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.

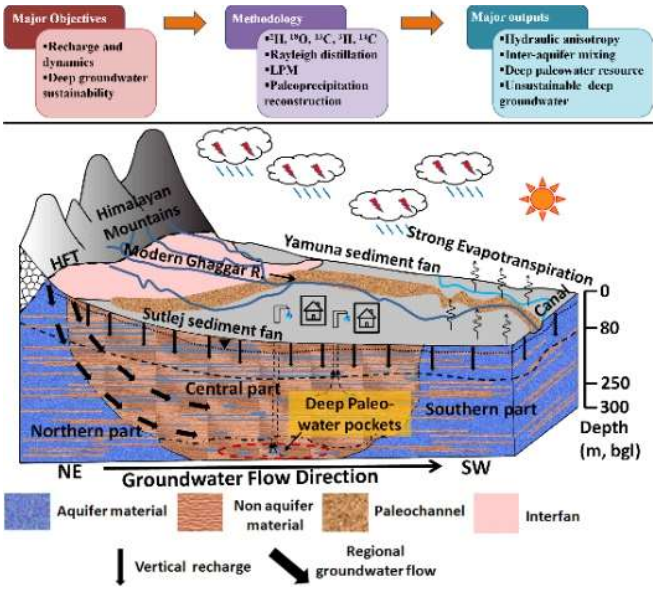

Fig.1: Conceptual diagram of hydrological systematics in Northern India

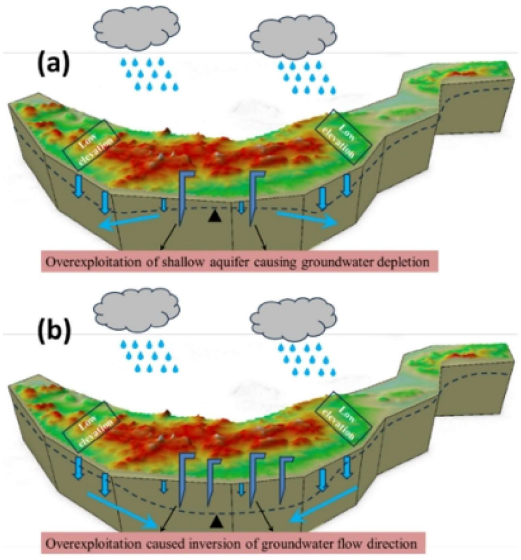

Fig.2: Conceptual diagram of hydrological systematics in Western India

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.