

Groundwater-Level and Thermal Dynamics Following Severe Drought: Insights from High-Frequency Monitoring in the Bekaa Valley, Lebanon

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Abstract

Groundwater resources are essential for agricultural sustainability in semi-arid regions, yet continuous empirical observations of deep aquifer dynamics remain scarce. This study addresses this empirical gap by presenting the first multi-year, high-frequency telemetry record of groundwater-level, thermal, and Total Dissolved Solids (TDS) dynamics from a dedicated 400 m unpumped observation borehole in Kfardane, Northern Bekaa Valley, Lebanon. A total of 2998 piezometric observations (6-hour logging intervals) collected between April 2024, and August 2026 were analyzed alongside daily precipitation, air temperature, and *in-situ* TDS data across two contrasting hydrological cycles following a severe drought. Results reveal pronounced seasonal drawdown driven by regional agricultural abstraction, reaching an absolute maximum water-table depth of 233.0 m b.g.l. in July 2025 following an anomalously dry wet season (126 mm rainfall). Conversely, a wetter 2025-2026 winter (311 mm precipitation) generated a robust 17.0 m hydraulic head recovery by April 2026 (216 m b.g.l.), buffering the aquifer against extreme stress during the subsequent 2026 irrigation season (summer drawdown reaching 227.2 m b.g.l.). Subsurface temperature remained stable overall (15.8°C - 16.4°C) despite surface air fluctuations exceeding 40°C. Transient downhole cooling events ($\Delta T = -0.51^\circ\text{C}$) coincided with rapid, concurrent drops in TDS ($\Delta\text{TDS} = -64.8$ ppm) following peak winter precipitation and rapid mountain snowmelt. Overall, the findings demonstrate that seasonal groundwater stress in the deep Bekaa aquifer is governed by the interaction of irrigation pressure, precipita-

tion variability, and multi-year antecedent storage memory (highlighting the importance of telemetry).

Keywords

Carbonate Aquifer, Aquifer Memory, Groundwater Recharge, Irrigation Demand, Hydraulic Response, Groundwater Temperature, Telemetry Monitoring

1. Introduction

Groundwater represents a strategic water resource in semi-arid agricultural regions because it buffers seasonal rainfall variability and provides a reliable supply during periods of limited surface-water availability [1] [2]. This buffering function is particularly vital in areas where agricultural production depends heavily on groundwater abstraction [2] [3]. However, expanding irrigation demand, land-use conversions, recurrent drought conditions, and shifting precipitation regimes can intensify pressure on groundwater systems, especially when regional abstraction is concentrated during dry seasons and recharge remains highly episodic [4]–[6]. Consequently, establishing high-resolution tracking of these dynamics is imperative for evaluating the true operational boundaries of semi-arid agricultural aquifers.

The Eastern Mediterranean region faces growing challenges regarding groundwater sustainability due to the combined pressures of climate variability, population growth, and intensifying irrigation requirements [7] [8]. Mountainous headwater catchments act as critical “water towers” supplying crucial recharge to adjacent lowlands [9] [10]. In Lebanon, extensive carbonate aquifer systems serve as the primary source of domestic, agricultural, and industrial water supply [11] [12]. The Bekaa Valley, the country’s primary agricultural belt, has experienced rapid expansion of groundwater-based irrigation as cropping intensity increased and surface-water supplies became increasingly unreliable [13] [14]. In the Northern Bekaa, regional irrigation extraction reaches its maximum during the warm dry season (May to October), coinciding with minimal precipitation and peak crop evapotranspiration rates [15] [16]. Understanding the localized magnitude of this seasonal drawdown is therefore essential for mitigating long-term risks to regional agricultural security.

Previous hydrogeological research across the Bekaa Plain and Litani River Basin has primarily relied on two approaches: (1) regional space-borne remote sensing (e.g., GRACE satellite gravity anomalies [16] [17], InSAR surface deformation, and Landsat/SEBAL evapotranspiration mapping [14]) and (2) basin-scale water-balance assessments and periodic manual soundings [10] [13]. While these macro-scale investigations have successfully mapped broad regional depletion signals and identified long-term stress zones across the Bekaa [17], they suffer from fundamental spatial and temporal limitations:

Satellite remote sensing (GRACE/InSAR) integrates total storage changes over vast spatial domains ($>10,000 \text{ km}^2$) or detects surface deformation, lacking the fine vertical and temporal resolution needed to capture localized hydraulic head fluctuations, short-term pumping-recovery cycles, or immediate storm-event recharge responses.

Periodic manual soundings provide intermittent static head measurements (often monthly or seasonally), which fail to resolve high-frequency dynamic responses, diurnal pumping stresses, rapid fracture/conduit flow velocity, or transient thermal dynamics in complex dual-porosity carbonate systems [18]–[23].

Consequently, a critical empirical research gap remains: no study in the Northern Bekaa Valley has continuously tracked real-time hydraulic head, thermal, and hadrochemical variations at fine temporal intervals in a dedicated, deep, unpumped observation borehole following extreme climate shocks [24] [25]. Without high-frequency telemetry, it remains impossible to separate natural geothermal and recharge signals from localized wellbore noise, or to evaluate how antecedent aquifer storage memory influences single-year seasonal drawdown extremes.

To bridge this gap, this study presents the first multi-year, high-frequency telemetry record (6-hour logging intervals, $n = 2, 9$ on the aquifer system 98) of piezometric depth, subsurface temperature, and Total Dissolved Solids (TDS) from a dedicated 400 m unpumped monitoring borehole in Kfardane, Northern Bekaa Valley, Lebanon, spanning April 2024 to August 2026. By isolating ambient hydraulic head fluctuations and natural hadrochemical/thermal signals from operational well turbulence, this study directly addresses three key research questions: How do deep carbonate groundwater levels respond to high-intensity seasonal abstraction compared to short-term precipitation events? To what extent does multi-year antecedent storage memory buffer the aquifer against extreme stress during dry versus wet hydrological cycles? Can continuous downhole temperature and TDS telemetry serve as passive tracers to detect rapid, conduit-dominated recharge pulses from mountain snowmelt and peak winter precipitation?

