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REVIEW

Re-evaluating Legacy Well Data for Natural Hydrogen Exploration

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ABSTRACT

Natural hydrogen (H_2), also referred to as white, gold, or native hydrogen, is a geologically sourced form of molecular hydrogen occurring as free gas within the Earth's crust, including continental and oceanic lithospheres, volcanic exhalations, and hydrothermal systems. Unlike anthropogenically produced hydrogen via steam methane reforming or water electrolysis, natural hydrogen is generated in situ through ongoing geological processes such as serpentinization, radiolysis, and mantle degassing, offering a continuous, low-emission energy resource. Recent accidental detections, most notably in France's Lorraine Basin during coalbed methane investigations have revitalized global interest in subsurface natural hydrogen exploration. These discoveries suggest that hydrogen accumulations may have been historically overlooked in conventional hydrocarbon wells due to prior analytical limitations and the absence of targeted detection methodologies. This study proposes a systematic re-evaluation of legacy well logs from abandoned and active oil and gas wells to identify Petrophysical, Geophysical and Geochemical signatures indicative of natural hydrogen. Preliminary evidence from regions such as Spain (Helios Aragón Project) and the United States (Koloma Inc.) supports the viability of this approach. Cost projections for natural hydrogen extraction ($0.5–$1.5/kg) indicate a substantial economic advantage over green hydrogen. Exploration activities are gaining traction in Mali, Australia, USA, France, and in other parts of the world. In India also ONGC has initiated hydrogen seep investigations in the basins of Gujarat and Assam. The primary objective of this study is to develop interpretive log-based frameworks capable of discriminating hydrogen-bearing intervals using existing datasets, thereby enabling rapid screening and derisking of prospective hydrogen-bearing reservoirs.

KEY WORDS

Natural hydrogen exploration; Geological hydrogen generation; Hydrogen seep detection; Petrophysical log interpretation; Subsurface hydrogen accumulation

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Introduction

Natural hydrogen, also referred to as "White hydrogen", "Gold hydrogen', or "Native hydrogen", is hydrogen gas (H_2) found naturally in the Earth, formed through geological processes. It is rapidly emerging as a clean, sustainable alternative energy source. Natural hydrogen is gaining recognition as a potential game-changer in the clean energy landscape [1]. Unlike industrial "Green hydrogen", which is produced via electrolysis, natural hydrogen is continuously generated in the Earth's crust and can be extracted as a clean energy resource, making it environmentally friendly [2].

This form of hydrogen is found as a free gas within the Earth's continental and oceanic crusts, as well as in volcanic gases, geysers, and hydrothermal systems [3]. If natural hydrogen is indeed trapped in underground reservoirs and has gone largely unnoticed until now, it raises a crucial question: Could similar deposits exist in the millions of exploration wells and production wells, drilled over the past century? Since historical exploration efforts primarily focused on oil and methane gas, the presence of natural hydrogen may have been overlooked and, therefore, unreported [4].

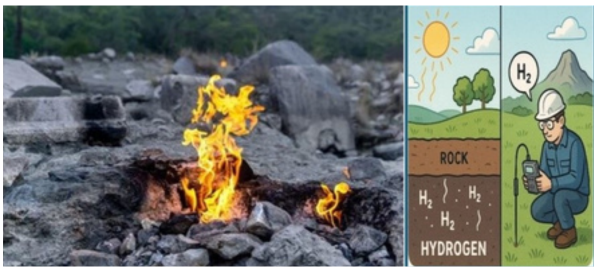

Figure 1. Fire fueled by hydrogen seepage at Mount Chimaera in Turkey

France recently made a groundbreaking discovery of white hydrogen; interestingly, an accidental one. Scientists were originally investigating coal bed methane and had developed an instrument designed to enter boreholes and measure gases associated with methane [5,6]. However, when they took measurements in one of the wells, they were astonished to detect hydrogen instead. This unexpected discovery in coal bed methane wells in France led to the Lorraine Project.

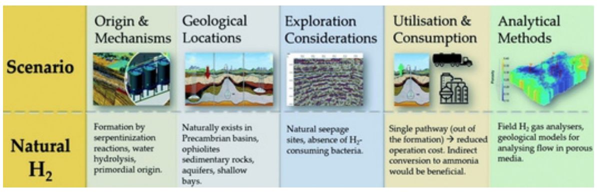

Figure 2.

