Isotope Hydrology in India

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

R. D. Deshpande
desh@prl.res.in

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 $^{4}He/^{222}Rn$, 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 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).

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.

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.