2. Materials and Methods

2.1. Study Area

The monitoring site is in Kfardane, Northern Bekaa Valley, Lebanon (34.0226°N , 36.0701°E), at an elevation of approximately 1040 m above sea level. The region has a Mediterranean to semi-arid climate characterized by cool, relatively wet winters and hot, dry summers. Agricultural activities are strongly dependent on irrigation, with groundwater providing an essential source of water for crops including potatoes, onions, vegetables, and fruit trees.

The Bekaa Valley is situated between the Lebanon and Anti-Lebanon mountain ranges (**Figure 1** and **Figure 2**). Winter precipitation and mountain snow accumulation contribute to regional water availability, whereas irrigation demand increases mainly from spring through summer. Consequently, groundwater systems experience strong seasonal pressure associated with agricultural abstraction fol-

lowed by partial recovery during cooler and wetter periods [8].

The Kfardane monitoring location provides a site-scale record of groundwater-level variability in a deep carbonate aquifer system. The record is interpreted as a local hydraulic response of the monitored borehole and is not assumed to represent basin-wide groundwater storage behavior.

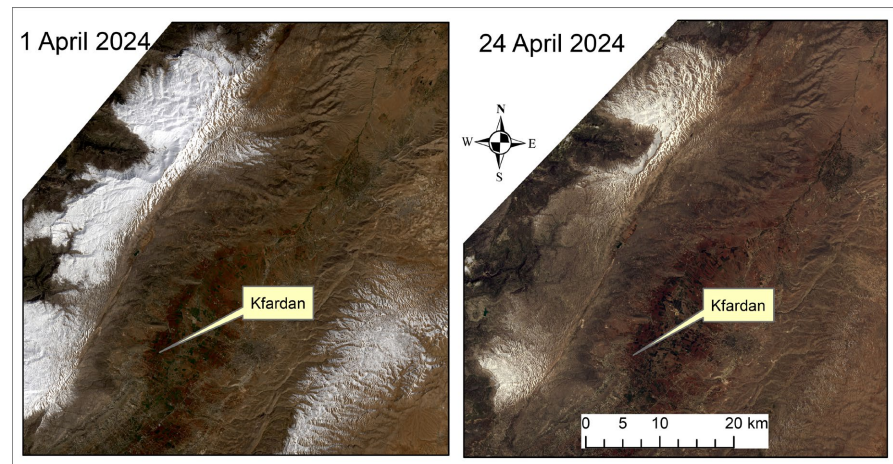


Figure 1. MODIS images from 1 April and 24 April 2024 showing rapid loss of snow cover in the mountains surrounding. The images provide qualitative evidence of spring snowmelt but do not by themselves quantify recharge to the monitored aquifer.

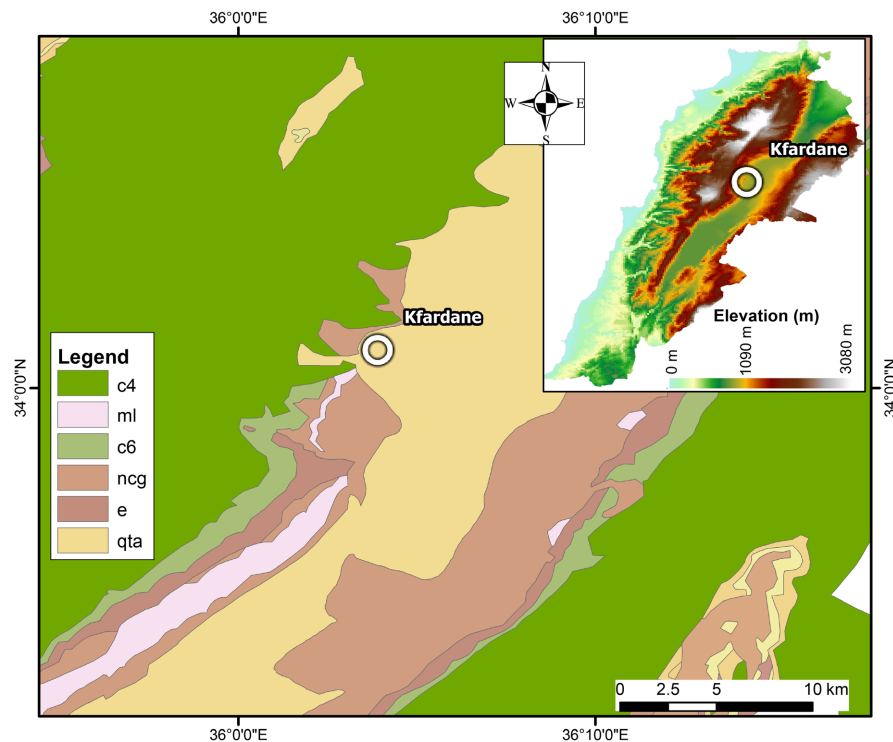


Figure 2. Location of the well (Inside the circle) with the geology of the area and elevation above sea level.

Spatial distribution data, lithological formations, and digital elevation models

(DEM) were integrated within a Geographic Information System (GIS) environment to define the hydrogeological framework of the study area (**Figure 2**). The target groundwater monitoring site is located at Kfardane on a central valley floor at an elevation of 1,090 m above sea level, situated within a broader catchment characterized by steep topographic relief reaching elevations up to 3,080 m (**Figure 2**).

The monitoring well is constructed within Quaternary alluvial and terrace deposits (qta), which consist of unconsolidated to semi-consolidated silt, clay, gravel, and stream sediments. The surrounding bedrock geology is defined by a diverse stratigraphical sequence comprising:

- qta (Quaternary Alluvium/Terraces): Unconsolidated to semi-consolidated silt, clay, gravel, and stream deposits occupying the central valley floor.
- c4 (Sannine Formation): Upper Cretaceous (Cenomanian) fractured limestone and dolomite, representing a major regional karstic aquifer.
- c6 (Chekka Formation): Upper Cretaceous (Senonian) chalky limestone and marly limestone sequences.
- e (Eocene Units): Eocene limestone and marly limestone formations.
- ml (Mio-Pliocene Lacustrine Deposits): Neogene freshwater limestones, marls, and lacustrine sediments.
- ncg (Neogene Conglomerates): Continental coarse clastic deposits and cemented gravels originating from mountain erosion.