It is most likely that reanalysing well log data from the millions of wells drilled worldwide in past could lead to numerous new discoveries of natural hydrogen. A promising strategy is to re-examine historical and operational oil and gas well data for traces of hydrogen [7]. This approach has already proven successful in other regions, for instance, hydrogen seeps were identified in abandoned oil wells in Spain, leading to the Helios Aragon Project.

Countries such as Mali, Australia, the USA, Spain, and France are now spearheading exploration efforts for the discovery of natural hydrogen deposits [4]. A Denver-based startup, Koloma, backed by major investors, is making significant strides in this direction. Investment trends show

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growing interest, with projected extraction costs ranging from $0.5 to $1.5 per kilogram of hydrogen, significantly lower than the cost compared to green hydrogen [8]. Koloma is working to develop technology that can identify, access, and produce natural hydrogen efficiently.

Figure 3. Natural Hydrogen Seep site in San Francisco Basin, A "fairy circle" in Brazil

The key now lies in determining how natural hydrogen signatures appear in various types of well logs. The present study focuses on identifying natural hydrogen deposits through the re- analysis of well logs from both abandoned and currently producing wells [9].

Figure 4. Natural Hydrogen Projects Globally

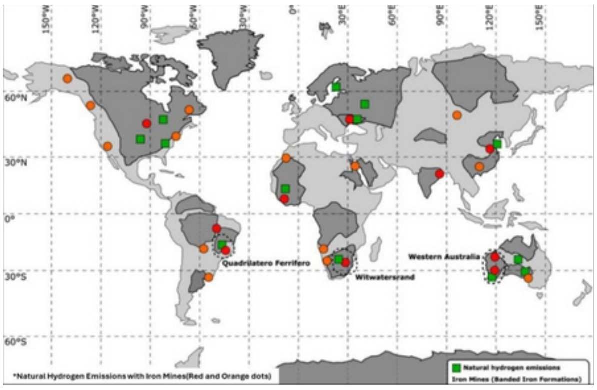

Figure 5. Natural hydrogen emissions associated with Iron Mines

Although both natural hydrogen and green hydrogen are clean energy sources, they differ significantly in terms of production costs, scalability, and infrastructure requirements [10].

In India, Oil and Natural Gas Corporation (ONGC) is also actively studying natural hydrogen seeps in existing oil wells in Gujarat and Assam. This re-evaluation of historical data could reveal previously overlooked hydrogen accumulations, as earlier analytical techniques were not equipped to detect them [11].

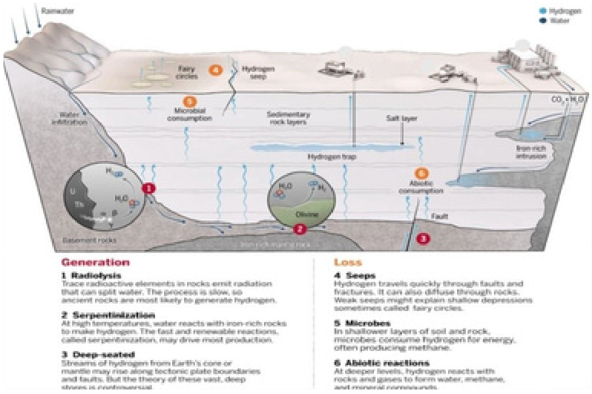

Figure 6. Natural Hydrogen Hydrogen generation process in the earth

Formation Processes, Sources and Entrapment

Natural hydrogen originates through various geological processes, including serpentinization, radiolysis of water, and deep-mantle degassing. It is commonly found in ultramafic rocks, mid- ocean ridges, granitic basements, and hydrothermal systems. These natural processes continuously generate hydrogen, making it a replenishable resource, unlike fossil fuels [12].

Natural hydrogen primarily originates deep within the Earth through both abiotic and biotic processes. Among the abiotic processes, the most probable is serpentinization. Serpentinization is a geochemical reaction in which water interacts with ultramafic rocks (low in silica and rich in iron and magnesium, such as peridotites) under high temperatures, releasing hydrogen [13]. This process is especially active in ophiolite belts (fragments of oceanic crust) and mid-ocean ridges.

Water radiolysis is another significant mechanism, where hydrogen is released during the natural radioactive decay of elements like uranium, thorium, and potassium. These decays break down water molecules, and this process is typically observed in granitic basement rocks and deep aquifers [14]. Primordial hydrogen from the Earth's mantle can also seep through fractures in the crust. Additionally, hydrogen can form through the thermal decomposition of hydrocarbons in the absence of oxygen.

