution sources, and climate impacts on water resources. Stable isotopes (δ^2H, $\delta^{18}O$) and radioisotopes (tritium, chlorine-36, uranium isotopes) help assess source, origin, dynamics and hydraulic interactions, etc. In addition, isotope techniques are also used for identifying sources pollutants and their pathways enabling sustainable groundwater management. Isotopes provide critical information essential for analyzing local water cycles, estimating recharge rates, and understanding land cover impacts on soil water movement. Table 1 summarizes isotopic indicators and key hydrological and environmental insights they provide. This article explores the usefulness of isotope hydrological techniques in arid zone studies and their potential role in water resource assessment, quality evaluation, and water resources management under changing climatic conditions and anthropogenic drivers.

Precipitation sources

Several studies have attempted moisture source identification using isotopes, revealing distinct moisture sources, movements and recharge patterns. The relationship between $\delta^{18}O$ and $\delta^{2}H$ in rainwater is used to derive moisture sources and for this purpose local meteoric water lines (LMWL) are established. In the Essaouira basin, δO and $\delta^{2}H$ values indicate that groundwater recharge primarily originates from Atlantic-derived precipitation (Rafik et al., 2022). Isotopic analysis of soil water in the Loess Plateau suggests recharge occurs primarily through precipitation, with variations at different depths (Suarez et al., 2015). Similarly, in the Idfu-Esna area, groundwater recharge sources are mainly precipitation, lateral flow, and deep aquifer leakage (Ahmed et al., 2019).

Isotopic studies were conducted in arid regions belonging to non-MENA regions to help deduce the source of groundwater. The isotopic trends of groundwater in Hulun Lake Basin suggest that groundwater recharge is facilitated by faults, with recharge primarily from basaltic formations (Ma et al., 2022). Isotopes also quantify evaporation losses and infiltration rates, critical for water management in arid regions. The Local Evaporation Line (LEL), derived from isotope data, indicates evaporation extent. Enriched $\delta^{2}H$ and $\delta^{18}O$ values in Ili-Balkhash Basin lake waters suggest intense evaporation compared to river waters (Li et al., 2017). In the Loess Plateau, isotopic tracers reveal dominant soil water migration pathways and plant water uptake sources (Suarez et al., 2015). In the Manas River Basin, isotopic ratios indicated that groundwater originates from glacial melt and precipitation, with flow paths influenced by irrigation return flow and vertical mixing due to pumping (Wang et al., 2021).

Groundwater recharge and its interaction with surface water

Stable isotopic ratios of water have been used to determine recharge zones in many arid regions. In Tula-Bustamante aquifer, $\delta^{2}H$ and $\delta^{18}O$ data was used to map recharge zones, while tritium concentration helped in evaluating the groundwater dynamics (Ibarra-Alejos et al., 2024). Similarly, in the Grombalia aquifer, the isotopic analysis revealed modern rainwater contributions to recharge and the effects of evaporation and human activities on water quality (Kammoun et al., 2018). Tritium and stable isotopes were used to identify the modern rainwater recharge in Tunisia (Kamel et al., 2014), while their integration with hydrochemical analyses improved groundwater interaction studies in the Vredefort Dome World Heritage Site. A detailed environmental isotopic characterisation of the groundwater system in southern Kuwait was been carried out and the study inferred that the groundwater salinity of the Kuwait Group aquifer generally increases from southwest to northeast, although locally, a few of them show low values (Hadi et al., 2016).

Age of Water and Paleo recharge

Paleo water identification using isotopes is crucial for distinguishing between modern and ancient groundwater. In the Gunii Khooloi basin, radiocarbon data revealed that deep groundwater was recharged during the glacial age, indicating its ancient origin (Bayanzul et al., 2019). Tritium analysis has also proven effective in groundwater dating, as seen in Erbil, Iraq, where it helped differentiate old and young water sources (Wang et al., 2010). Similarly, tritium concentrations in the Loess Plateau indicated that water below 7 meters depth was over 50 years old (Ma et al., 2022).

Table 1: Isotopic indicators for understanding hydrological and environmental processes in arid zones.

Process/Phenomenon	Isotopic Indicators	Key Insights
Evaporation	$\delta^{18}O$, $\delta^{2}H$	Isotopic enrichment in residual water. (Zhu et al., 2022)
Water Source Tracing	$\delta^{18}O$, $\delta^{2}H$	Differentiation of precipitation, surface, and groundwater (Suarez et al., 2015)
Paleoclimate Reconstruction	$\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$, ^{14}C, Noble gas isotopes	Historical climatic conditions and recharge (Sabarathinam et al 2020)
Hydrological Processes	$\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$	Soil water migration, groundwater recharge, plant uptake (Sang et al., 2023)
Environmental/Anthropogenic Influences	$\delta^{18}O$, $\delta^{2}H$, ^{3}H, $\delta^{15}N_{NO3}$, $\delta^{18}O_{NO3}$, $\delta^{11}B$, $\delta^{34}S$, $\delta^{13}C_{CH4}$, $\delta^{2}H_{CH4}$	Impact on water quality and recharge (Vera et al., 2021).
Submarine groundwater discharge	^{222}Rn, ^{224}Ra, ^{225}Ra, ^{226}Ra, ^{228}Ra	Discharge of terrestrial groundwater to the bay and open sea regions (Bhandary et al., 2020).

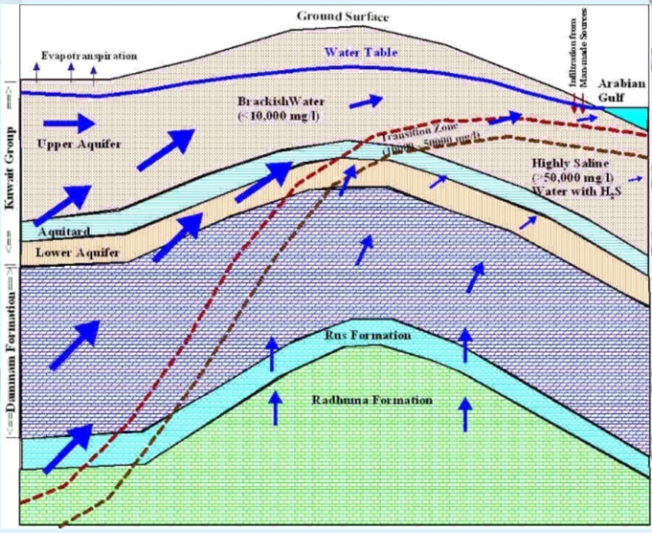

Fig.1: Conceptual groundwater flow in coastal region of Kuwait by understanding the age of groundwater and the regional hydrology (Source Hadi et al., 2016)

The Kuwait Group and Dammam Formation aquifers exhibit a wide range of d-excess values (+16.0 to −20.6‰ and +22.8 to −19.6‰, respectively), signifying multiple water sources with varying recharge histories (Hadi et al., 2016) Interconnection between these aquifers occurs near the coast and southwest border, refining the existing conceptual groundwater flow model (Fig.1).

Paleoclimate

Understanding the paleoclimate of the region are very important to assess the conditions that favoured or restricted the aquifer creation and expansion and determine the potential sources of aquifer recharge. A study in Kuwait analyzed major ions and isotopes to determine paleo-recharge sources in the Kuwait Group Aquifer (KGA) and Dammam Formation (DFm). The radiocarbon ages (^{14}C dating) of the groundwater ranged from 31.9 to 3.9 Ka (Ka – thousand years) in DFm and 23.3 to 0.8 Ka in KGA, reflecting very old and distinct recharge histories. Corrected ^{14}C ages using Tamer's model indicate that groundwater recharge to the Dammam Formation aquifer likely took place in cooler and humid phase. The paleoclimate conditions deduced from the stable and radioactive isotope signatures in groundwater for the Arabian Peninsula indicated two primary rainwater sources: an enriched southern Indian Ocean monsoon and a depleted northwesterly Mediterranean vapor source. A shift in the Intertropical Convergence Zone (ITCZ) between 7.8 and 4.9 Ka influenced the Holocene climate, likely driven by tropospheric easterly jet shifts due to Holocene volcanism. (Sabarathinam et al., 2020).

Water quality, Pollution and processes

Isotopes of dissolved compounds when integrated with water isotope can provide deeper insights into the source of the pollution and the mobilization processes (Table 2). Nitrate isotopes ($\delta^{15}N_{NO3}$ and $\delta^{18}N_{NO3}$) effectively traced agricultural runoff and wastewater pollution in Jordan (Yang and Fu, 2017). Additionally, boron and uranium isotopes helped to distinguish between anthropogenic and geological salinity sources in the Rio Grande River (Lin et al., 2018). Isotopes help identify salinization processes and quantify solute sources, including seawater intrusion and nitrate contamination (Ahmed et al 2016). In the Atacama Desert, isotopic studies linked groundwater salinization to seawater intrusion (González-Domínguez et al., 2024). Similarly, isotopic analysis in Tunisia evaluated mineralization processes affecting agriculture and drinking water (Hassen et al., 2016). In the La Yarada aquifer, isotopes revealed seawater intrusion and hydrogeological impacts on water quality (Vera et al., 2021). In the Southern Gobi Region, isotopic studies indicated weak interaction between shallow and deep aquifers, with ancient deep groundwater less affected by modern contamination (Bayanzul et al., 2019). In Kuwait, $\delta^{13}N_{CH4}$ analysis identified three major methane sources (methyl-substrate methanogenesis, carbonate substrates, and mixed sources) and processes (biogenic, abiogenic, and thermogenic), with distinct regional variations (Chidambaram et al., 2024). Isotope studies on water quality were carried out in many other arid regions across the globe. A multi-tracer approach combining uranium, strontium, and boron isotopes provided insights into water mass contributions and salinity sources in complex river systems (Lin et al., 2018). Similarly, isotopic and hydrochemical analyses help trace hydrological cycles, contamination sources, and land use impacts on water quality (Zhu et al., 2022). In North China, isotopes identified domestic sewage & agricultural activities as major contributors to groundwater contamination (Su et al., 2020).

Helium isotopes offer better insights in to groundwater age, migration patterns, and recharge zones. Concentrations of ^{4}He, ^{3}He/^{4}He, ^{20}Ne, and major ions in groundwater samples were analyzed. Helium concentrations in Kuwait Group aquifers ranged from 3.82×10^{-8} to 1.33×10^{-6} cm^{3} STP/g, while Dammam Formation ranged from 9.97×10^{-8} to 1.62×10^{-6} cm^{3} STP/g (Fig.2). Geological structures influence helium distribution, with concentrations decreasing alongside Cl and δ^{18}O signatures. Higher helium fluxes recorded during the Last Glacial Maximum rose steadily over time. North Kuwait samples (1650–348 years BP) exhibited tritiogenic helium linked to meteoric decay, inferred from R_A (air-normalized He ratios). Earthquake epicentres (magnitude 2–4) were more frequent in regions with lower R_A values. Lateral helium flow, along with in-situ (rock matrix-derived) and exogenous sources (vertical upward flow, atmospheric input, and hydrocarbon reservoirs), was observed (Rashid et al., 2023).