Groundwater recharge occurs predominantly via direct infiltration of rainfall and snowmelt across the high-altitude exposed karstic limestone outcrops of the c4 formation. Regional groundwater flows down-gradient through fractured and conduit-dominated pathways toward the valley, feeding the unconfined Quaternary alluvial aquifer (qta) at 1090 m elevation where the monitoring well captures both shallow alluvial and deep karstic recharge inputs.

2.2. Groundwater Monitoring System

Groundwater monitoring was conducted using an instrumented 400 m deep borehole located at Kfardane. An Aqua TROLL 200 multiparameter probe was installed at approximately 295 m below ground level and connected to a VuLink cellular telemetry unit (firmware version 1.78) for automated data transmission. The 400 m deep observation borehole was left unscreened and uncased across its open interval, allowing direct hydraulic connection with all intersected hydrostratigraphic units—primarily the Quaternary alluvial deposits at upper levels and the underlying fractured/karstic carbonate aquifer at depth. Because the borehole is fully open across multiple water-bearing zones without isolation packers, an artificial conduit exists that creates potential for ambient vertical intra-borehole cross-flow driven by vertical hydraulic head gradients. The multiparameter telemetry probe (Aqua TROLL 200) was deployed at a fixed depth of 295 m b.g.l., recording the integrated hydraulic head at this specific monitoring point rather than an isolated, discrete aquifer layer.

The monitoring system was configured for continuous groundwater-level

measurements with a nominal logging interval of 6 h. The dataset analyzed in this study contains 2998 groundwater-level observations collected between 16 April 2024 and 20 August 2026.

The transmitted data were stored in a secure database and processed using local time correction (UTC + 2) before analysis. Continuous telemetry allowed remote access to groundwater observations without requiring frequent manual instrument retrieval.

Because the monitored borehole is a monitoring well (this borehole is not used for pumping, it is only used for groundwater level monitoring), groundwater-level variations may reflect the combined influence of pumping conditions, aquifer pressure changes, recharge events, and recovery of the local pumping cone. Therefore, changes in measured groundwater depth are interpreted as hydraulic responses at the monitoring location rather than direct estimates of aquifer storage change.

Direct metered groundwater abstraction records are not available for individual agricultural boreholes in the study area. Consequently, spatial and temporal pumping patterns were inferred indirectly using the regional agricultural calendar, crop growth cycles (primarily seasonal irrigation from May through September), and local power-grid usage patterns. Because unmetered pumping cannot provide continuous volumetric rate data, observed seasonal water-level drawdowns are interpreted as a temporal association with intensive agricultural irrigation rather than a direct volumetric attribution.

2.3. Meteorological and Temperature Data

Daily precipitation data were obtained for the monitoring period from 6 October 2024 to 20 August 2026. Two wet-season precipitation periods were considered to compare differences in seasonal water availability:

- 126 mm accumulated between 8 October 2024 and 1 May 2025;
- 311 mm accumulated between 8 October 2025 and 5 August 2026.

These values are used as indicators of interannual precipitation variability rather than long-term climatological averages.

Paired air temperature and groundwater temperature measurements were analyzed to evaluate thermal buffering and possible recharge-related temperature variations. Groundwater temperature was measured by the downhole probe, while atmospheric temperature was obtained from the associated weather station. The available paired temperature record extends from 16 April 2024 to August 2026.

Site-specific meteorological data were recorded using a Pessl iMETOS automatic weather station owned and operated by the Lebanese Agricultural Research Institute (LARI), located approximately 200 m from the observation borehole.

2.4. Total Dissolved Solids (TDS) Monitoring

In-situ continuous hydrochemical monitoring of Total Dissolved Solids (TDS, reported in ppm) was performed using an Aqua TROLL 200 multiparameter probe (*In-Situ* Inc.) installed at a depth of approximately 295 m below ground level

within the 400 m unpumped observation borehole at Kfardane. The integrated sensor determines TDS indirectly by continuously measuring the electrical conductivity (EC) of dissolved ionized constituents and converting it via an internal cell factor algorithm.

Automated measurements were logged at high-frequency intervals and wirelessly transmitted via a VuLink cellular telemetry unit (firmware version 1.78) to a secure cloud database. The transmitted telemetry data were adjusted to local time (UTC + 2) and processed into daily median values to suppress short-term sensor noise and localized dynamic variations. The resulting temporal dataset (spanning April 2024 to August 2026) was analyzed alongside piezometric depth and meteorological series to assess seasonal solute dynamics, matrix water-rock interactions, and dilution signatures consistent with potential conduit-dominated recharge events.

2.5. Dataset Summary

The groundwater-level dataset was converted from high-frequency observations into daily median values to reduce short-term fluctuations associated with pumping cycles and measurement variability. Daily changes in groundwater depth were calculated as **Table 1**.

Table 1. Summary of dataset.

Variable	Period	Resolution used	Purpose
Depth to water	16 Apr 2024–20 Aug 2026	Daily median from 2998 observations	Seasonal drawdown and recovery
Daily precipitation	6 Oct 2024–20 August 2026	Daily total	Wet-season comparison
Groundwater temperature	16 Apr 2024–August 2026	Daily	Subsurface thermal variability
Air temperature	16 Apr 2024–August 2026	Daily	Atmospheric comparison

Seasonal periods were compared according to the dominant hydrological conditions:

- Warm irrigation period: approximately spring-summer, characterized by increased agricultural water demand;
- Cool/wet period: autumn-winter, characterized by reduced irrigation demand and potential recharge.

The analysis focused on:

- magnitude and timing of seasonal drawdown;
- duration and magnitude of recovery periods;
- differences between wet years and dry years;
- correspondence between groundwater response and precipitation timing;
- groundwater temperature response relative to atmospheric variability.

2.6. Data Transmission and Management

The VuLink Cellular system facilitated real-time data transmission to a secure database for processing and analysis. This ensured data availability without requiring frequent physical retrieval of the instruments. A time offset of UTC + 2 hours was applied to align the data with the local time zone.