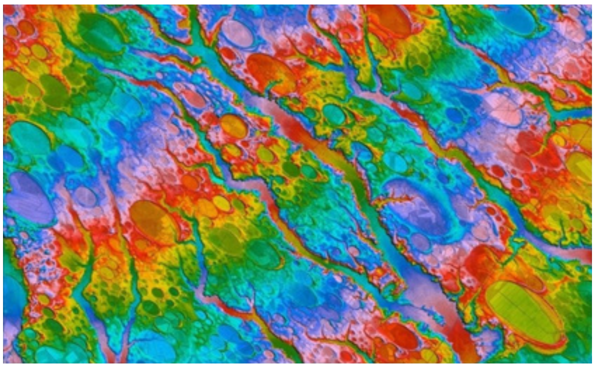

Figure 7. Fairy circles may be explained through presence of Hydrogen seepages. Some are more than 1 kilometre wide at coastal North Carolina.

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On the biotic side, although less significant, certain microbes produce hydrogen as a metabolic byproduct [12].

Unlike fossil fuels, hydrogen is very light and highly reactive, so it does not accumulate easily in large reservoirs. However, natural hydrogen can occur across a wide range of rock formations and geological settings. It is often found in hard rocks such as ultramafic and basaltic formations, where geochemical conditions favour hydrogen production via serpentinization [15]. Hydrogen may also be present in oil and gas fields, where both abiotic and biotic processes contribute to its generation. Another notable source is hot water springs, which signal active hydrothermal systems that facilitate hydrogen formation and migration.

Once generated, hydrogen can be trapped beneath impermeable rock layers such as salt or shale, which act as seals to prevent its escape into the atmosphere. Fault closures, structural traps, and domes can also provide favourable conditions for hydrogen accumulation [16]. However, since hydrogen is the lightest element and molecule on Earth, perfect rock entrapment may be difficult to achieve. Even micro-fractures or micro-darcy permeabilities can allow hydrogen to escape.

Despite these challenges, hydrogen can still accumulate in geological traps. Notable accumulations have been found in places like the Bourakébougou field in Mali, notably the first place where 98% pure hydrogen is being commercially extracted and used for electricity generation [17]. Exploration of such deposits involves advanced geochemical, geophysical, and geo-microbial techniques.

In 1987 a well was drilled in Mali to search for water. The well turned out to be dry but unexpectedly produced significant volumes of H2. The company put the native H2 into production. The well was unplugged in 2011 to use it for a pilot to generate electricity for a small village [18]. The hydrogen that comes out of the well is almost pure (more than 96%) so it can be directly burned in a gas turbine. The initial well has been producing for last more than six years without any pressure decrease from its initial baseline of approximately 4 bars, which implies continuous recharging of the reservoir.

The surface measurements do not show any leakage. It is seen that H2 can be produced there at much less than a dollar per kilogram, which is significantly cheaper than conventional costs for hydrogen production by electrolysis or steam methane reforming with carbon capture [20].

Detection of Hydrogen on well Logs

The basic logs studies for detecting hydrocarbon reservoirs are Gamma, Resistivity, Neutron and Density. When comparing the log response of a hydrogen-filled reservoir to an oil or gas (methane) filled reservoirs, key petrophysical log measurements such as density, neutron porosity, resistivity, and sonic logs will exhibit notable differences due to the unique properties of hydrogen (H_2) and methane (CH_4) [21].

Density log response

Hydrogen-filled reservoir will have lower bulk density than methane-filled because hydrogen has a much lower molecular weight (≈2 g/mol) than methane (≈16 g/mol). As a result, the density log will read slightly lower values in a hydrogen-filled reservoir compared to a methane-filled reservoir [22].

Neutron porosity log response

Neutron tools are highly sensitive to hydrogen index (HI), and since hydrogen molecules in H_2 are fewer per unit volume than CH_4, the neutron porosity may appear lower than actual porosity for Hydrogen-filled reservoir. Higher neutron response due to the higher hydrogen index of methane [23]. Therefore, the neutron log will read lower porosity in hydrogen-filled reservoirs compared to methane-filled ones.

Resistivity log response

Since hydrogen is a non-conductive gas, resistivity will remain high for Hydrogen-filled reservoirs similar to Methane-filled reservoirs. There may be a slight difference, but it may not be that significantly to distinguish between hydrogen and methane.

