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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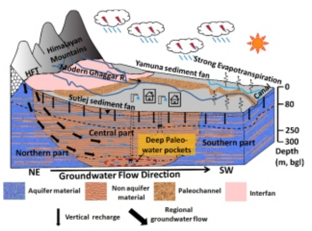

उत्तरी हरियाणा के समग्र जलवैज्ञानिक परिदृश्य का अवधारणात्मक आरेख ([1] के बाद संशोधित)

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 पुन:भरण 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 पुन:भरण 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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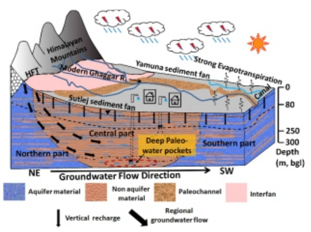

Conceptual diagram of overall hydrological scenario of northern Haryana (modified after [1])

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 (^{2}H, ^{18}O, ^{13}C, ^{3}H, ^{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 (^{2}H, ^{18}O), 41 for ^{3}H, 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 ^{3}H 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 (^{2}H, ^{18}O, ^{13}C) and environmental radioisotope (^{3}H, ^{14}C) analysis respectively.

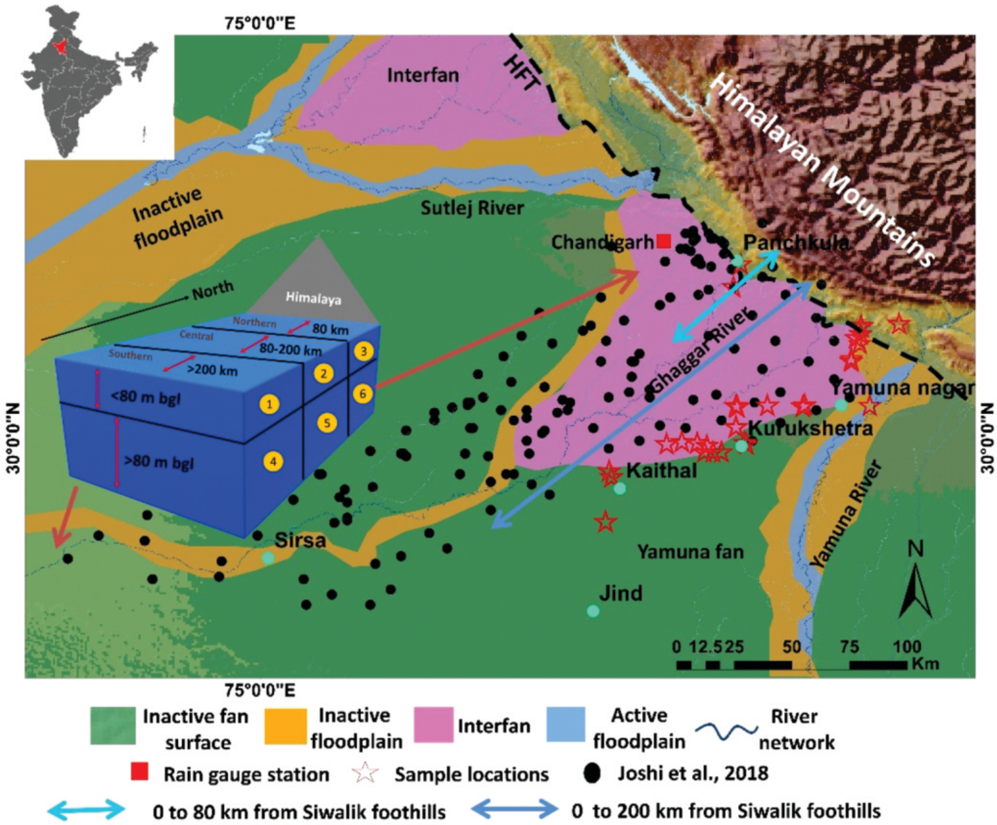

Fig.1: Study area locations overlaid on major geomorphological units of northern Haryana (inset maps include index map of India and 3D conceptual block diagram showing major zonation of the region) (modified after [1]).