3. Results and Discussions

3.1. Seasonal Groundwater-Level Dynamics

The Kfardane record shows three successive warm-season drawdown phases separated by partial recovery (**Figure 3** and **Table 2**). At the start of monitoring on 16 April 2024, depth to water was 204 m b.g.l. The water table deepened rapidly through spring and summer and reached 223 m b.g.l. on 08 September 2024. This represents a drawdown of 19.2 m from the initial observation.

After the September 2024 low, the water table recovered to 218.6 m b.g.l. on 04 March 2025, a recovery of 4.3 m. The 2025 drawdown then developed from early spring and reached 233 m b.g.l. on 05 July 2025. The drawdown from the 2025 spring high-water position to the summer minimum was 14.7 m, and the July 2025 level was the deepest value observed in the full record.

From July 2025 to April 2026, a strong recovery of 17 m occurred, bringing depth to water to 216 m b.g.l. on 13 April 2026. A third warm season decline followed, reaching 227 m b.g.l. on 27 July 2026, a drawdown of 11.2 m from the spring 2026 recovery maximum. By 20 August 2026 the water table had recovered slightly to 226 m b.g.l.

These repeated cycles demonstrate a strong seasonal hydraulic signal. The record end is substantially deeper than the record start, but the two dates occur at different positions within the seasonal cycle.

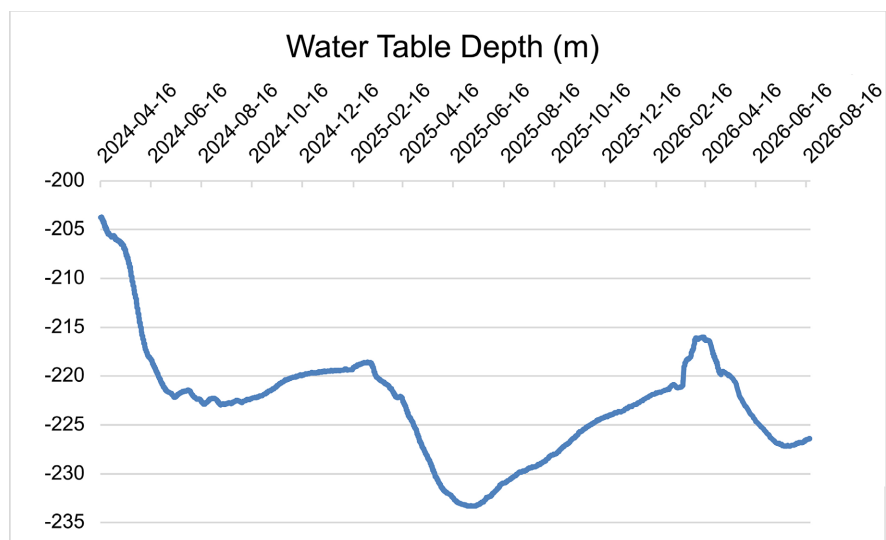


Figure 3. Temporal variation of groundwater table depth from April 2024 to August 2026, showing seasonal drawdown during dry and irrigation periods and partial recovery during rainy season.

Table 2. Drawdown and recovery episodes.

Episode	Start depth (m b.g.l.)	End depth (m b.g.l.)	Change (m)
Apr-Sep 2024 drawdown	204	223	+19
Sep 2024-Mar 2025 recovery	223	219	−4
Mar-Jul 2025 drawdown	219	233	+15
Jul 2025-Apr 2026 recovery	233	216	−17
Apr-Jul 2026 drawdown	216	227.2	+11

The daily groundwater-level variations shown in **Figure 4** reveal a pronounced seasonal response of the Bekaa Valley aquifer to irrigation-driven abstraction. The dominance of negative daily changes during the irrigation period (approximately May–September) indicates persistent groundwater depletion, reflecting abstraction rates that exceed natural recharge. This pattern is consistent with previously documented groundwater dynamics in the Bekaa Valley, where limited recharge, semi-arid climatic conditions, and intensive agricultural water use collectively impose significant stress on the aquifer system [9] [24] [25].

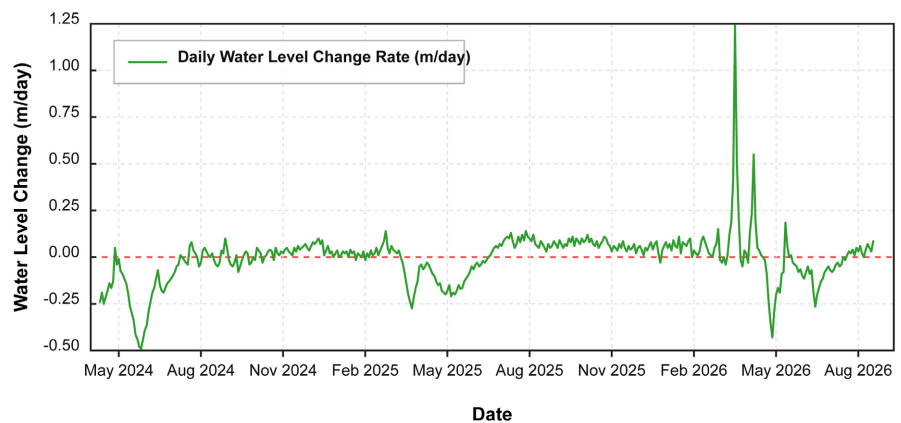


Figure 4. Daily rate of groundwater-level change (m day^{-1}) between April 2024 and August 2026, derived from pumping and non-pumping periods. Negative values = net groundwater depletion, while positive values = reduced abstraction.

A gradual shift toward near-zero or slightly positive groundwater-level changes is observed from early October onward, coinciding with the end of the irrigation season. Reduced agricultural demand, declining evapotranspiration, and the onset of early rainfall contribute to this partial recovery. However, the magnitude of the rebound remains limited, suggesting that seasonal recharge is insufficient to compensate for cumulative drawdown incurred during the irrigation months. This incomplete recovery highlights the reduced resilience of the aquifer under sustained abstraction pressure.

Short-lived positive spikes in daily groundwater change, particularly during September and October, likely represent episodic recharge events or temporary reductions in pumping. Similar transient recharge responses have been reported

elsewhere in the Bekaa Valley and other semi-arid basins, where early precipitation events briefly interrupt declining groundwater trends without reversing long-term depletion [18]. The rapid attenuation of these positive signals indicates limited infiltration efficiency and continued dominance of abstraction processes.