Sonic (Acoustic) log response

Hydrogen-filled reservoir: Hydrogen has a much higher sound velocity (~1300 m/s) compared to methane (~450 m/s) due to heavier gas molecules of Methane [11]. The compressional wave travel time (Δt) will be read lower on a sonic log for hydrogen-filled reservoirs compared to a methane-filled one.

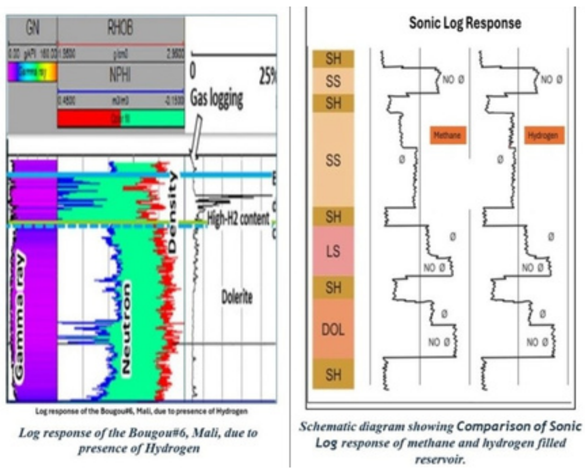

Figure 8.

Table 1. Showing relative log responses are summarised in table

Log Type	Hydrogen-Filled Reservoir	Methane-Filled Reservoir
Density Log	Lower density	Higher density
Neutron Log	Lower apparent porosity	Higher apparent porosity
Resistivity Log	High resistivity (similar)	High resistivity (similar)
Sonic Log (Δt)	Lower Δt (fastervelocity)	Higher Δt(slower velocity)

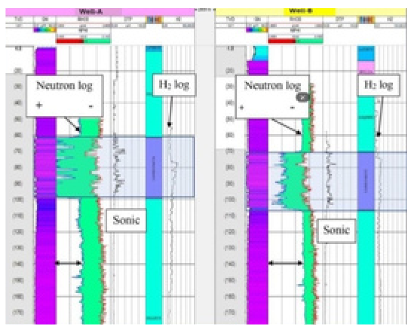

Figure 9. Well log response Sonic, Gamma, Neutron and density Hydrogen bearing reservoir of two wells of Mali

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Case Study1.Differentiating Hydrogen and Methane in a Reservoir

A European energy company initiated a pilot project to store hydrogen (H_2) in a depleted offshore methane reservoir in the North Sea. The objective was to evaluate the feasibility of large-scale hydrogen storage and retrieval while monitoring gas migration using well logging techniques [24]. The objective was to use well logging techniques to detect hydrogen migration and distinguish it from residual methane.

Reservoir characteristics

Location: North Sea, offshore

Depth: ~3,200 meters

Formation: Sandstone with high porosity (~20%)

Initial gas: Methane (CH_4)

Injected gas: Hydrogen (H_2)

Well logs were again recorded in wells after the hydrogen injection and were compare with original well logs when the reservoir was methane filled. The comparison is given in following table.

Table 2. Showing well log responses before and after hydrogen injection

Log Type	Before Injection (Methane-filled)	After Injection (Hydrogen-filled)
Density Log (g/cc)	2.30 - 2.35	2.20 - 2.25 (Lower)
Neutron Porosity (%)	15 - 18%	8 - 12% (Underestimated)
Resistivity (Ω·m)	High (~50-100 Ω·m)	High (~50-100 Ω·m)
Sonic Δt (μs/ft)	250 - 260 μs/ft	180 - 200 μs/ft (FasterVelocity)

As observed, the Sonic Log was found to be most effective tool for distinguishing between hydrogen and methane. A significant reduction in Δt (faster velocity in hydrogen) provided clear evidence of gas replacement. The observations can very well be used as a basic tool to identify new hydrogen reservoir fields [25]. The well log response against the reservoir before (initial stage when methane was filled) and after the hydrogen injection are tabulate below.

Key observations

Density log response

After hydrogen injection, the density log showed a ~0.1 g/cc drop, confirming the presence of lighter hydrogen gas in place of methane. However, the change is not significant.

Neutron porosity log response

A false porosity reduction was observed in hydrogen-filled zones due to hydrogen's lower hydrogen index [9]. This created an illusion of lower porosity, which required correction using sonic and density logs. However, this could be one of the indicators for hydrogen.

Resistivity log response

No significant change was observed, as both hydrogen and methane are highly resistive gases. This proved that resistivity logs alone could not differentiate between hydrogen and methane.