Quantifying submarine groundwater discharge (SGD) is crucial for sustainable groundwater management, as it delivers nutrients, dissolved carbon, and trace elements to the sea. Naturally occurring radioactive isotopes were used to estimate SGD along Kuwait's

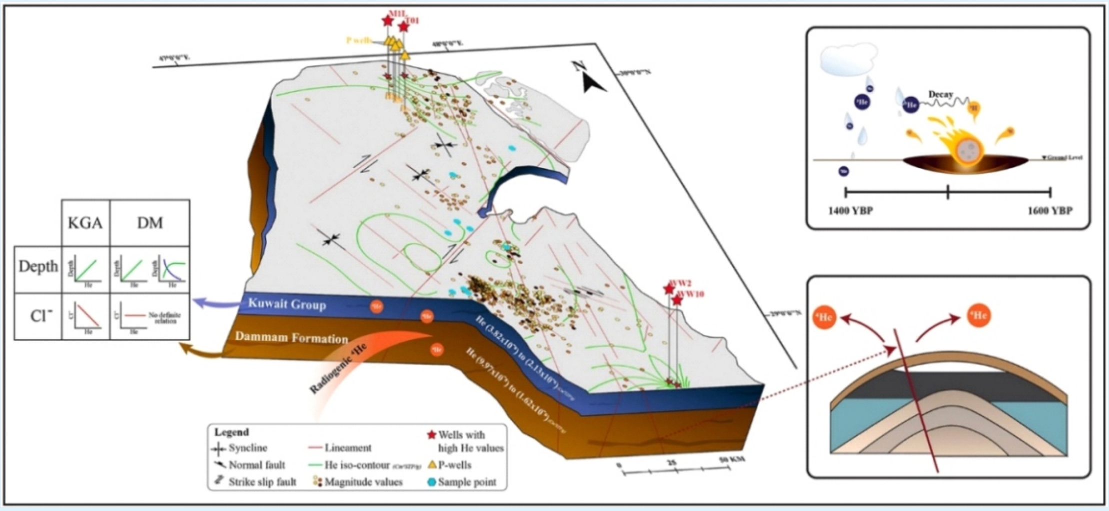

Fig.2: Variation of Helium concentration in brackish groundwater of Kuwait aquifers, related to geological structures and other processes (source Rashid et al., 2023)

coastal strip in the Arabian Gulf (Bhandary et al., 2020). The research is significant in assessing brackish groundwater loss in arid regions. Groundwater samples were collected from coastal wells, while seawater samples were taken from Kuwait Bay and the open sea. Samples were analyzed for major ions, nutrients, and radium isotopes (^{223}Ra, ^{224}Ra, ^{226}Ra & ^{228}Ra). The box model and offshore gradient model approaches were used to estimate SGD. Variations in radium isotopes across transects were influenced by the Kuwait coastal jet. The water mass residence time in Kuwait Bay and the open sea ranged from 10–58 and 12–64 days, respectively. SGD fluxes, estimated using ^{226}Ra & ^{228}Ra, were 3.05×10^{6} & 5.46×10^{6} m^3/day in Kuwait Bay, and 2.92×10^{8} & 3.0×10^{7} m^3/day in the south Arabian Gulf.

Summary

Integrating isotope data with hydrochemical and geophysical information supports conceptual groundwater models, which is very essential for evolving the sustainable protocols for water management. Isotopic techniques are precise, non-invasive and comprehensive in nature. They provide accurate insights into water origin, aquifer dynamics and contamination risks, benefiting arid regions. However, isotopic heterogeneity, evaporation, and human activities yet times limit the potential of isotope data. Combining isotopic methods with computational and geochemical techniques will further enhances the understanding of the water resources in arid regions.

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Dr. Sabarathinam has published over 200 articles in peer-reviewed journals and has edited 10 books in the field of hydrogeochemistry. His contributions to hydrogeology and environmental geochemistry were recognized by the Indian Society of Applied Geochemists in 2016. Additionally, he has participated in training programs organized by the International Atomic Energy Agency (IAEA) and has served as an expert for several IAEA expert missions.

Radiocarbon as isotope chronometer and tracer in hydrological sciences

The potential & diverse dating and tracing applications of radiocarbon using Accelerator Mass Spectrometer

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Radiocarbon (^{14}C) acts as an "isotope chronometer" allowing to determine the age of carbon-bearing materials based on its predictable radioactive decay. ^{14}C is formed naturally in the upper atmosphere through interactions between cosmic ray neutrons and nitrogen. By measuring the remaining ^{14}C in a sample and comparing it to the initial levels, scientists can date the samples up to ~50,000 years of age. This makes radiocarbon a powerful chronometer for dating archaeological, geological, and environmental samples, helping reconstruct past events and processes across a range of scientific fields. Additionally, during 1950s-1960s, ^{14}C has been formed anthropogenically due to sudden increase of neutrons in the atmosphere caused by on surface testing of nuclear bombs. This article showcases the potential and diverse dating and tracing applications of radiocarbon using Accelerator Mass Spectrometer (AMS), helping reconstruct past events and processes in paleoclimatology and marine sciences.

Discovery of radioactivity was one of the highly significant gifts to the human kind. Out of the known 3349 isotopes, 3303 isotopes are radioactive and only 246 isotopes are stable. These isotopes have played a vital role in the modernization of healthcare, environmental research and many other domains of the human life. Carbon is one element with three isotopes ^{12}C, ^{13}C (both stable) and ^{14}C (radioactive) which plays a vital role being ubiquitous on the planet earth (Fig.1A). The half-life of 5730 years make radiocarbon a unique isotope as it is the most ideal isotope to characterize not only the development of human civilization but also to understand the climate, sea level and environmental changes in recent geological past called Holocene and beyond, upto ~50ka. Radiocarbon as a dating tool was discovered by Willard F. Libby in 1946 (Libby et al. 1949) for which he was awarded Nobel Prize in 1960, and at that time it brought revolution in establishing accurate chronology in archaeology and related domains, and even now perhaps ^{14}C is the most used radionuclide in studying the all spheres of our environment. Invention of AMS in 1977 out of nuclear physics research laboratories brought second revolution in radiocarbon dating as it drastically reduced the required sample size and measurement time and increased sensitivity and accuracy of age estimation.

Radiocarbon is produced in the upper atmosphere by the interaction of cosmic rays with ^{14}N. Following production, ^{14}C is oxidized to $^{14}CO_2$ and quickly dispersed throughout the atmosphere, then transferred to other carbon reservoirs like the biosphere and oceans through processes like photosynthesis and air-sea exchange of CO_2. This production channel in nature has been since time immortal with some fluctuations depending on the availability of cosmic ray neutrons and ^{14}N. However, very recently this, natural ^{14}C levels were disturbed by large amounts of bomb ^{14}C; produced during atmospheric nuclear weapons tests in the 1950s and 1960s. Peak concentration of ^{14}C in atmosphere, in 1963 was 1000 times higher than the natural cosmogenic background. This bomb ^{14}C has moved throughout the environment, including into organic matter present on land and sea. Being a recent phenomenon, Bomb carbon has been measured in various archives at land and sea and it is well documented for regions of southern and northern hemispheres. Bomb pulse dating and tracing is highly useful in forensic, biological in oceanography research. Thus, radiocarbon became a powerful tool for investigating water circulation on regional and global scales in marine environment. Isotopic fractionation occurs naturally during processes like photosynthesis and air-sea CO_2 exchange, measured ^{14}C concentrations are typically corrected using $\delta^{13}C$ values.

Inter-University Accelerator Centre (IUAC), New Delhi has established India's first facility for AMS measurement of various isotopes viz. ^{10}Be ($T_{1/2}$= 1.38Ma), ^{14}C ($T_{1/2}$= 5730a) and ^{26}Al ($T_{1/2}$= 0.75 Ma) radioisotopes (Kumar P et.al 2015, Sharma et.al, 2019) by modifying its 15UD Pelletron Accelerator and later with a dedicated 500kV ion accelerator system. The recent developments in Accelerator Mass Spectrometry (AMS) have significantly advanced oceanic and environmental investigations that were previously limited by sensitivity or sample availability. AMS allows for the analysis of long-

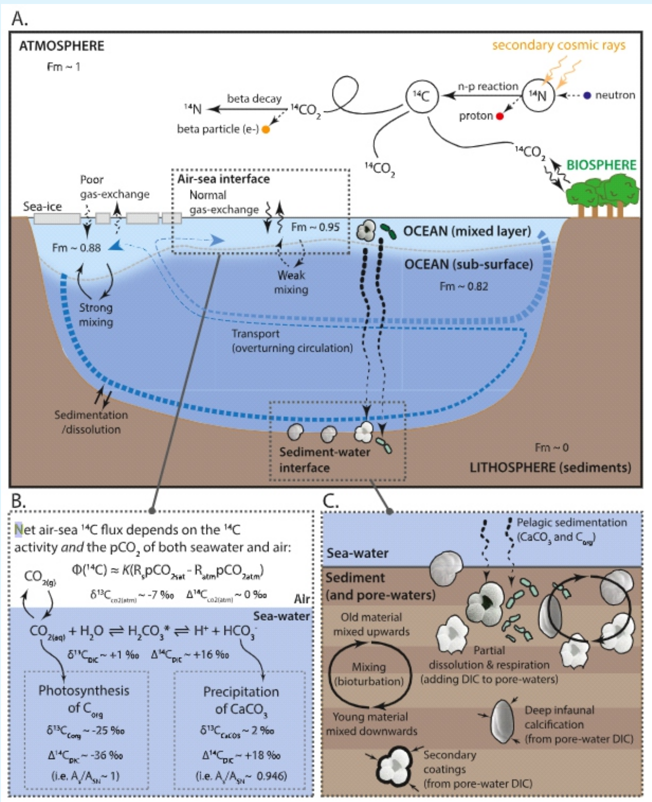


Fig.1: Pictorial representation of radiocarbon production mechanism in the atmosphere and its transport into the marine radiocarbon cycle (A), including chemical processes happening at the air-sea interface (B) and the sediment-seawater interface (C). (taken from Skinner, L. C., & Bard, E., 2022).

THE RECENT DEVELOPMENTS in Accelerator Mass Spectrometry (AMS) have significantly advanced oceanic and environmental investigations that were previously limited by sensitivity or sample availability.

lived natural and anthropogenic radionuclides at ultra-low levels. Few applications of radiocarbon in marine science research are presented in Fig.1.

Sea Level Rise Research

Climate change driven sea level rise is major cause of concern for the coastal population across the globe. The behaviour of sea level in past specially the Holocene has been investigated and contributing factors could be global as well local. The global factors are those related to the change in the global ocean volume affected by the melting of the ice at polar regions as well as other ice reservoirs (e.g. Himalaya) feeding the large quantity of water into ocean through rivers. Local factors are responsible for the change in costal morphology driven by the tectonics and cause the sea level change due to upliftment or subsidence. Both factors are time-dependent and the accurate reconstruction of sea-level variations requires the use of suitable sea-level indicators, whose age can be ascertained by proper absolute dating methods. Most of the times these indicators are carbonaceous and siliceous materials such as shells, foram aggregate, coral, wood materials and peat etc. and have been given importance as they are the good indicators of sea level as well as datable with radiocarbon. V.J. Loveson and R. Nigam (2019) have complied 75 radiocarbon dates performed on several sea level indicators and have generated Holocene Sea level curve for the east coast of India (Fig.2).

Submerged speleothems have also been used as past sea level indicators and in these cases ^{14}C dating is performed on the last layer formed in aerial continental conditions. In sea-level rise research, radiocarbon plays an important role to provide an absolute date to the sea level markers (Antonioli, F., et.al 2021).

Tracing Global Ocean Movement

Radiocarbon enters the ocean from the atmosphere via air-sea CO_2 exchange at the sea

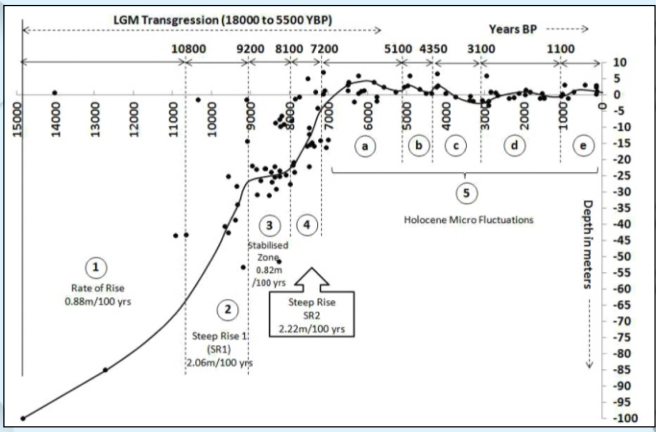


Fig.1: Holocene sea level curve for the east coast of India based on the ^{14}C age data

surface, which in turn is influenced by temperature and salinity effects on CO_2 solubility, once radiocarbon has entered the surface ocean, it is re-distributed within the "mixed layer" relatively quickly (the top ~100 m or so of the water column is mixed on a timescale of order ~years), and can then be transported into the ocean interior via advective and diffusive processes, with radiocarbon decaying away over time as this occurs (Fig.1B). Through continuous exchange with the atmosphere the ocean surface water approximately reflects the atmospheric $^{14}C/^{12}C$ ratio, whereas the deep ocean water shows a reduced ratio depending on how long it had been disconnected from exchange with the surface (Fig.1C). In order to obtain better insights into the ocean circulation and to validate ocean circulation models (Broeker, 1991), a dedicated AMS facility The National Oceanographic Sciences AMS (NOSAMS) at Woods Hole USA was set-up in 1990, with the goal to map the world oceans with ^{14}C measurements in an unprecedented way. As compared to the first mapping performed in the 1980s with beta-counting, which required 250 L water samples, but now 0.5 L of water provides sufficient carbon for a ^{14}C AMS measurement. As a result, over 20,000 water samples have been measured for ^{14}C within the World Ocean Circulation Experiment project (WOCE), literally mapping the world oceans in three dimensions (McNichol, 2000) and supplying a wealth of information on global ^{14}C and $\delta^{13}C$ distributions.