During peak irrigation months, the persistence and magnitude of negative daily changes underscore the intensity of groundwater withdrawal for agricultural and domestic uses. These conditions promote progressive aquifer depletion and heighten the risk of long-term impacts such as declining water quality, reduced baseflow contribution to surface waters, and land subsidence, as documented in other over-exploited aquifer systems worldwide [7] [10].

A notable feature of the record is the low-pumping period toward the end of 2025, during which daily groundwater-level changes stabilize and variability decreases. This phase corresponds to a marked reduction in pumping following the cessation of irrigation activities. The observed stabilization suggests that the aquifer can temporarily equilibrate when abstraction pressure is relaxed. Nevertheless, the absence of a strong positive recovery trend indicates that natural recharge from the rainy season (fall and winter of 2025-2026) is still insufficient to restore groundwater levels within a single non-irrigation season, emphasizing the cumulative nature of groundwater depletion.

Irrigation records indicate that groundwater deepening occurred on approximately 60% of the days between April and December 2024, reflecting a highly intermittent abstraction regime. While short non-pumping intervals reduce instantaneous drawdown, they do not significantly alter the long-term declining trend. This finding demonstrates that intermittent pumping does not necessarily equate to sustainable groundwater use when overall abstraction volumes remain high.

From a management perspective, these results highlight the need for demand-side interventions and improved recharge strategies. Enhancing irrigation efficiency, regulating pumping during peak demand periods, and implementing managed aquifer recharge measures could mitigate seasonal drawdown and improve aquifer sustainability [11]. Without such measures, continued reliance on groundwater for irrigation is likely to exacerbate long-term aquifer degradation, particularly under increasing climate variability and water demand in the Bekaa Valley.

3.2. Groundwater vs Rainfall Response

The total precipitation recorded between November 2024, and May 2025 accumulated 126 mm across 51 rainy days (Figure 5). Given that the long-term average annual precipitation in the investigated area is approximately 450 mm, the 2024-2025 wet season (September 2024-May 2025) represents a severe dry year with rainfall totals substantially lower than historical averages.

Due to this precipitation deficit, groundwater recharge was minimal, yielding a net seasonal water table recovery of approximately 4 m at the monitoring well. Concurrently, active groundwater abstraction continued over the same period.

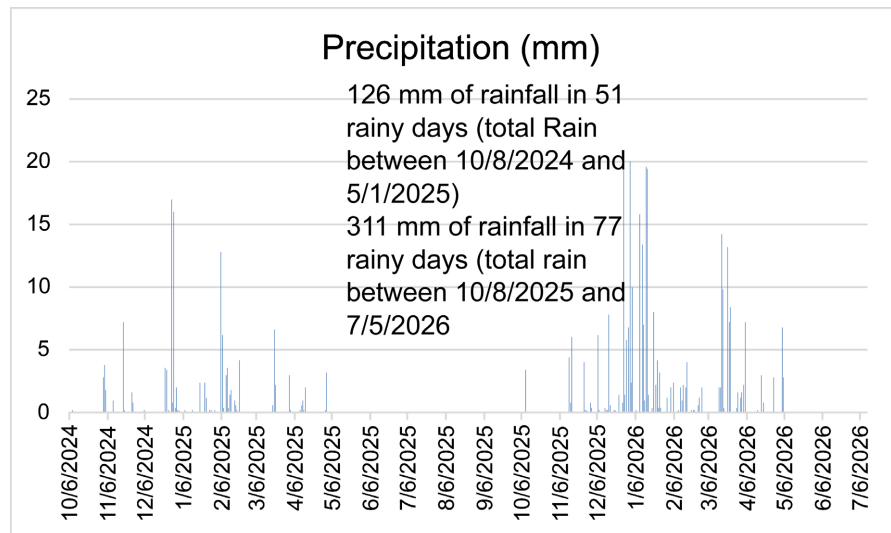


Figure 5. Daily precipitation distribution during the 2024–2025 and 2025–2026 rainy seasons, showing a total accumulation of 126 mm over 51 rainy days. The reduced rainfall and shortened wet season indicate limited recharge potential compared to the long-term average precipitation of the study area.

The temporal relationship between groundwater level, daily precipitation, and seasonal pumping from April 2024 through August 2026 demonstrates that water table dynamics in the Kfardane borehole are governed primarily by agricultural abstraction rather than immediate local rainfall recharge.

During the 2024–2025 wet season, precipitation totaled only 126 mm across 51 rainy days—substantially below the long-term regional average of approximately 450 mm. The sparse rainfall failed to generate meaningful immediate water table recovery. Following the initial 2024 drawdown from 204 m b.g.l. to 223 m b.g.l., winter recovery reached only 219 m b.g.l. by March 2025. Deepening began early in March 2025, driving an intense decline to the deepest recorded level of 233 m b.g.l. in July 2025.

From late July 2025 through April 2026, the water table underwent a sustained, multi-month recovery. This phase coincided with a significantly wetter winter season (2025–2026), which accumulated 311 mm of precipitation with multiple high-intensity rainfall events (peaking above 15–20 mm day⁻¹ between December 2025 and February 2026). In contrast to the previous year, the combination of complete pumping cessation and substantially higher recharge allowed the water table to recover from 233 m b.g.l. to 216 m b.g.l. by mid-April 2026—a net hydraulic head recovery of 17 m.

The initiation of the 2026 irrigation season in late April caused an immediate reversal in water table trajectory. From mid-April to late July 2026, intensive groundwater extraction deepened the water table from 216 m b.g.l. to 227.2 m b.g.l. (an 11 m seasonal drawdown). By August 2026, the water table stabilized slightly around 226.4 m b.g.l. Notably, because the 2025–2026 winter recovery was far more robust than the 2024–2025 recovery, the summer 2026 minimum (227.2

m b.g.l.) remained roughly 6 m higher than the peak stress level recorded in July 2025 (233 m b.g.l.).

The hydrograph shows a distinct delay between peak rainfall months (Dec-Feb) and the peak water table position (April). This indicates that recharge moves through a thick unsaturated zone before reaching the deep aquifer.

The depth reached during summer drawdown depends directly on the water level at the end of the preceding winter. High winter recharge in 2025-2026 buffered the system against reaching extreme depths in summer 2026 (Figure 6).