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

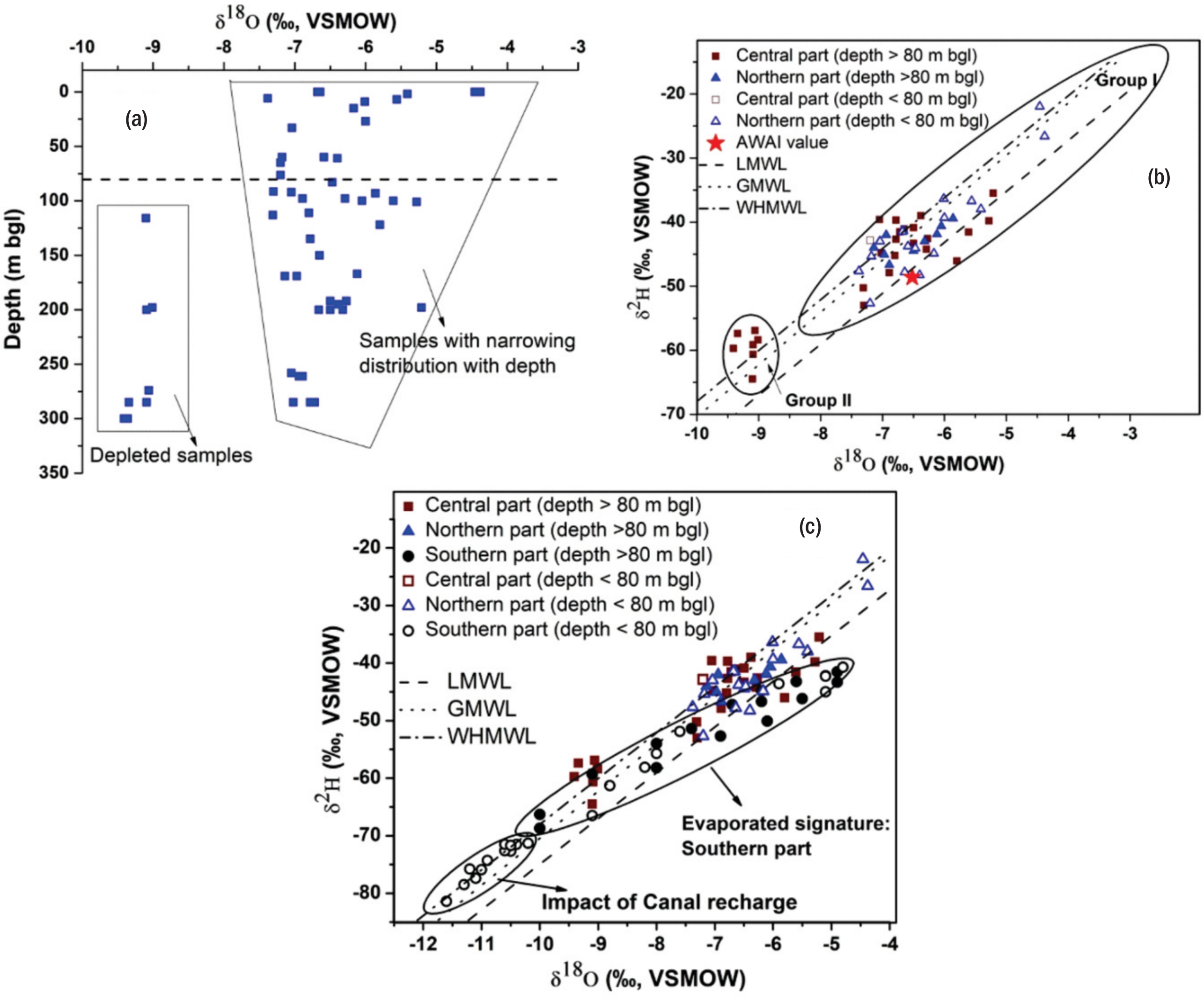

Fig.2: (a) Depth variation of stable isotope data (^{18}O); (b) ^{2}H vs. ^{18}O plot; (c) ^{2}H vs. ^{18}O plot including southern part of the study area (modified after

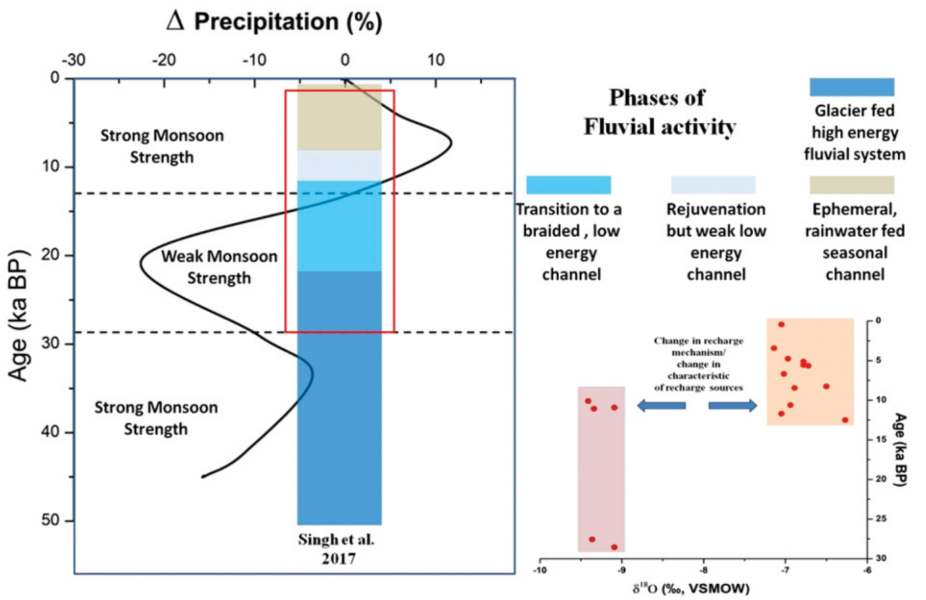

Fig.3: Phases of fluvial activity during last 50 ka and C-14 corrected age vs. ^{18}O plot (modified after [1]).