A LARGE POPULATION OF INDIA (~65%) is dependent on monsoon rainfall driven agriculture and it is imperative to model the future trends of Indian monsoon for better preparedness and policy formulation to maintain sustainable development, supported by long term temporal and spatial monsoon variation data.

Paleomonsoon reconstruction

A large population of India (~65%) is dependent on monsoon rainfall driven agriculture and it is imperative to model the future trends of Indian monsoon for better preparedness and policy formulation to maintain sustainable development of the country. For this purpose, it is required to have long term temporal and spatial monsoon variation data. There have been numerous studies taken up on land and marine archives to create such a dataset in Indian subcontinent (Sengupta et.al, 2025, Palar et.al, 2025). Marine environments, especially Oceans offer long, uninterrupted and continuous records and therefore, for paleomonsoon studies, sediment cores collected from high sedimentation rates zones (e.g. Bay of Bengal) are studied to generate sub-centennial to decadal resolution paleo-monsoonal records. Often microfossils, like foraminifera, radiolarians, diatoms, ostracodes, coccolithophores, pollens, spores, alkenone, corals and other microfossils are picked up from sediment cores and studied. Radiocarbon dating of these microfossils (sea water derived ^{14}C present in $CaCO_3$) collected from different depths in the sediments cores helps in establishing absolute chronology up to 50 Ka.

Tracing anthropogenic radionuclides

Beyond bomb ^{14}C, anthropogenic radionuclides released from sources like, nuclear reprocessing facilities and the Fukushima accident are used as tracers. ^{14}C enrichment from Sellafield has been tracked in the Irish Sea and West of Scotland, showing higher levels in mussels and shells above background, though decreasing over time with reduced releases (Tierney, K.M., et.al , 2016, Muir, G.K.P., et.al 2015). Elevated ^{14}C has also been found in sediments, where the enrichment appears to be increasing. Studies confirmed a detectable, though relatively small (9% above global fallout), contribution of ^{14}C from the Fukushima accident to the sea (Povince, P.P., et.al, 2017, Kaizer J., et.al 2023)

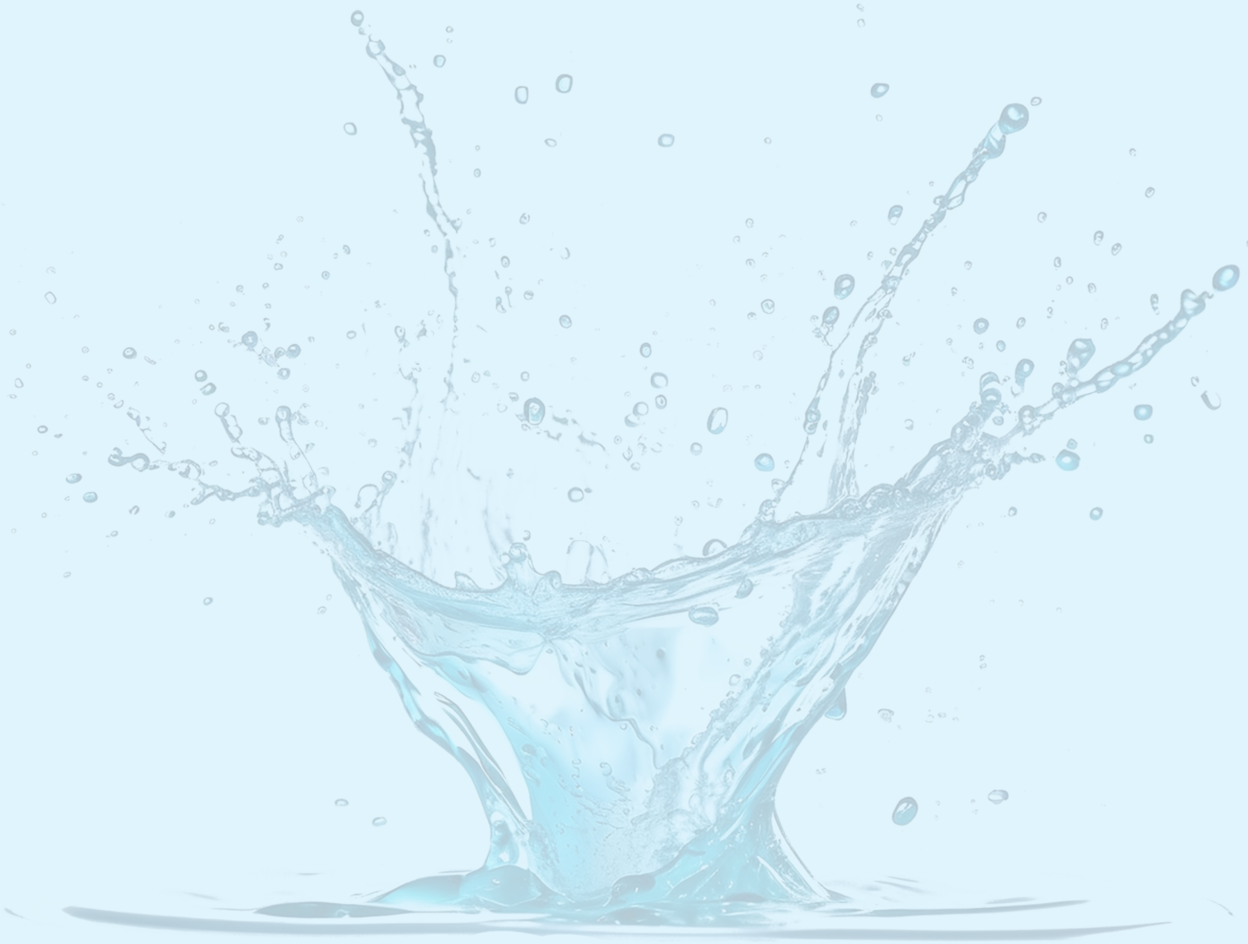
Tsunami periodicity

The 26th December 2004 tsunamigenic earthquake took more than 280,000 lives and post this event, there have been efforts (Malik et.al, 2019, J. Sanwal et.al, 2023) to find out paleo tsunami events and their recurrence interval, if any, so to better plan the infrastructure activities near the densely populated coastal areas in India. In order to understand the tsunami periodicity, if any, by analysing the sediment cores collected from the southern Andaman Island. Several cores and trenches at Badabalu along the south cost of Andaman were dug and 7 tsunami events were identified ranging over past 8000 years. Radiocarbon dating of charcoal, coconut clast, root, buried wood and foraminifera, confirmed the presence of Paleo-tsunami events occurred in 2004CE (recent), historic tsunami in 1881, 1762, 1679CE, prehistoric tsunami in 1300-1400CE, in 2000-3000BCE and 3020-1780BCE and before 5600-5300BCE. This study suggested a recurrence of 420–750 years for mega-earthquakes having different source, and a shorter interval of 80–120 years for large magnitude earthquakes.

Conclusion

Radiocarbon is a potential dating tool having wide applications in hydrological, archaeology, paleoclimatology, and marine sciences. Accelerator Mass Spectrometry (AMS) is a well-established and absolute dating technique for measuring radiocarbon in small sample sizes with fast measurement times and it also provides accurate and precise measurements. However, site specific marine reservoir correction and calibration are essential to deduce accurate calendar ages. A few research studies presented in the article showcases diverse applications of radiocarbon dating using AMS in oceanography.

Dr. Pankaj Kumar, Senior Scientist in IUAC (Delhi), is a physicist with research interest in geochronology and isotope research using accelerator mass spectrometer and low energy mass spectrometers. He has played a key role in advancing India's capabilities in geochronology and environmental radionuclide analysis by establishing MoES funded National Geochronology Facility at IUAC. He has published more 110 publications in peer reviewed journals. Dr. Kumar is a recipient of S.N. Seshadri Memorial Award-2020 by Indian Physics Association (IPA), in recognition of his key role in developing Accelerator Mass Spectrometry (AMS) facility at IUAC. He is a Life-Member of IPA, NASI and Indian Society of Particle Accelerator. He has been selected member of Indian National Young Academy of Science (INYAS) of INSA and served as a national core committee of INYAS. Currently, he is executive council member and joint secretary of IPA.



Study on Uranium in Groundwater of Madurai district, Tamil Nadu

Uranium and other radionuclides in water can cause health issues if present in higher concentrations. This study aimed at studying the behavior of Uranium in groundwater in Madurai district. Over 200 samples were collected from different seasons [Pre-monsoon (PRM), South-west monsoon (SWM), Northeast monsoon (NEM), and Post-monsoon (POM)] across diverse lithological units for U, ^{222}Rn, δ^{18}O and δD along with major ions and trace metals measurements. Electrical resistivity surveys were conducted to characterize the subsurface and the results were confirmed with the lithologs. It was observed that the order of U concentrations in different seasons was SWM > PRM > POM > NEM according to maximum values.

The comparison between the U concentration and groundwater level indicates that the uranium concentration varies primarily due to hydrological conditions. Rainfall recharge raises groundwater levels, dissolving uranium and increasing the U concentration during SWM. However, during NEM, the increase of groundwater recharge lowers U concentration. The substantial correlation between U and ^{222}Rn suggests that U could be the source of ^{222}Rn in groundwater during PRM, SWM, and NEM. The fact that the pH-Mg relationship is negative indicates that ion exchange mechanisms are predominant. Uraninite and the U_4O_7(c) field are more prevalent in the samples from SWM, NEM, and POM. It is also observed that only a small percentage of SWM samples are saturated in the Uraninite field. The dominant species of U in PRM and POM is $UO_2\,(CO_3)_2^{2-}$ and in SWM and NEM is $UO_2\,(HPO_4)_2^{2-}$. The good correlation was observed between the U and the $UO_2(CO_3)_2^{2-}$, $UO_2(CO_3)_3^{4}$, $UO_2(OH)_3^{0}$, $UO_2(HPO_4)_2^{2-}$, Mg, PO_4, HCO_3 and H_4SiO_4.

There are two major factors influencing the resistivity, viz. lineament and lithology. The greater weathered thickness is noted in the southeastern part of the study area. In contrast, the northeastern part of the study area has higher U concentration, corroborated with increased weathered thickness of the area. Stable isotopes reflect two different signatures: enrichment of δ^{18}O with low U content and depleted δ^{18}O with high U levels. This is due to the recharge from precipitation or weathering-induced factors. The enriched isotopic signatures indicate that evaporated surface water bodies, such as lakes are contributing to groundwater recharge. PCA analysis indicated four significant processes/factors, viz., anthropogenic, ion exchange, weathering and fluoride dissolution. The spatial distribution of these processes reveals that lineament, water level, land use, and lithology are the major driving forces for the observed changes in the chemical composition of groundwater including uranium distribution in the study area.