The steep, immediate slope changes in April (downward) and August/September (upward) confirm that pumping controls the timing of high-frequency head variations, whereas winter rainfall controls the annual magnitude of head recovery.

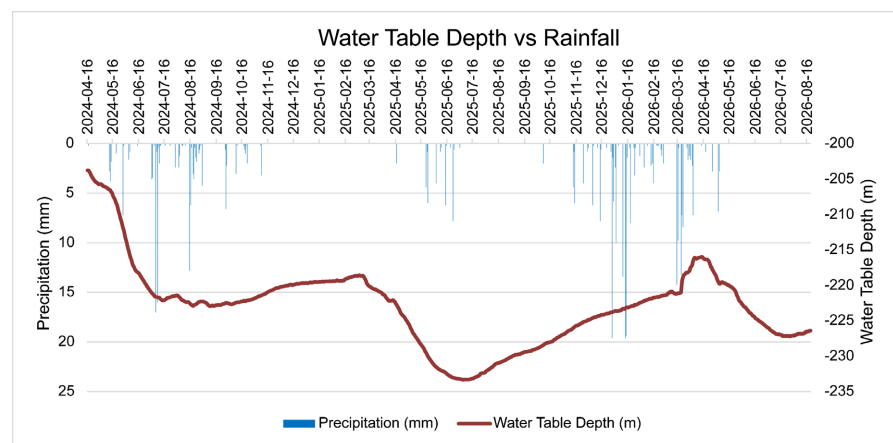


Figure 6. Temporal variation of water table depth in the monitored borehole in relation to daily precipitation from April 2024 to August 2026. The figure illustrates a pronounced groundwater decline beginning in early March 2025, coincidence with intensified pumping, and a lack of immediate groundwater response to rainfall events.

3.3. Groundwater Temperature Response and Thermal Dynamics

The continuous monitoring of paired air and downhole groundwater temperatures ($n = 858$ days) reveals strong subsurface thermal buffering coupled with distinct, event-driven advective pulses associated with winter recharge. Across the entire observation period (16 April 2024 to 20 August 2026), downhole groundwater temperature recorded at a depth of approximately 295 m b.g.l. remained remarkably stable, varying within a narrow thermal range of 15.8 to 16.4°C ($\Delta T = 0.6^{\circ}\text{C}$). In contrast, daily atmospheric air temperatures exhibited extreme seasonal and diurnal fluctuations, ranging from -2°C in late February 2025 to 39°C in August 2025 (Figure 7).

The extreme dampening of atmospheric temperature signals at depth underscores the high thermal inertia of the thick carbonate unsaturated zone (~ 200 m) and surrounding geological matrix. While surface air temperatures fluctuate by over 40°C annually, conductive heat transport from the atmosphere is strongly attenuated with depth. The baseline groundwater temperature of ~ 16.0 - 16.4°C

primarily reflects the local geothermal equilibrium, governed by the long-term regional mean annual surface temperature and the local geothermal gradient [12] [26] [27].

Despite this overarching conductive stability, the high-frequency temperature series reveals key transient cooling episodes that directly correspond to rapid cold-water recharge during the 2024-2025 and 2025-2026 hydrological cycles [28]-[30].

Spring 2024 Thermal Baseline Re-equilibration: At the start of monitoring in mid-April 2024, groundwater temperature was at its record low of 15.8°C. This reduced temperature reflects the lingering signature of cold meltwater infiltration from the 2023-2024 winter snowpack (as corroborated by MODIS imagery showing rapid mountain snowmelt in April 2024). As active pumping commenced for the 2024 irrigation season, the temperature rose steadily by ~0.4°C, reaching 16.2°C by June 2024 as the cold recharge pulse dissipated and the downhole environment re-equilibrated with the warmer geological matrix.

Winter 2024-2025 Transient Cooling: Between late January and March 2025, groundwater temperature dropped abruptly to a localized minimum of 16.0°C ($\Delta T = -0.34^\circ\text{C}$). This transient cooling coincided with winter rainfall and snowmelt infiltration during the coldest months of the year (where air temperatures dipped below 0°C). Following the cessation of winter recharge and the onset of early spring pumping in March 2025, temperatures rebounded rapidly back to 16.4°C by May 2025.

Winter 2025-2026 Severe Thermal Disturbance: A significantly larger and more prolonged thermal drop occurred during the 2025-2026 wet season. Beginning in late February 2026, groundwater temperature plunged steeply from 16.41°C to 15.9°C by late March 2026 ($\Delta T = -0.51^\circ\text{C}$). This sharp decline directly mirrors the heavy precipitation period documented in **Figure 5**, where 311 mm of rainfall and rapid snowpack melt introduced a large volume of cold water into the deep aquifer system.

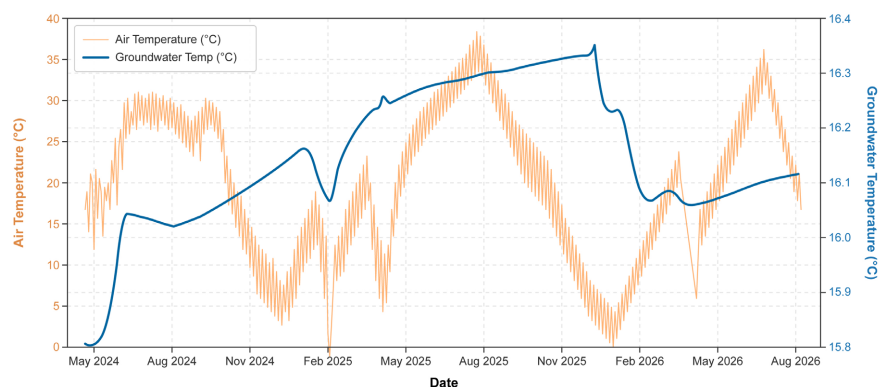


Figure 7. Groundwater temperature trends (April 2024-August 2026).

Summer 2026 Thermal Recovery: Following the March 2026 thermal minimum, groundwater temperature exhibited a two-step recovery. As cold recharge

ceased and intense summer pumping resumed in April 2026, temperatures rose quickly to 16.03°C by May, followed by a gradual warming trend toward 16.2°C by August 2026.

