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.

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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).

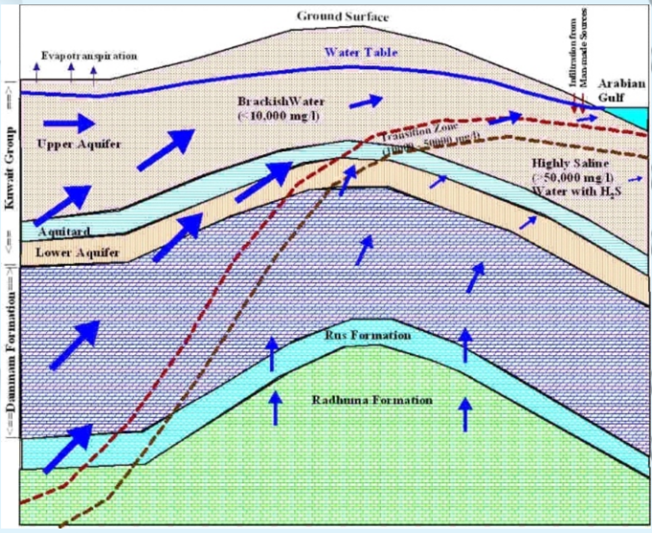

Fig.1: Conceptual groundwater flow in coastal region of Kuwait by understanding the age of groundwater and the regional hydrology (Source Hadi et al., 2016)

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 $\delta^{18}O$ 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

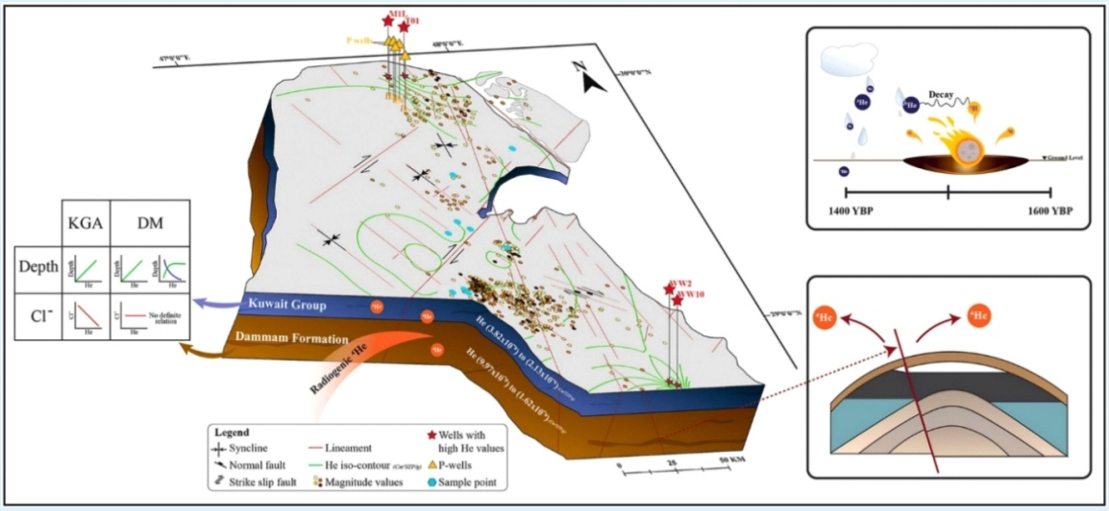

Fig.2: Variation of Helium concentration in brackish groundwater of Kuwait aquifers, related to geological structures and other processes (source Rashid et al., 2023)

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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