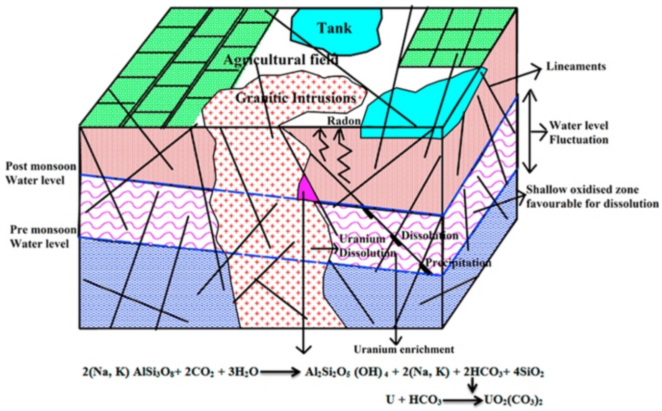


Fig.1: Schematic representation of the occurrence of uranium and radon in the groundwater of the Madurai district of Tamil Nadu, India

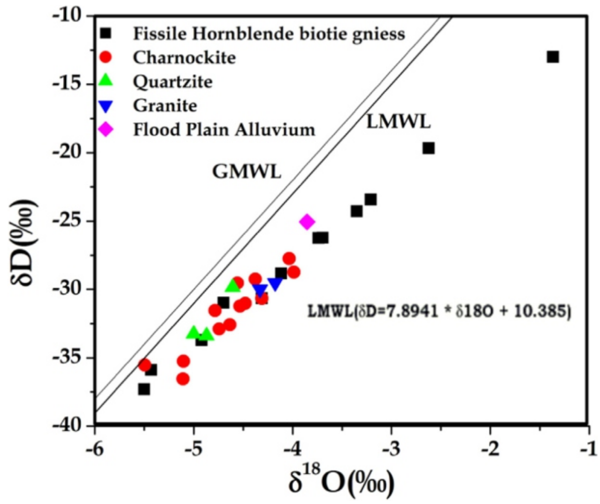


Fig.2: Plot for δ^{18}O versus δD of groundwater samples compared with GMWL (Global Meteoritic water line) and LMWL (Local Meteoritic water line) of the Madurai district of Tamil Nadu, India

Highlights of the work carried out by **Dr. C. Thivya** under the supervision of **Prof. S. Chidambaram** as a part of her doctoral thesis work. She was awarded PhD degree from Annamalai University, Tamil Nadu in Department of Earth Sciences in 2014 supported by Board of Research in Nuclear Sciences (BRNS), Research Project vide Ref. No.2012/35/12/BRNS/1918 dated 2012.

Hydrogeochemistry of Organic Carbon in Groundwater of Pondicherry Region

Carbon is an essential element found in rocks and minerals, playing a key role in sustaining life by serving as an energy source. One of its forms, dissolved organic carbon (DOC), is a useful indicator of water pollution, particularly from landfills and natural sources. This study investigated DOC levels in layered coastal aquifers of the Pondicherry region. Groundwater samples (93 sites) were collected across the major lithological formations and seasons. The collected samples were examined for heavy metals and isotopes of $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$. Higher DOC and electrical conductivity (EC) were observed in Alluvial samples, indicating anthropogenic influence, while SWM samples showed lower DOC levels, suggesting dilution by rainwater.

Increased HCO_3^- and DOC levels in Upper and Lower Cuddalore, other Tertiary and mixed aquifers suggest calcite dissolution due to CO_2 from organic matter degradation. Stable isotope data indicate that enriched $\delta^{18}O$ and $\delta^{2}H$ isotopes (Fig.1), along with high DOC. This might be a result of contribution from evaporated waters or sewage infiltration.

Lower DOC with enriched $\delta^{18}O$ in Alluvium, Cretaceous, and Lower Cuddalore samples suggest landfill decomposition or bacterial activity. Some samples showed recharge from evaporated water and anthropogenic DOC input, while kankar in soil exhibited relatively lighter $\delta^{13}C$. A few samples from Lower Cuddalore and Cretaceous formations, fall close to the GMWL, suggesting direct recharge or anthropogenic influence. Enriched $\delta^{18}O$ with lower d-excess in certain formations indicates evaporation before recharge, likely from lakes or reservoirs. Isotope data suggests new sources influenced by precipitation or storm runoff in Lowe Cuddalore, Cretaceous and other Tertiary aquifers, while lower d-excess indicates recharge from evaporated sources through lateral flow or surface runoff retention.

$\delta^{13}C$ analysis suggests lignite/peat leaching in Upper Cuddalore and marine organic deposits in Cretaceous formations. Heavy metal and DOC analysis revealed strong correlations between Fe and Sr in Upper Cuddalore and Other Tertiary formations. SWM samples from Alluvium, Upper Cuddalore, and Cretaceous exhibited elevated DOC and Radon levels, potentially due to prolonged residence time, agricultural pollution, or landfill leaching. A positive correlation between organic carbon and iron was observed in Upper Cuddalore but was weaker in Lower Cuddalore and Other Tertiary and absent in Alluvial aquifers.

Statistical analysis indicates inter-aquifer mixing of parental and anthropogenic factors, with DOC migration from Lower to Upper Cuddalore driven by reducing conditions associated with Marcasite (Fig.2). A good positive correlation has often been observed between the contents of dissolved organic carbon and metal concentrations in few samples irrespective of formation, which is due to the metal bonding by organic substances, since a number of mechanisms produce simultaneous accumulation of organic material as well as typical metals. Vulnerability assessment highlights high susceptibility in the East and Southeast of Alluvial and Upper Cuddalore sandstone formations, while Cretaceous aquifers in the Southwest and Northeast are more prone to anthropogenic impacts, affecting groundwater quality. This study underscores the importance of monitoring DOC and associated parameters to assess groundwater vulnerability and potential contamination sources in coastal aquifers.

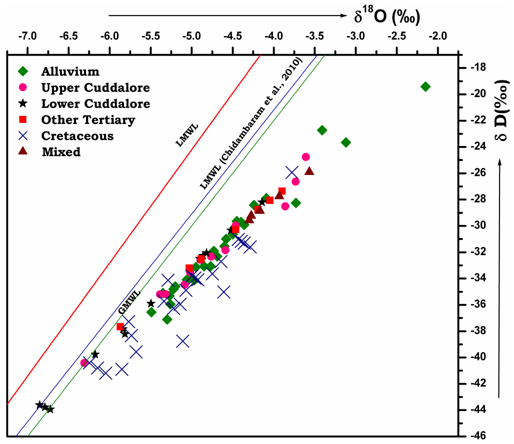


Fig.1: Conceptual diagram showing the relation between $\delta^{18}O$ and δD for groundwater samples

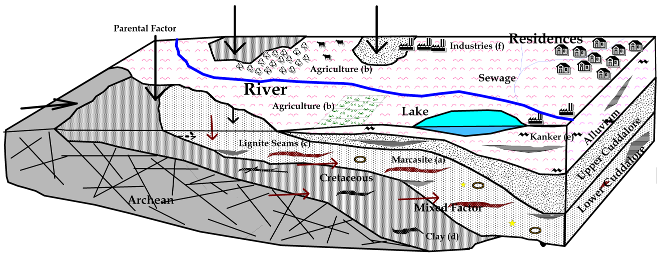


Fig.2: Systematic diagram shows the hydrochemical set up of the study area. (a) Marcasite shows FeS_2 oxidation (b) In agriculture shows addition of K, NO_3 and PO_4 (c) Industries shows NO_3 and PO_4 influences. (d) Lignite show DOC reduction processes (e) Clay show ion exchange, DOC reduction processes (f) Kankar show dolomite or calcite weathering

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Highlights of the work carried out by **Thilagavathi Rajendiran** under the supervision of **Dr. S. Chidambaram (Guide)** as a part of her doctoral thesis work. She was awarded a Ph.D. degree from Department of Geology, Annamalai University Tamil Nadu in 2015. Supported by BRNS with sanction letter No. F: 36(4)/14/14/2014 Dated 16 July 2014.

Investigations of Source of Uranium and its Geochemical Pathways in Aquifer Systems in Parts of Southwest Punjab using Environmental Isotope Techniques

Uranium in drinking water has been a subject of great concern in India and rest of the world as prolonged consumption might lead to nephrotoxicity and osteotoxicity in humans. U is considered as a confirmed human carcinogen (group A) and WHO has set a safe acceptable limit of 30 µg/L and AERB has established the radiological limit of 60 µg/L for drinking purposes. In this research work, two districts, Bathinda and Mansa districts of SW Punjab (5538 km^2) were investigated to obtain deeper insights into the sources and processes responsible for uranium contamination in groundwater. The tools applied were hydrogeology, hydrochemistry, environmental stable and radioisotopes, geochemical and statistical modeling.

The entire study area showed groundwater uranium concentration from 0.6 to 590 µg/L (Fig.1(a)) while canal waters showed negligible U values (<2 µg/L). A declining trend was observed in U concentration along the depth. U dose calculations indicate that there is chemical as well as radiological toxicity health risk to the inhabitants of this region. Geogenic factors show high positive values with U while anthropogenic factors show poor correlations indicating geogenic sources being the actual controls on U distribution. NO_3^- showed fairly positive correlation with dissolved U hinting that NO_3^- can be a potential agent to drive U release into groundwater. Saturation indices of U minerals indicate that groundwater is under-saturated with most of the uranium containing minerals and hence there is a possibility of more U leaching into groundwater with time. Speciation calculations indicate that the dominant species of U in groundwater are, UO_2CO_3, $UO_2(CO_3)_2^{2-}$ and $UO_2(CO_3)_3^{4-}$. $^{234}U/^{238}U$ Activity Ratio (AR) values reflect stable accumulation zone and leaching of low AR U source. A very narrow range of AR values in both seasons reflect that similar process governs the U distribution in groundwater.

Isotope data indicates that zone (i) is recharged by local precipitation with some component from evaporated surface water (irrigation return flow) and recycled vapor source. In the case of zone (ii), the main recharge is by precipitation. $\delta^{13}C$ values show that groundwater in zone (i) indicate mostly root respiration. The contribution of irrigation return flow to zone (i) and (ii) was examined by employing ^{222}Rn. A clear indication of surface water contribution to zone (i) is noticed from ^{222}Rn depth profiles. ^{3}H values indicate modern recharge to both zones. Both fast and slow recharge occurs in zone (i) while groundwater in zone (ii) is relatively older.

Groundwater fluctuations affect the geochemical condition of the water i.e. oxidation and redox potential and trigger the release of U on the sediments by oxidation of U (IV) to U (VI). In addition, hydrogeological processes like recharge and discharge also impact U distribution in groundwater. The schematic representation (Fig.1(b)) displays irrigation return flow and water logging favor the release of U into the zone (i) groundwater while sand dunes aids in diluting the U concentration in groundwater by easy percolation of precipitation. No significant changes in U concentration are noticed in groundwater of zone (ii). From the above research findings, the following hypothesis is proposed: U present in sediment is mobilized by reacting with oxidants (DO and NO_3^-). Once U oxidizes to UO_2^{2+}, it complexes with the dissolved HCO_3^- in groundwater and forms $UO_2(CO_3)_2^{2-}$ and $UO_2CO_3)_3^{4-}$ complexes, which are stable and mobile in groundwater. Zone (ii) shows less U contamination as the dissolved HCO_3^- and oxidants are less in concentration.

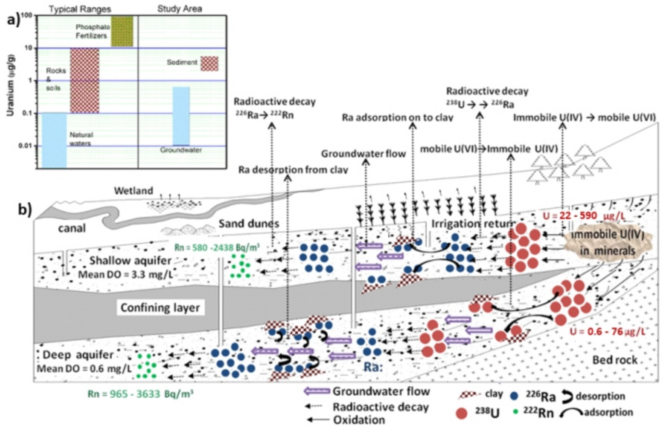

Fig.1(a) Uranium concentration in different environmental media vs study area, (b) Conceptual model for Uranium distribution in groundwater

Based on the above studies, it is recommended that canal water may be used for drinking and domestic purposes in the affected regions of Punjab after treatment with conventional techniques. Secondly, places where canal network is not accessible, usage of deep groundwater for drinking can be recommended.

Highlights of the work carried out by **Anoubam Diana Sharma** under the supervision of **Dr. Madhuri Rishi (guide)** and **Dr. Naval Kishore (co-guide)** as a part of her doctoral thesis work. This work was a part of BRNS, DAE project, Sanction no. 35/14/11/2014-BRNS-193, and **Dr. Tirumalesh Keesari** was the Principal Collaborator. She was awarded Ph.D degree from Panjab University, Chandigarh in 2019.