Sonic log response – most effective tool

Biggest change was seen in compressional wave travel time (Δt):

Before injection (Methane): 245 - 255 μs/ft

After injection (Hydrogen): 180 - 200 μs/ft

Hydrogen's higher velocity caused a faster sonic wave travel, making the sonic log the best indicator of hydrogen presence [18].

Case Study 2.

Hydrogen Storage in a Depleted Gas Field (Underground Energy Storage Project)

Another case study like previous one is also for monitoring the movement and behaviour of hydrogen gas in depleted gas reservoir through well logs and comparing responses to methane- filled zones [25].

Project overview

Location: Western Europe

Reservoir Type: Depleted sandstone gas reservoir

Depth: ~1,200 meters

Porosity: ~20%

Permeability: ~200 mD

Original gas: Methane (CH_4)

Injected gas: Hydrogen (H_2) for seasonal energy storage

Table 3. Showing well log analysis before and after hydrogen injection, western europe

Log type	Before injection (Methane-filled)	After injection (Hydrogen-filled)
Density Log (g/cc)	2.35 g/cc	~2.25 g/cc
Neutron Porosity (%)	15-18%	8-10%
Resistivity (Ω·m)	High ~80 Ω·m	High ~80 Ω·m
Sonic Δt (μs/ft)	260 μs/ft	190 - 210 μs/ft (FasterVelocity)

Key observations & challenges

Sonic log as the best indicator

Hydrogen-filled zones showed a distinct reduction in Δt (faster sound velocity). Sound waves travel significantly faster in hydrogen compared to methane due to hydrogen's lower density. At standard temperature and pressure, the speed of sound in hydrogen is roughly 1284 m/s, while in methane it's approximately 450 m/s. This difference is primarily because sound waves propagate more quickly through less dense mediums [21].

Neutron log

The neutron porosity tool showed significantly lower porosity, making it unreliable for hydrogen quantification.

Resistivity log ineffectiveness

Resistivity remained high for both methane and hydrogen, proving that resistivity logs alone cannot distinguish between the two gases.

Density

Density log showed a minor lower compared to hydrocarbon filled reservoir.

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This study of well logs during a hydrogen injection project in depleted shallow gas reservoir indicated that Sonic logs are the most effective tool for identifying hydrogen in underground reservoirs [16,17]. Density logs can confirm hydrogen presence due to the lower molecular weight of H_2. Neutron porosity logs underestimate porosity in hydrogen-filled formations, but the resistivity logs are ineffective for distinguishing hydrogen from methane.

The neutron porosity log which gives a false indication of lower porosity must be a reason for discarding the hydrogen reservoirs as tight reservoirs. Sonic log also required to be corrected for pressure and temperature effect at large depths. sonic logs should be prioritized for detecting hydrogen storage and movement, while neutron logs should be carefully corrected to avoid misinterpretation.

Global Discoveries and Commercial Projects

Natural hydrogen discoveries remain rare worldwide. The Bourakébougou field in Mali stands out as the first commercial natural hydrogen production site, operational since 2012. Initially discovered by accident in 1987, a single well there has been supplying hydrogen to power a local fuel cell for electricity generation [26].

In Australia, Gold Hydrogen's Ramsay Project and HyTerra Ventures are actively exploring natural hydrogen, having reported significant concentrations. In the United States, Natural Hydrogen Energy LLC and Koloma are advancing pilot projects in Nebraska and Colorado, respectively.

Notably, hydrogen seeps have been identified in abandoned oil wells as part of Spain's Helios Aragón Project, which holds an estimated 1.1 million tons of recoverable hydrogen [27]. In France, the Lorraine Project reported unexpected hydrogen concentrations of 15–20% in coalbed methane wells, prompting ongoing feasibility studies.

Early-stage exploration is also underway in Brazil, Oman, and South Korea, with further potential being evaluated in Canada, Russia, and India.

Economic Comparison with Green Hydrogen

Both natural (if extracted without leaks) and green hydrogen have near-zero or zero carbon footprints, respectively.

Natural hydrogen offers a potentially lower-cost alternative to green hydrogen (produced via electrolysis using renewable electricity). Natural hydrogen is estimated at $0.5-$1.5/kg, with a potential to drop to $0.3-$1.0/kg, primarily driven by exploration and drilling costs [28]. Green hydrogen currently costs $3-$6/kg and is expected to fall to $2-$4/kg, with costs dependent on renewable electricity prices and electrolyser efficiency.