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

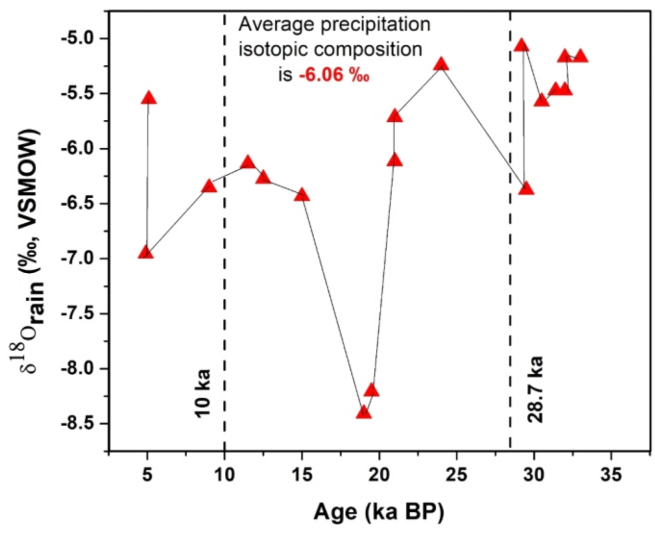

Fig.4: The Paleoprecipitation isotopic composition ($^{18}O_{rain}$) modelled based on ^{18}O data of carbonate nodules ($^{18}O_{nod}$).

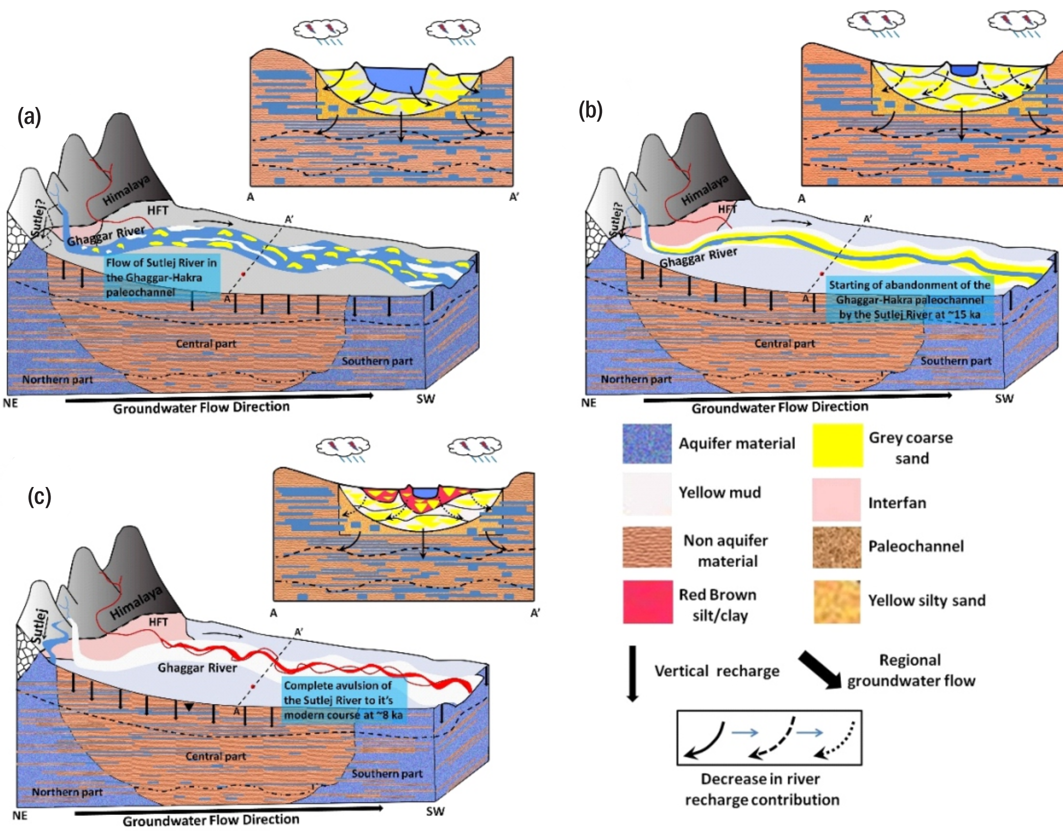

Fig.5: Conceptual models depicting hydrological scenario under varying fluvial activity of the northern Haryana region during (a) 62-30ka (b) 25-12ka and (c) 12-4.5ka (modified after [1]).

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.

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