Isotope and Hydro-chemical Investigation on Uranium in Groundwater of South-west Punjab and Central Rajasthan

High uranium concentrations are reported in groundwater of Punjab, Rajasthan, Madhya Pradesh, Andhra Pradesh, Chhattisgarh and Haryana by researchers. These high concentrations are not limited to one kind of geological formation but are spread across the diverse geological setups in India. Hence, it is very important to understand the role played by aquifer geology, geochemistry and dynamics towards the mobilization of uranium into groundwater. This study focuses on uranium contamination in groundwater, analyzing its occurrence, mobilization mechanisms, and hydro-chemical controls in Punjab and Rajasthan, two regions with different geological settings but similar climatic and agricultural conditions. Environmental isotopes (δ^2H, $\delta^{18}O$, ^3H), hydrochemistry (Cl^-, NO_3^-, SO_4^{2-}, F^-, HCO_3^-, Na^+, K^+, Mg^{2+}, Ca^{2+}), total uranium and its isotope activity ratio ($^{234}U/^{238}U$), geochemical and statistical modeling approaches were applied to address the stated objectives.

The study reveals that a significant percentage of groundwater samples in both Punjab and Rajasthan exceed WHO's permissible limit of 30 µg/L, making the water unsafe for human consumption. In Punjab, the percentage of contaminated samples decreases in the postmonsoon season due to dilution, whereas in Rajasthan, contamination levels increase postmonsoon, worsening the health risks. In Punjab, uranium levels are higher in the premonsoon season due to increased oxidation of U(IV) to U(VI), driven by elevated nitrate concentrations. However, in the postmonsoon season, recharge from rainfall leads to dilution and reduced contamination levels. In contrast, Rajasthan experiences an increase in uranium concentration in the postmonsoon season, attributed to delayed recharge and the dissolution of salts from the vadose zone. Stable isotope analysis supports these findings. In Punjab, contamination is higher in shallow aquifers due to active oxidation processes, while deep aquifers show occasional pockets of high uranium concentrations due to mixing with shallow water. In Rajasthan, uranium contamination is more uniformly distributed across different depths, with both alluvial and hard rock aquifers exhibiting similar contamination patterns. In Punjab, where alluvial aquifers dominate, uranium mobilization is primarily driven by oxidative dissolution facilitated by high nitrate concentrations from agricultural runoff and irrigation return flow (Fig.1). The study reveals that uranium contamination is more pronounced in shallow aquifers, where oxidation processes are more active, and decreases in the postmonsoon season due to dilution effects. In Rajasthan, which has both alluvial and hard rock formations, uranium mobilization occurs through leaching and prolonged water-rock interactions. The study also examines uranium isotopic activity ratios ($^{234}U/^{238}U$) as a tool for understanding groundwater dynamics. In Punjab, the activity ratio remains close to equilibrium, suggesting oxidative dissolution as the dominant mobilization process. In Rajasthan, higher activity ratios indicate disequilibrium caused by alpha recoil and selective leaching, which are influenced by the long residence time of groundwater (Fig.1). Optimal use of fertilizers and using surface sources or deep groundwater for drinking can help mitigate uranium contamination in Punjab while removal of uranium through membranes or ultrafiltration techniques can be applied to in the case Rajasthan. The study provides a comprehensive understanding of uranium contamination in groundwater, highlighting its complex geochemical behavior, seasonal and spatial variations, and the influence of hydrochemical drivers.

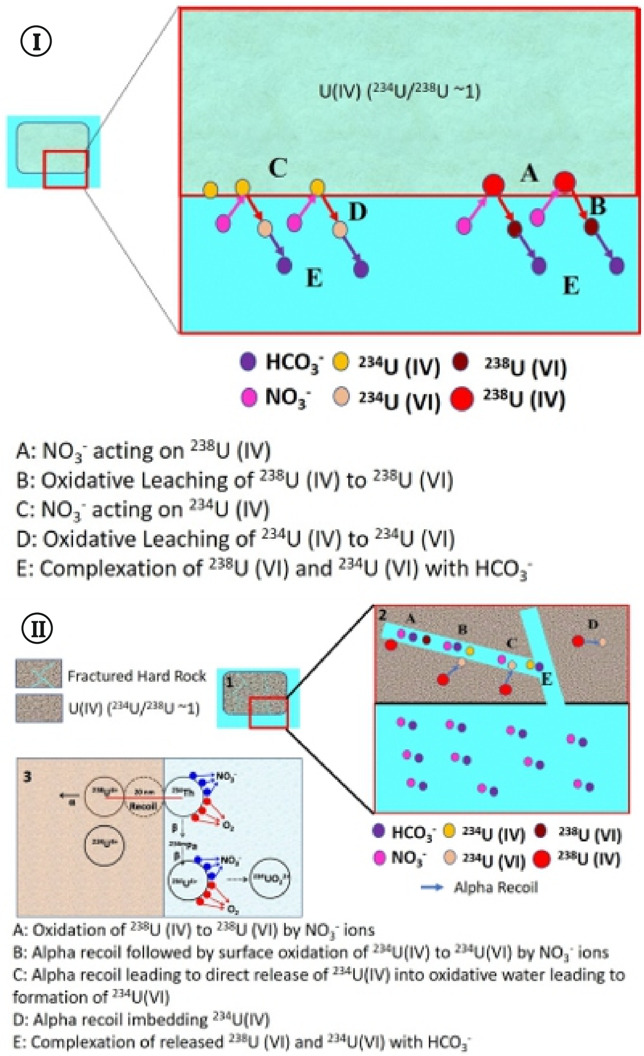

Fig.1: Conceptual model of uranium release in I) alluvial formation of Punjab and II) hard rock formation of Rajasthan

Highlights of the work carried out by **Diksha Pant** under the supervision of **Dr. K. Tirumalesh** as a part of her doctoral thesis work. She was awarded PhD degree from Homi Bhabha National Institute in Chemical Sciences in 2021.

Integrated Isotope-geochemical Investigation in the Selected Geothermal Areas of India

The term 'Geothermal' originates from two words: 'geo', means earth whereas 'therme', means temperature/heat. Therefore, the geothermal heat is basically the thermal heat stored beneath the earth surface which serves as an energy source in diverse applications, ranging from large-scale power stations to smaller heat pumping systems. Integrated isotope (both stable and radioactive) and geochemical characterization of the thermal waters are extremely valuable in providing information about the origin of thermal fluid, identification of their possible recharge area, geochemical evolution, source of dissolved solutes, estimation of subsurface reservoir temperature etc. Among various stable isotopes, the variations in the $^{18}O/^{16}O$, $^{2}H/^{1}H$, $^{13}C/^{12}C$, $^{34}S/^{32}S$ and $^{87}Sr/^{86}Sr$ isotopic ratio have been widely used in accessing different hydrological characteristics of thermal fluids. On the other hand, radioactive environmental isotopes like tritium (^{3}H) and ^{14}C are mainly used for estimating the residence time of the thermal waters.

The thesis enumerates the in-depth isotope-geochemical assessment of three promising geothermal areas (Tural-Rajwadi area, Godavari valley area and Tapoban-Badrinath area) situated in the three distinct geological settings. It was observed that all the thermal springs found in the Tural-Rajwadi (Deccan Trap region, Maharashtra), Godavari Valley (Sedimentary formation, Manuguru region) and Uttarakhand region (Himalayan belt) are meteoric in origin. Based on the isotopic evidence, the probability of magmatic water was found to be negligible even in the Uttarakhand geothermal region which is a part of tectonically active Himalayan geothermal system (Fig.1). Tural-Rajwadi geothermal area located near the seashore exhibited enriched stable isotopic value than the Godavari valley geothermal area which was situated deep inside the island (continental effect). The Badrinath thermal water (BTHS-1) of Uttarakhand area showed most depleted isotopic signature due to its highest altitude of recharge. Geochemically, thermal waters in the Tural-Rajwadi region were more mature (Na-Cl type) compared to the thermal waters in Godavari valley and Uttarakhand region (bicarbonate type). Application of the lumped parameter models (LPM) along with the tritium time series data in precipitation was found to be very useful in constraining the mean transit time (MTT) of the thermal water. Tritium dating also allowed in quantifying the extent of mixing of the thermal water with the non-thermal water. The highest extent of mixing (up to 70%) was observed in the Tapoban thermal spring (THS-1) of Uttarakhand area. Carbon-14 dating technique helped to estimate the transit time of the very old thermal water present in the Tural-Rajwadi and the Godavari valley geothermal area. Among the three geothermal areas, the thermal waters from the Uttarakhand area were found to be the youngest one (age ranged from 40 to 112 years). The geothermal systems from the peninsular India i.e. Tural-Rajwadi (age varies from 6000 to 15000 years) and Godavari valley (age varies from 9900 to 18600 years) contained much older fraction of thermal waters. Chemical geothermometers, mixing models as well as multicomponent geothermometry techniques were simultaneously applied to better constrain the reservoir temperature. The subsurface reservoir temperature was found to be highest in the Tural-Rajwadi geothermal area ($160^{0} \pm 10^{0}C$) whereas the estimated reservoir temperature in Uttarakhand and Godavari valley geothermal area was found to be similar ($\sim 130 \pm 10^{0}C$) (Fig.2).

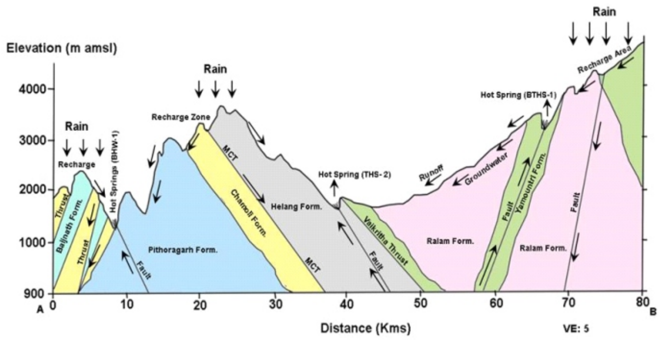

Fig.1: Conceptual diagram showing origin and evolution of Uttarakhand geothermal area

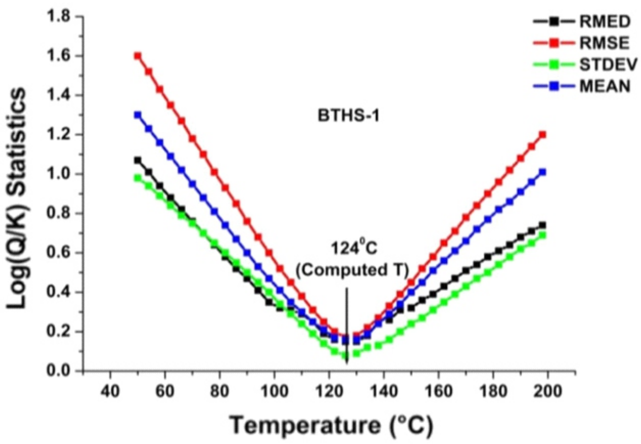

Fig.2: Reservoir temperature estimation in Uttarakhand geothermal area using multicomponent geothermometry method

Highlights of the work carried out by **Sitangshu Chatterjee** under the supervision of **Dr. Ashutosh Dash** as a part of his doctoral thesis work. He was awarded PhD degree from Homi Bhabha National Institute in Chemical Sciences in 2021.

Hydrological Investigation of Regional Aquifer Systems in Contrasting Climatic Regions of North-west India using Isotope–geochemical Modeling Approaches

The North West Indian Aquifer System (NWIA) is one of the world's most critical regional aquifer systems, supporting socioeconomic stability of the Indian subcontinent. Rapid population growth and changing agricultural practices have significantly impacted groundwater resources resulting in declining water levels as well as deteriorating water quality. Existence of a wide network of paleochannels in this region provides an excellent opportunity to improve the groundwater condition by adopting managed aquifer recharge (MAR). Given the diverse climatic settings, contrasting regional recharge dynamics, and knowledge gaps, this research was conducted in both the upstream and downstream stretches of this paleochannel system to study the groundwater recharge mechanism, dynamics, interconnection, geochemical evolution using environmental isotopes, hydrochemical data, and modelling techniques. A total of 186 samples were collected from monitoring bore wells, tube wells, dug wells, surface water bodies etc. during 2017 to 2020 across northern Haryana and northwest Gujarat regions. Rainfall samples were also collected during monsoon period of 2017 to 2020 for isotopic analysis. Isotope Ratio Mass Spectrometer (IRMS), Liquid Scintillation Counter (LSC) and Ion Chromatography (IC) instruments were used for stable isotope (^{2}H, ^{18}O, ^{13}C, ^{34}S), environmental radioisotope (^{3}H, ^{14}C) and major/minor ion analysis respectively.