Satellite remote sensing provided independent spatial verification of the rapid seasonal hydrological drivers influencing early-spring recharge and downhole thermal responses. Multi-temporal imagery acquired by MODIS clearly captures the rapid depletion of the mountain snowpack in the high-altitude catchments surrounding the Northern Bekaa Plain (**Figure 1**) [31] [32]. The satellite scene from 1 April 2024 reveals continuous, high-albedo snow cover spanning the upper elevations of the Mount Lebanon and Anti-Lebanon ranges adjacent to the Kfardane monitoring site. By 24 April 2024, a span of just 23 days, the subsequent scene MODIS demonstrates near-total snowpack disappearance across these same mountain catchments. This abrupt spatial reduction in snow-covered areas suggests a period of rapid, concentrated snowmelt driven by rising early-spring ambient air temperatures [32]. The rapid melting of the snowpack generated a substantial volume of surface runoff and mountain-front recharge within a narrow temporal window. This cold meltwater infiltrated the fractured carbonate karst network, providing a transient recharge pulse that directly accounts for the suppressed downhole groundwater temperature (15.8°C) recorded at the onset of monitoring in mid-April 2024 (**Figure 7**). The optical remote sensing sequence thus provides crucial physical evidence linking high-elevation snowpack dynamics to downhole advective thermal disturbances and early-season piezometric recovery in the deep Kfardane aquifer.

3.4. Bivariate Statistical Correlations

3.4.1. Air Temperature vs. Groundwater Temperature

Bivariate regression between daily surface air temperature and downhole groundwater temperature yielded an extremely weak coefficient of determination ($R^2 = 0.036$) (**Figure 8**). This near-zero R^2 value may reflect that daily atmospheric surface temperature fluctuations have no direct predictive or causal effect on deep subsurface thermal dynamics. Due to strong temporal autocorrelation in daily hydrogeological time series, standard p-values overestimate statistical significance; adjusted effective sample size evaluations confirm the lack of direct thermal coupling on daily timescales. Heat transport across the ~200 m thick unsaturated zone occurs via slow thermal conduction, maintaining a stable geothermal baseline (~16.0°C - 16.4°C) that is insulated from high-frequency atmospheric variations [26]-[28].

3.4.2. Daily Precipitation vs. Water Table Depth

Comparing daily precipitation events directly with piezometric depths similarly revealed an absence of immediate linear correlation ($R^2 = 0.019$) (**Figure 9**).

The fact that daily rainfall accounts for less than 2% of daily water-table variance demonstrates that individual precipitation events do not trigger instantaneous, proportional water-table responses. This reflects significant percolation lags

across the deep unsaturated zone and non-linear karstic infiltration thresholds, as well as the overarching dominance of seasonal abstraction over short-term weather events.

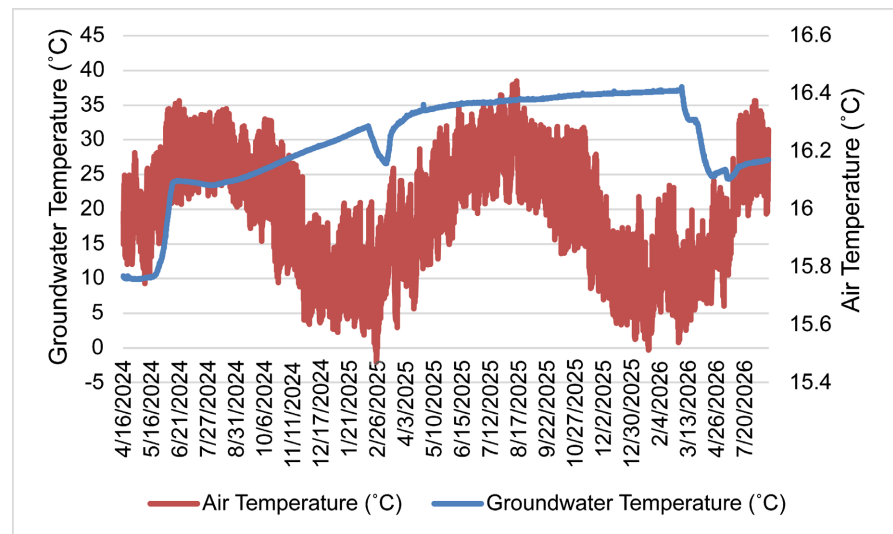


Figure 8. Temporal variation of air temperature and groundwater temperature from April 2024 to August 2026, illustrating strong seasonal fluctuations in air temperature and a damp, delayed groundwater temperature response.

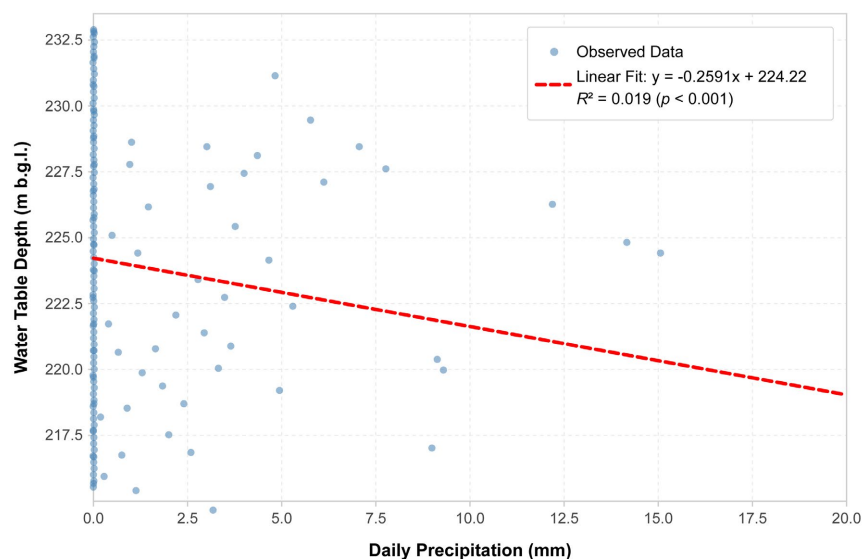


Figure 9. Correlation of water table depth vs daily precipitation.