Natural hydrogen requires no external energy input as it is self-generating geologically, unlike green hydrogen, which needs approximately 50 kWh/kg for electrolysis. However, Natural hydrogen's scalability is limited by geological reserves, which are still uncertain.

Discussions

Natural hydrogen is indeed trapped in underground reservoirs and has likely gone unnoticed in many of wells out of millions drilled in the past, as the primary focus of exploration has traditionally been on oil or methane gas. Consequently, the presence of natural hydrogen may have been overlooked and left unreported.

Re-analysing well log data from the millions of wells drilled worldwide holds significant potential for uncovering previously undetected natural hydrogen deposits.

Studies indicate that the sonic log (Δt) is the most effective tool for identifying hydrogen accumulations. The density log can be used to further confirm the presence of a lighter hydrogen gas. Interestingly, neutron porosity logs tend to underestimate porosity in the presence of hydrogen, which can serve as an additional indicator for detecting hydrogen pools. In deeper reservoirs, sonic logs, along with density logs, should be prioritized for hydrogen detection, while neutron logs should be interpreted cautiously.

Hydrogen is rapidly gaining global attention as a key pillar in the transition to a low carbon future. As the most abundant element in the universe, hydrogen offers immense potential as a clean, efficient, and versatile energy carrier.

Unlike fossil fuels, hydrogen combustion emits only water vapor, making it a zero-emission fuel when produced from renewable sources (green hydrogen).

Furthermore, natural hydrogen (or white hydrogen), generated naturally in the Earth's crust through geological processes, is now being explored as an even cleaner and potentially cheaper alternative.

With global efforts to achieve net-zero emissions, hydrogen stands out as a scalable, flexible, and green energy solution, poised to reshape the global energy mix in the coming decades.

Conclusions

The principal aim of this study was the comprehensive evaluation of the physicochemical properties and general quality of groundwater within the designated region. A total of 35 locations were surveyed, and the findings suggest that the groundwater quality is generally favourable, based on the analysis of various monitored elements and physicochemical parameters. The pH values, ranging from 6.7 to 7.6, confirm that the water is slightly alkaline, making it favourable for a broad spectrum of uses, including human consumption and agricultural applications. EC and TDS measurements classify the groundwater as slightly saline, indicating its suitability for irrigation and agricultural use. However, localized areas with higher salinity may require careful management to mitigate potential soil quality impacts. The water in the study area is predominantly hard to very hard, with Ca^{2+} being the dominant cation, and HCO_3^- as the primary anion, a pattern confirmed by the Piper diagram. The order of cationic abundance is Ca > Na > Mg > K, whereas the order of anionic abundance is HCO_3 >Cl > SO_4. Carbonate weathering exerts a primary influence on groundwater chemistry in the study area, although silicate weathering also contributes to the presence of some dissolved ions. Analysis using the Gibbs diagram further reinforces the conclusion that rock weathering is the dominant control on groundwater chemistry, indicating minimal anthropogenic impact and suggesting a largely natural, unpolluted system. Evaluation of salinity and sodium hazards, employing the Wilcox and USSL Richards diagram methodologies, demonstrates that the majority of the analysed groundwater samples present conditions suitable for irrigation practices [24,25]. However, some areas with higher salinity require careful management to avoid potential negative impacts on soil quality. Evaluation using the Water Quality Index (WQI) suggests that groundwater in the study area is generally suitable for a variety of applications, including domestic and agricultural uses. This suitability is supported by the fact that most

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samples met the quality standards established by the WHO and BIS [17,18]. However, the study also underscores the presence of localized issues, such as high hardness and salinity, which may require targeted management strategies. While the majority of groundwater samples were deemed acceptable for drinking, certain locations exhibited elevated iron levels exceeding the permissible limits. This suggests a need for specific treatment interventions, such as the use of oxidizing filters, green-sand filters, or mechanical filtration, to mitigate iron contamination and ensure water safety for human consumption. The findings emphasize the importance of continued monitoring and proactive management of groundwater resources to address site- specific challenges. Implementing appropriate water treatment technologies and sustainable management practices will be crucial to maintaining the quality and usability of groundwater for both current and future needs. This study provides valuable insights into groundwater quality in the region and highlights areas requiring attention to sustain its use for domestic, agricultural, and other purposes.

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Disclosure Statement

No potential conflict of interest was reported by the author.

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