The results suggest that in northern Haryana (upstream part, Fig.1), groundwater recharge is spatially variable due to hydrologic anisotropy. The deeper aquifers receive recharge from western Himalayan precipitation, with isotopic evidence indicating a paleorecharge event dating back to ~29 ka Before Present (BP). This suggests a glacier-fed paleoriver system that contributed 48–61% of recharge between 29 to 10 ka BP.

In northern and western Gujarat (downstream part), aquifer sustainability is threatened by salinity, fluoride (F^-), nitrate (NO_3^-) contamination as well as groundwater depletion. The northeastern zone exhibits faster recharge, while the western part is dominated by older recharge (~33 ka BP). Groundwater quality in this region is controlled by halite dissolution, ion exchange and nitrification processes. In the Bhuj sandstone aquifer (western Gujarat, Fig.2), recharge is influenced by local topography with isotope data showing a paleorecharge component (~3 ka BP). Limited modern recharge has led to rising salinity and therefore groundwater sustainability is a major concern.

An isotope-based geospatial vulnerability model was developed to delineate prioritised zones for remediation effort in NWIA, the model has achieved 82% accuracy and was validated with respect to groundwater NO_3^- data. Additionally, hybrid machine learning (ML) models were proposed in this study, which provided a high groundwater quality prediction accuracy (up to 89.66%) and were proved effective for real-time water quality monitoring in data-scarce regions.

Overall, the integrated methodology developed in this research provides a comprehensive framework for groundwater sustainability assessment and water resource management in NWIA, supporting future MAR initiatives and targeted remediation based on isotopic, geochemical and machine learning inputs.

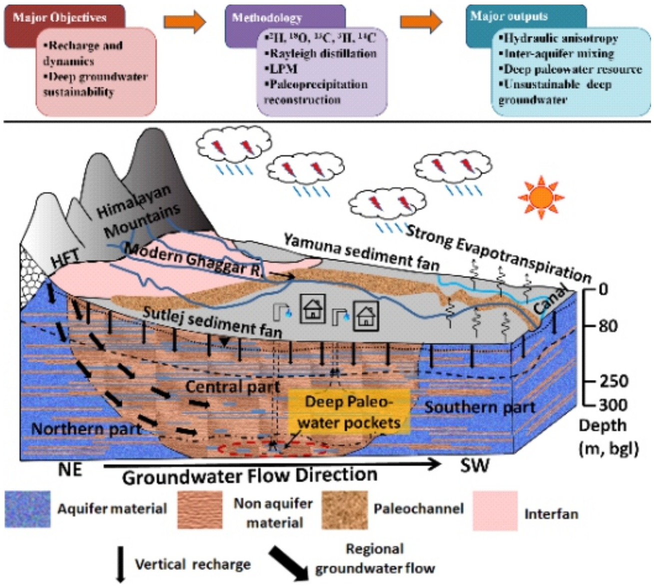

Fig.1: Conceptual diagram of hydrological systematics in Northern India

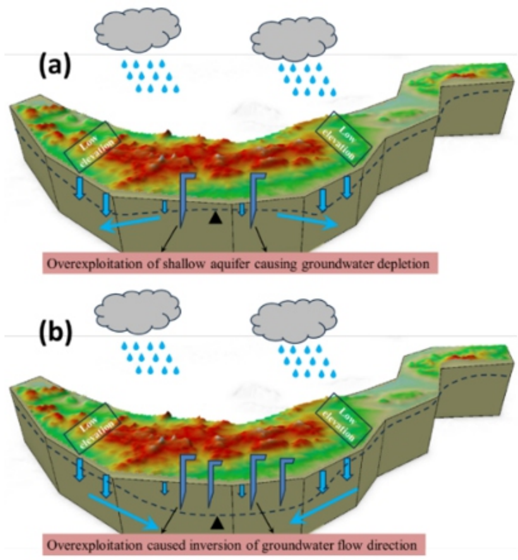

Fig.2: Conceptual diagram of hydrological systematics in Western India

Highlights of the work carried out by **Annadasankar Roy** under the supervision of **Dr. Tirumalesh Keesari** as a part of his doctoral thesis work. He was awarded PhD degree (provisional) from Homi Bhabha National Institute in Chemical Sciences in March 2025.

BARC Q&A

Tête-à-tête with Shri Subodh Yadav

Additional Secretary
River Development and Ganga Rejuvenation
Ministry of Jal Shakti

The points in the interview were shared as answers to an email questionnaire by Dr. K. Tirumalesh of RC&IG, BARC.

With India's over dependence on groundwater, what strategies can ensure sustainable usage of water for present and future?

At the national level, groundwater is increasingly becoming the backbone of India's water security. It caters to nearly 65% of irrigation needs, 85% of rural drinking water demand, and supports growing urban and industrial use. This widespread reliance, while vital to socio-economic development, has also led to significant stress. Ensuring sustainable use of this invisible lifeline is not just a technical necessity, but a national imperative.

India's groundwater utilization patterns are shaped by diverse geological, climatic, and socio-economic contexts. Therefore, a balanced approach which encompasses blending demand management, supply augmentation, regulation, and community participation is essential.

On the supply side, replenishment of groundwater resources through artificial recharge structures, watershed management, and revival of traditional systems is crucial. The Jal Shakti Abhiyan and Amrit Sarovar Mission are already creating thousands of such structures across the nation. Additionally, re-using the water generated from treatment of wastewater can significantly curtail the need for tapping new groundwater resources.

On the demand side, micro-irrigation, crop diversification, and precision agriculture offer scalable solutions. The Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) and incentives for water-smart farming are steps in the right direction.

Institutionally, programmes like the Atal Bhujal Yojana and National Aquifer Mapping (NAQUIM) are empowering communities and stakeholders with tools to understand aquifer behavior and prepare Water Security Plans at the Gram Panchayat level. Tools like IN-GRES have brought transparency and scientific rigor to groundwater estimation.

Only through this integrated and inclusive strategy can we ensure groundwater remains a secure, equitable, and resilient resource for generations to come.

With increasing urbanization, do you think India has a robust policy framework for managing water demand in cities? What reforms are urgently needed to avoid any near-future eventualities and "zero water-day" situations?

India's rapid urbanization is emerging as one of the most pressing challenges to water security. By 2036, nearly 40% of the country's population is expected to reside in urban areas, thereby significantly increasing the demand on already strained water resources and infrastructure. While notable strides have been made in recent years, urban water management in India must evolve further to meet this growing pressure.

Multiple ministries are working collaboratively to address the issue. The Ministry of Housing and Urban Affairs is spearheading the Jal Jeevan Mission (Urban), which aims to ensure 100% household tap water connections and promote the reuse of treated wastewater. Under AMRUT 2.0, cities are developing Water Balance Plans and upgrading water supply and sewerage infrastructure. The Smart Cities Mission is incorporating advanced technologies such as smart metering, real-time monitoring, and automated leak detection to enhance water efficiency. The Ministry of Jal Shakti is leading the Jal Shakti Abhiyan, focusing on rooftop rainwater harvesting, water body rejuvenation, and aquifer recharge. Simultaneously, the Ministry of Environment, Forest and Climate Change is promoting wetland conservation and regulating environmental flows

…Presently, there's a shift towards integrated and sustainable water resource management in India, combining traditional wisdom with modern strategies. Yet, overcoming the legacy challenges requires holistic planning, community participation, and resilient infrastructure that can adapt to climate and demographic pressures…

Shri. Subodh Yadav

to protect urban ecosystems. To make cities truly water-resilient, an Integrated Urban Water Management (IUWM) approach is being promoted, linking surface water, groundwater, stormwater, and wastewater systems. Water pricing reforms and metering are being introduced to incentivize efficient use while safeguarding affordability for vulnerable populations.

India possesses the policy framework, institutional capacity, and technical tools necessary for transformation. What is needed now is stronger convergence across agencies, effective enforcement, and widespread public participation.

How has the Indian National Water Policy evolved over time, and what changes are necessary for future water security, with reference to both drinking and irrigation water demands?

India's National Water Policy (NWP) has evolved significantly over the past few decades, reflecting the country's changing priorities and growing understanding of water as a finite and shared resource. The maiden policy, formulated in 1987, was focused primarily on the development and utilisation of water resources through construction of large-scale infrastructure projects such as dams, reservoirs, and canal systems. This aligned with the national objective of achieving food security and supporting industrial growth in the post-independence era.

The revised 2002 policy marked an important shift by acknowledging the need for participatory irrigation management, conjunctive use of surface and groundwater, and water pricing as a conservation tool. The 2012 policy represented a more integrated and forward-looking approach. It introduced the concept of Integrated Water Resources Management (IWRM), emphasized ecological flow requirements, climate resilience, and water-use efficiency. Importantly, it brought groundwater into sharper focus and recognised it as a common-pool resource. India's National Water Policy is a dynamic guideline. As water challenges become more complex, policy framework will continue to evolve, in order to guide the stakeholders for initiating appropriate actions in a timely manner. Of late, there is an increasing shift from supply-side approaches to demand management, community participation, decentralized governance, and science-based planning. Emphasis is growing on treating water as a common public resource, ensuring equitable access, and promoting water security for all.

How are extreme rainfall events impacting water resources, and what approaches can develop climate-resilient water systems, particularly considering the receding Himalayan glaciers that feed major rivers?

Extreme rainfall events, marked by their unpredictability, intensity, and frequency, are becoming more common due to climate change, with profound impacts on India's water resources. On one hand, sudden downpours lead to urban and riverine flooding, damage to water infrastructure, and reduced groundwater recharge as runoff flows rapidly. On the other hand, prolonged dry spells and shifting monsoon patterns are contributing to droughts, crop failures, and declining reservoir levels. These twin extremes have potential to destabilise India's historically monsoon-dependent water systems. In parallel, the receding Himalayan glaciers which feed major rivers like the Ganga, Yamuna, Brahmaputra, and Indus pose an even greater long-term risk. Glacial melt initially increases river flows but will eventually lead to reduced base flows, especially in the dry season, severely affecting water availability for millions downstream.

In response, India has begun integrating climate resilience into water resource planning. Under the National Hydrology Project, real-time hydro-meteorological data is being used for flood forecasting and reservoir operation. The Namami

…India possesses the policy framework, institutional capacity, and technical tools necessary for transformation in water resources management. What is needed now is stronger convergence across agencies, effective enforcement, and widespread public participation…

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Gange programme is incorporating ecological flow monitoring to protect river health amid changing flow patterns. Many states are increasingly adopting Water-sensitive Urban Design and building rainwater harvesting and recharge structures under schemes like Jal Shakti Abhiyan and Amrit Sarovar. To address infrastructure safety, the enactment of the Dam Safety Act, 2021 has established a comprehensive regulatory framework for monitoring, inspecting, and maintaining dams in the country critical in a time of rising hydrological variability.

Additionally, glacier monitoring stations and snowmelt models are being developed in collaboration with agencies like the IMD, NRSC, and CWC. India is not just preparing for future climate impacts it is actively managing the challenges already unfolding, by blending traditional water wisdom with modern science, and embedding resilience into its water governance systems.

How important is restoring natural surface water bodies and incorporating traditional water conservation methods into modern management systems, particularly in the context of climate change?

Restoring natural surface water bodies and integrating traditional water conservation methods into modern management systems has become increasingly critical, especially in the context of climate change and water management. Natural systems such as ponds, tanks, lakes, wetlands, and floodplains serve as vital buffers against extreme weather events. They regulate floods by absorbing excess rainfall, support groundwater recharge, maintain base flows in rivers, and moderate local microclimates. However, rapid urbanization, encroachment, siltation, and pollution have severely degraded many of these ecosystems across India.

Equally important is the revival of traditional water harvesting systems. These systems were historically designed to suit local geo-climatic conditions and were managed collectively by communities. They provide a template for decentralized, low-cost, and climate-resilient water management. By integrating these systems with modern science through GIS mapping, hydrogeological surveys, and data-based planning they can be rejuvenated as part of mainstream water policy.

India's First ever Water Body Census has been completed by the Government wherein physical features along with the geo coordinates of water bodies have been recorded. Government initiatives like the Amrit Sarovar Mission, Jal Shakti Abhiyan, MGNREGA-based water conservation works, and urban lake rejuvenation under Smart Cities initiative are already enabling large-scale restoration.

Incorporating traditional wisdom with modern techniques offers a hybrid approach that is not only sustainable but also socially inclusive and ecologically sound. As India builds resilience against climate risks, such nature-based solutions must be recognized as central to achieving long-term water security and environmental sustainability.

How do you rate the success of programs like Jal Shakti Abhiyan and Atal Jal Mission in reviving overexploited areas and conserving water resources?

The Jal Shakti Abhiyan (JSA) and Atal Bhujal Yojana (Atal Jal) represent two of the most transformative initiatives undertaken by the Government of India to address groundwater stress and promote sustainable water management, particularly in overexploited and water-stressed areas. Both programs, while distinct in their approach, share a common goal community-led water conservation, built on data-driven planning, convergence of resources, and behavioral change.

The JSA, launched in 2019, followed a campaign-style model focusing on five key interventions rainwater harvesting, renovation of traditional water bodies, reuse of water, afforestation, and

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...Isotope hydrology can play a pivotal role in ensuring our groundwater security and aquifer sustainability. As India builds resilience against climate risks, such nature-based solutions must be recognized as central to achieving long-term water security and environmental sustainability...

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awareness. Its success lies in the convergence it achieved across ministries and schemes, leveraging the implementation strength of programs like MGNREGA, PMKSY, and AMRUT. It revived lakhs of water bodies and structures, improved groundwater recharge, and fostered a nationwide movement of "water warriors," particularly under the 'Catch the Rain' campaign. Importantly, it made water conservation a mass movement, extending beyond just the government machinery to involve citizens, NGOs, and local institutions. Recently, Hon'ble Prime Minister of India has launched "Jal Shakti-Jan Bhagidari (JS-JB)" initiative under the Jal Shakti Abhiyan to promote community-driven water conservation and groundwater recharge across the country.

The Atal Bhujal Yojana, with its focused implementation in 80 water-stressed districts across seven states, has added depth to this movement. It introduced a bottom-up, community-centric approach where over 8,000 Gram Panchayats have prepared Water Security Plans based on aquifer-specific data and scientific guidance. With more than 1.2 million stakeholders trained, including farmers and women, Atal Jal has successfully fostered ownership at the grassroots level. Early results show promising outcomes, including improved groundwater levels in over 1,300 Gram Panchayats, adoption of efficient irrigation practices, and better awareness about aquifer behavior.

Together, these programs have marked a shift from reactive crisis management to proactive aquifer stewardship. While challenges remain such as scaling beyond pilot districts, ensuring long-term behavioral change, and institutionalizing groundwater governance the foundation laid by JSA and Atal Jal is robust. They demonstrate that empowering communities, backed by technology and convergence of schemes, can indeed lead to measurable improvements in India's water-stressed landscapes.

Contaminants like arsenic, fluoride, nitrate and salinity along with other emerging pollutants are affecting millions of people in India. What would be the most impactful approach to tackle water contamination effectively in both urban and rural areas?

Water contamination in poses a serious public health and environmental challenge. Tackling this issue requires a multi-pronged, area-specific and technology-backed approach with strong institutional support. Recognizing the importance of systematic intervention, the Ministry of Jal Shakti has prioritized regular groundwater quality monitoring as a core activity. To enhance standardization and reliability, a detailed Standard Operating Procedure (SoP) has been recently issued to streamline groundwater quality assessment practices nationwide.

In rural areas, the most impactful solution lies in community-level water purification systems, such as Community Water Purification Plants (CWPPs), which provide access to treated water at low cost. The Jal Jeevan Mission (JJM) has made water quality a top priority. The National Water Quality Management Framework with a network of over 2,000 water testing laboratories has made accessible to the public quality services with Field Test Kits distributed at the village level. In highly contaminated zones, alternative safe sources, such as deeper aquifers or treated surface water, are being identified and integrated into piped water supply systems. Technologies like reverse osmosis (RO), ion exchange, activated alumina filters, and electrocoagulation are being deployed based on contaminant type and feasibility.

In urban areas, the emphasis is on upgrading sewage and industrial effluent treatment infrastructure, enforcing Zero Liquid Discharge (ZLD) norms, and preventing illegal discharge into water bodies.

As part of technological innovation, the Central

...The heightened Centre-State coordination efforts reflect a significant shift from fragmented water management to a more integrated, collaborative and digitally enabled approach, paving the way toward India's commitment to SDG-6 and the national vision of Aatmanirbhar Bharat by 2047...

Shri. Subodh Yadav

Ground Water Board (CGWB) has developed specialized well construction techniques to access arsenic-free aquifers in the Indo-Gangetic plains. Over 500 such wells have been successfully constructed and handed over to state governments for public use, along with knowledge transfer for further replication. Similarly, designing of wells to minimize fluoride contamination have been developed and implemented in fluoride-affected areas.

Education and awareness are also critical ensuring that communities understand the risks of contaminated water and are empowered to participate in local water safety planning. With convergence between Jal Jeevan Mission, Swachh Bharat Mission, and Namami Gange, and strong leadership from both the Centre and States, India is moving towards a future where access to safe and clean drinking water is not a privilege, but a universal right.

Nuclear techniques have been significantly contributing to energy security, health security and food security. How do you see the prospects of Isotope Hydrological techniques in providing deeper insights into complex hydrological issues and helping in designing sustainable water resources development and management for India?

Nuclear techniques, particularly isotope hydrology, are emerging as powerful tools in addressing complex water-related challenges and supporting sustainable water resource development in India. While nuclear science has long contributed to the nation's energy, health, and food security, its application in the water sector through stable and radioactive isotopes offers unique understanding of hydrological systems.

Isotope techniques help in tracing the origin, age, movement, and recharge sources of groundwater, especially in regions with complex geology or where conventional methods are limited. India, with its highly diverse hydrogeology, growing dependence on groundwater, and mounting pressure from climate variability, stands to benefit significantly from wider adoption of these techniques. Isotope hydrology can precisely distinguish between shallow and deep aquifer systems, identify zones of natural recharge, and determine interactions between surface water and groundwater, which is essential for integrated water resource planning. It can also help track pollution pathways, evaluate the sustainability of springs, and validate artificial recharge interventions thereby supporting better policy and infrastructure decisions.

Recognizing the growing importance of isotope hydrology in water resource assessment and management, the ministry has initiated isotope hydrological projects in collaboration with Bhabha Atomic Research Centre, DAE. Concerted efforts are also being made with the help of BARC for training of manpower on isotope hydrology, technical collaborations and developing new isotope methodologies to solve real-time problems persistent in India. National Institute of Hydrology (NIH) and the Central Ground Water Board (CGWB) have recently procured advanced Isotope Ratio Mass Spectrometers (IRMS) for precise isotopic analysis of water samples. These state-of-the-art instruments enhance the ability to trace groundwater origin, age, recharge zones, and contamination pathways with high accuracy.

To further strengthen data integration and collaboration, CGWB has developed a dedicated web-based software platform that enables upload, visualization, and download of isotope-related data. This user-friendly digital system serves as a common platform for information sharing, fostering coordination among researchers, groundwater professionals, and policymakers. By bringing isotope data into a centralized repository, the Ministry has taken a significant step towards promoting transparency, collaboration, and scientific rigor in the field of groundwater resource management.

As India advances toward data-driven and climate-resilient water governance, isotope hydrology can

...Nuclear techniques, particularly isotope hydrology, are emerging as powerful tools in addressing complex water-related challenges and supporting sustainable water resource development. BARC's domain expertise is being leveraged for training of manpower on isotope hydrology, developing new isotope methodologies to solve real-time problems persistent in India...

Shri. Subodh Yadav

play a pivotal role in ensuring our groundwater security and aquifer sustainability quietly but decisively, much like groundwater itself.

In India's federal structure, how can Centre-State cooperation be optimized for sustainable water management, and what critical policy shifts must happen today to positively transform India's water scenario over the coming decades targeting "Access to clean drinking water and sanitation for all"- UN Sustainable Development Goal-6 as a part of Aatmanirbhar Bharat (self-reliant India) by 2047?

In a country as diverse and vast as India, water governance is inherently complex made more so by the fact that water is a State subject under the Constitution, while many water-related challenges and solutions transcend state boundaries. Therefore, optimizing Centre-State cooperation is not just desirable but essential for achieving sustainable water management and meeting the targets of UN Sustainable Development Goal-6 (Clean Water and Sanitation for All) by 2047, in alignment with the national vision of Aatmanirbhar Bharat.

In recent years, Centre-State collaboration has significantly strengthened through key flagship initiatives. The Jal Jeevan Mission stands out as a model of decentralized execution, where the Centre provides funding, technical support, and monitoring tools, while states plan and implement the delivery of tap water supply to every rural household. Over 140 million functional household tap connections have been provided under this mission, transforming the rural drinking water landscape. Similarly, the Atal Bhujal Yojana empowers States to take ownership of groundwater management by preparing community-based Water Security Plans in over 8,000 Gram Panchayats across seven states.

To ensure data transparency and informed decision-making, the Centre has established the National Water Informatics Centre (NWIC) as a centralized platform to host, visualize, and share water-related data with States and other stakeholders. NWIC, through the India Water Resource Information System (India-WRIS), enables seamless data integration across departments and promotes real-time monitoring of reservoirs, river basins, and groundwater levels. The recently developed IN-GRES platform for groundwater estimation is another example of Centre-State technical collaboration under a unified digital framework.

Furthermore, regulatory mechanisms have been formalized through updated Groundwater Regulatory Guidelines by CGWA, which have been adopted and customized by many State Ground Water Authorities (SGWAs). These include area-specific water extraction charges, mandatory recharge obligations, and promotion of water-use efficiency. Inter-state cooperation is also evident in the Ken-Betwa Link Project, which represents a coordinated water-sharing agreement between Madhya Pradesh and Uttar Pradesh under central facilitation.

Major national missions like Namami Gange, PMKSY, Swachh Bharat Mission, and Jal Shakti Abhiyan are all designed as centrally supported but state-led initiatives, where funding, planning, and execution are done collaboratively.

These coordinated efforts reflect a significant shift from fragmented water management to a more integrated, collaborative and digitally enabled approach, paving the way toward India's commitment to SDG-6 and the national vision of Aatmanirbhar Bharat by 2047.

**Dr. Tirumalesh Keesari is a Scientific Officer-H & Head, Isotope Hydrology Section of Isotope and Radiation Application Division, BARC. His research interests include isotope hydrology, water contamination studies, geochemical modelling, groundwater recharge and application of AI/ML tools.*

Industry

BARC's Nuclear

By Technology Transfer & Collaboration Division and SIRD Newsletter Editorial Team

During March-April, 2025, the Technology Transfer and Collaboration Division (TT&CD) of Bhabha Atomic Research Centre (BARC) and Atal Incubation Centre (AIC-BARC) conducted a significant technology transfer ceremony in Mumbai. The AKRUTI programme for propagation of BARC-DAE technologies among the rural environs too witnessed significant new developments. The ceremony underscored BARC's commitment to technological innovation and entrepreneurial support across multiple domains. A brief update on these developments is presented here.

Transfer of Technologies

Mixed-Matrix Membrane Diaphragm Technology

Technology Transfer and Collaboration Division, BARC, organized an agreement signing ceremony on April 16, 2025, at BARC Trombay, Mumbai. The event marked the signing of a Technology Transfer Agreement with M/s. Bharat Heavy Electricals Limited (BHEL), New Delhi, for the transfer of know-how related to the Mixed-Matrix Membrane Diaphragm technology for separator applications in electrochemical cells.

The Mixed-Matrix Membrane Diaphragm, developed by BARC, is designed for use in alkaline water electrolyser cells. This technology serves as an effective, low-cost substitute for imported zirfon membranes and asbestos-based diaphragms, which are commonly used in electrolysers. The membrane has demonstrated reliable performance, with cell voltage at a current density of 5000 A/m² comparable to that of asbestos diaphragms and commercially available zirfon membranes.

Officials of Chemical Engineering Group, BARC and TT&CD, BARC exchanged technology transfer agreement with M/s. BHEL, New Delhi during a ceremony organized in BARC Trombay on April 16, 2025.

Senior officials of TT&CD and Food Technology Division in BARC and industry partners exchange technology transfer agreement related to Food technologies.

Additional Technology Transfers

During March-April 2025 period, BARC also transferred several other notable technologies to industry partners, which included:

- The NISARGRUNA Biogas Plant technology for processing of biodegradable waste was transferred to Nilgiri Builders Pvt. Ltd., Indore, on March 28, 2025.
- The Rapid Composting Technology for decomposition of dry leaves, kitchen waste, and temple waste was transferred to Neev Bioroots LLP., Indore, on March 28, 2025.
- The Radiation Assisted Adsorbent Technology for

beckons

Spin-off technologies

Left to Right: Dr. B. Tata (GITAM), Prof. G. Ravi Kumar (GITAM), Shri Raja Phani Pappu, Dean School of Business (GITAM), Shri Gunasekaran D., Registrar (GITAM), Shri Daniel Babu P., Head, TT&CD (BARC) & Head, PA&MID (DAE), Dr. Errol D'Souza, Vice Chancellor (GITAM), Smt. Bharti A. Bhalerao, Group Leader (AKRUTI), TT&CD, Dr. S. T. Mehetre, Scientific Officer, BioScience Group, BARC.

Textile Effluent Decolouration (Rad-TED) was transferred to Maharaja Enterprises, Balotra, Rajasthan, on March 3, 2025.

AKRUTI Programme Activities

Signing of Agreements

TT&CD, BARC signed agreements with Jai Hind College, Churchgate (Mumbai) on March 3, 2025, and GITAM University, Visakhapatnam on April 24, 2025, to establish AKRUTI Kendras.

Technology Transfers & Trainings

Technology Transfer agreements were signed by the Technology Transfer & Collaboration Division (TT&CD) through the AKRUTI Kendra at Tarapur with applications in food and engineering domains. An agreement was inked with Tech Indra Organic for transfer of Ready-to-Eat Fruit Cube Technology (developed by FTD, BARC). Also, under the Entrepreneurship development programme of AKRUTI, two agreements for transfer of technologies related to Banana Health Drink (developed by FTD) and BLDC Motor based HP Pump (Chemical Engg. Group) were inked with Pune-based Organic India LLP., and Palghar-based Shree Ganesh Electricals, respectively.

Faculty from D.Y. Patil College of Science, Arts and Commerce situated at Pune attended AKRUTI Kendra–DYPSCA training at BARC Trombay, organized by the Nuclear Agriculture & Biotechnology Division, Bio Science Group, BARC. AKRUTI Kendra-Tarapur held an entrepreneurship workshop-cum-awareness program at Sonopant Dandekar College, Palghar on March 3, 2025, and two BARC food technology workshops for a Self-Help Group in Phopharan Village on March 15th and 25th, 2025.

Outreach & Visits

Nuclear Recycle Board Tarapur hosted an outreach event on "Societal Applications of BARC Technologies" at AKRUTI Kendra-Tarapur on March 18, 2025, discussing BARC technologies and Kendra's progress. The Kendra was set up under a CSR arrangement with NPCIL. AKRUTI Center products were showcased at the exhibition stall, attracting over 200 attendees from various communities, with a strong interest in BARC technology licenses.

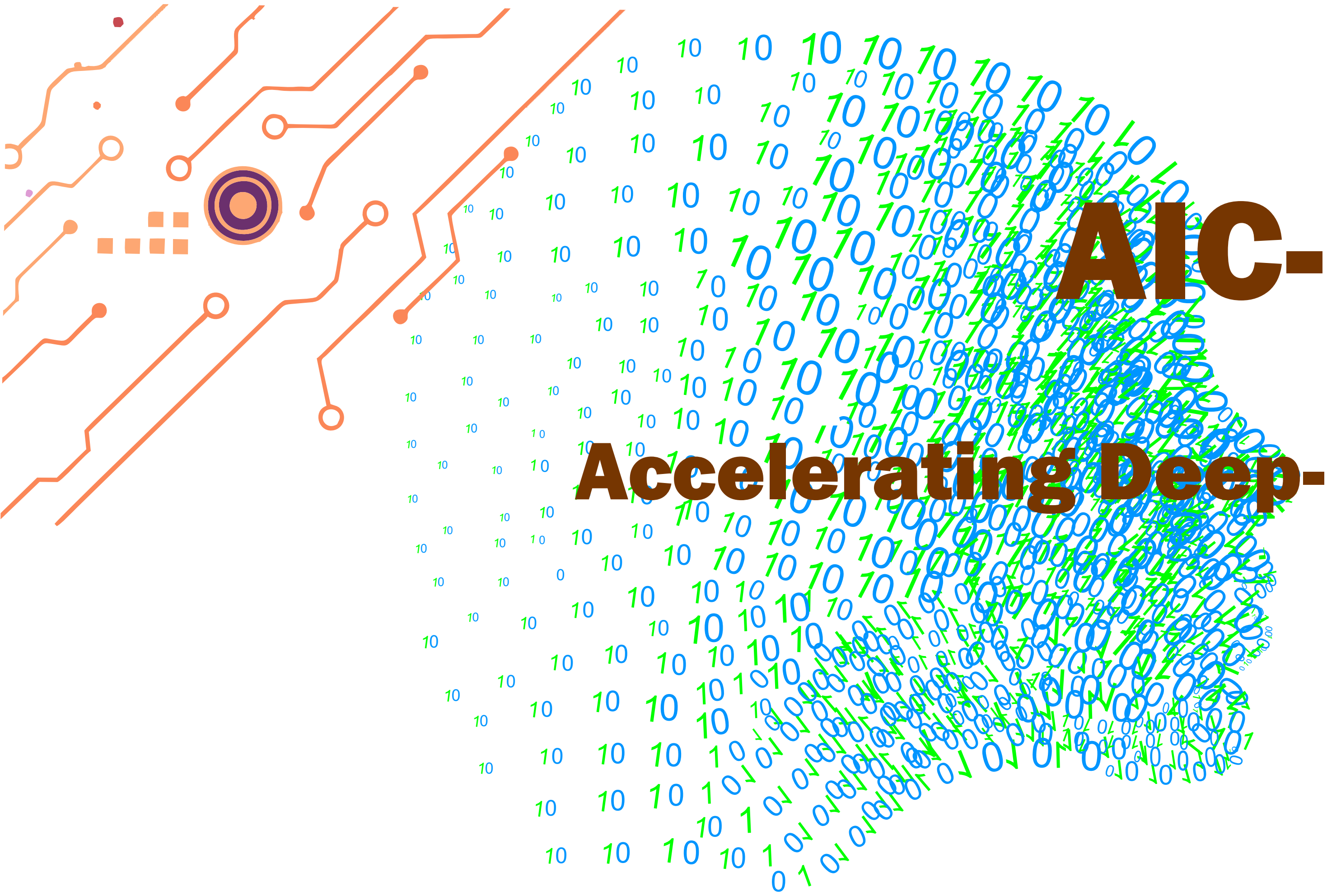
On March 23, 2025, AERB Chairman along with other senior officials of the Board visited AKRUTI Kendra Tarapur, where TT&CD officials made a detailed presentation on BARC technologies and ongoing rural development and entrepreneurship activities at the Kendra.

Inaugurations

A new AKRUTI Kendra of BARC was inaugurated at Mahatma Gandhi University Campus at Kottayam in Kerala on April 24, 2025.

Transfer of BARC's BLDC Motor-based HP Pump Technology: Shri M.S. Deshpande, Director, Chemical Technology Group, BARC and senior officials of BARC exchanges agreement with Palghar based Shree Ganesh Electricals.

AIC-Accelerating Deep-



By Technology Transfer & Collaboration Division and SIRD Newsletter Editorial Team

Established under the Government of India's flagship Atal Innovation Mission (AIM), the Atal Incubation Centre at Bhabha Atomic Research Centre (AIC-BARC) was launched in October 2020 as one of the Department of Atomic Energy's (DAE) Aatmanirbhar Bharat initiatives. AIC-BARC's mission is to foster startups and emerging entrepreneurs, opening new employment avenues and partnering with MSMEs to scale up and adapt BARC technologies for industrial use.

In line with AIM guidelines, 'AIC BARC Anushakti Foundation' was incorporated as a Section 8 company under the Ministry of Corporate Affairs on March 29, 2025, and is now known commercially as AIC-ANUSHAKTI. Supported by BARC and owned by the DAE, the company is managed by a Board of Directors appointed by Director, BARC. With a share capital of Rs. One Lakh, AIC-ANUSHAKTI aims to nurture a vibrant, sustainable technology translation ecosystem focused on advanced, globally competitive technologies.

Mission and Vision

AIC-ANUSHAKTI is committed to becoming a leading state-of-the-art incubation centre in deep technology, promoting creativity, innovation, and entrepreneurship. Its vision is to be among the top incubation centres in India, facilitating the commercialization of cutting-edge technologies and supporting the country's drive towards self-reliance.

Incubation Programs and Partnerships

To date, AIC-ANUSHAKTI has signed 15 incubation agreements with startups and MSMEs. Eight incubation programs are based on BARC's in-house spin-off technologies, including:

- *X-band LINAC Technology for Medical Applications (Panacea Medical Technologies, Karnataka)*
- *Water Treatment Plant using Electron Beam Accelerator (AnandSparX Technology, Surat)*
- *Alkaline Water Electrolyzer for Hydrogen Production (Pratishna Engineers, Mumbai)*
- *Handheld Gamma Spectrometer using Cesium Iodide Single Crystal (Ace-Ex Industries, Mumbai)*
- *Nisarguna Biogas Technology (Gir Gau Jatan Sansthan, Rajkot)*
- *Process System for Clean-up of Oil-contaminated Wastewater (ONGC Energy Centre, Delhi)*
- *Chitosan-based Sustainable Crop Formulation (Vasantdada Sugar Institute, Pune)*
- *Plasma pyrolysis of methane for zero-emission hydrogen (Hyurja Pvt. Ltd, Mumbai)*

Notably, Ace-Ex Industries and AnandSparX Technology have successfully graduated from the program, having completed their prototypes and are moving towards commercialization phase.

Collaborative Incubation and Mentorship

AIC-ANUSHAKTI has also entered collaborative incubation agreements with four additional incubatees, where BARC scientific community mentors industry partners for co-development. These collaborations cover technologies such as Hydrogen Production via the Iodine Sulphur Thermo-chemical Process, Biogas Optimization from Biodiesel By-products, Bio-

ANUSHAKTI

Tech Innovation in India

available Nutraceutical Formulations, and Sensor Electrodes for Food Safety Devices.

Fostering Startup Entrepreneurship

Entrepreneurship incubation for startups with low capital requirements is underway, with companies like M/s. Wastech Pvt. Ltd and M/s. Cassion, Mumbai, selected through workshops and pitching sessions. These initiatives ensure that BARC's technologies reach a broader base of entrepreneurs, supporting innovation at multiple levels.

Future Roadmap

With its registration as a Section 8 company, AIC-ANUSHAKTI will soon appoint a CEO and incubation managers to oversee daily operations. The centre's scope will expand to include technology transfer, consultancy, training, and incubation services. Currently operating from the DAE Convention Centre, AIC-ANUSHAKTI will shift to a dedicated facility at Project House situated in the vicinity of AERB (Anushakti Nagar), further strengthening its incubation capabilities.

By bridging government research and industry, AIC-ANUSHAKTI is poised to play a pivotal role in India's innovation and entrepreneurship ecosystem, translating advanced technologies into impactful commercial solutions.

Group photograph of participants and coordinators at a Start-up Entrepreneurship Workshop conducted by TT&CD, BARC at DAE Convention Centre in May 2024 under the auspices of Atal Incubation Centre-BARC.

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