3.4.3. Groundwater Temperature vs. Water Table Depth

Plotting groundwater temperature directly against piezometric depth reveals a clear relationship between hydraulic stress, deep geothermal equilibrium, and rapid advective recharge events (**Figure 10**).

Initial Spring 2024 Re-equilibration: In April 2024, the lowest groundwater temperature 15.8°C, coincided with the shallowest water table (204 m b.g.l.). As

summer pumping commenced and drew down deepened the water table toward 223 m b.g.l, groundwater temperature rose rapidly by $\sim 0.35^{\circ}\text{C}$, stabilizing at 16°C as cold meltwater recharge dissipated and stored matrix water was mobilized.

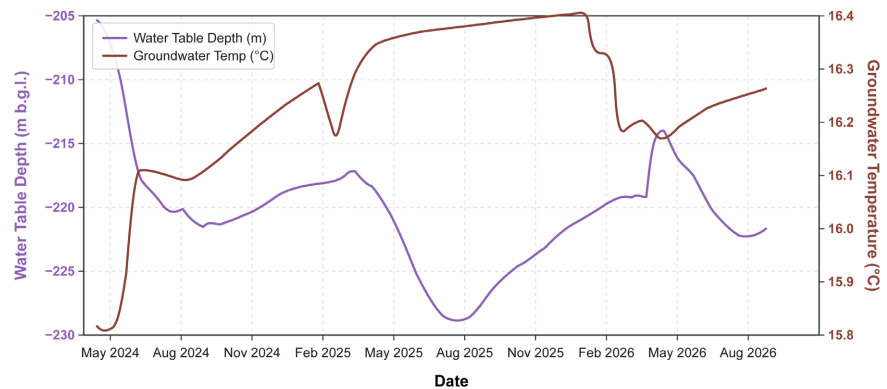


Figure 10. Temporal variation of downhole groundwater temperature.

This suggests that winter recharge reaches the deep aquifer via rapid fracture or conduit flow pathways [33] [34]. Transient temperature drops occur during peak winter recharge windows. In February–March 2025, a temperature drops to 15°C coincided with winter rainfall. A larger thermal disturbance occurred during the wet 2025–2026 winter: as the water table recovered by 17 m (reaching 216.0 m b.g.l. in April 2026), groundwater temperature plunged from 16.41°C down to 15.9°C ($\Delta T = -0.51^{\circ}\text{C}$). This may reflect that winter recharge reaches the deep aquifer via rapid fracture or conduit flow pathways, introducing cold water into the monitored zone.

Groundwater deepening and Geothermal Re-equilibration: Following the cessation of winter recharge and the onset of heavy summer groundwater deepening (April–August 2025 and April–August 2026), downhole temperatures rebounded toward $16.2 - 16.4^{\circ}\text{C}$. Intensive groundwater extraction draws warm water from the surrounding deep rock matrix toward the well screen, overriding the temporary cooling caused by winter infiltration. A moderate-to-strong linear relationship of groundwater depth and temperature (**Figure 11**).

3.5. Groundwater Total Dissolved Solids (TDS) Hydrodynamics

Continuous telemetry of groundwater Total Dissolved Solids (TDS) concentrations (measured in ppm) from April 2024 through August 2026 provides additional insight into solute dynamics and recharge timing in the deep carbonate aquifer (**Figure 12**).

Throughout the entire monitoring period, TDS concentrations remained consistently between 267.5 ppm and 337.8 ppm, remaining well below the EPA Secondary Drinking Water Standard of 500 ppm. Groundwater TDS levels rose steadily from an initial low of ~ 267.8 ppm in April 2024 before stabilizing around 320 ppm by October 2024. Concentrations remained highly stable for roughly 16 months, hovering between 320 ppm and 337.8 ppm. Peak concentrations were

observed in late 2025 (~337.8 ppm), reflecting prolonged water-rock interaction during extended residence times.

A steep decline occurred starting in March 2026, reaching a low of ~273.0 ppm in late April 2026. This sharp dilution event ($\Delta\text{TDS} \approx -64.8$ ppm) directly mirrors the hydraulic head recovery and downhole cooling episode documented during the wet 2025-2026 winter (Figure 5 and Figure 6). The concurrent drop in TDS suggests significant seasonal fresh-water recharge entering the deep aquifer through rapid conduit networks, effectively diluting ambient matrix groundwater. Following the spring dilution minimum, TDS levels exhibited a clear upward trend back toward baseline levels, climbing above 313 ppm by August 2026 as irrigation extraction resumed and low-TDS recharge dissipated.

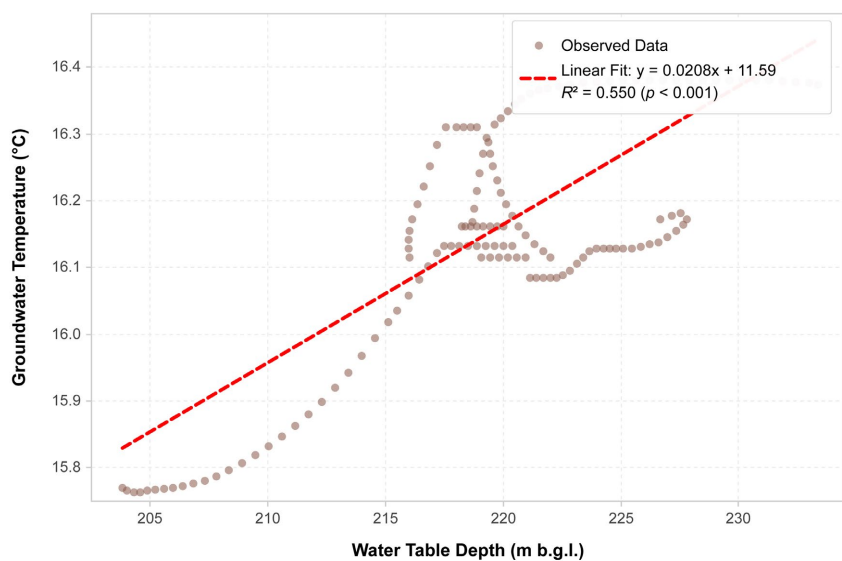


Figure 11. Correlation of temperature vs groundwater depth.

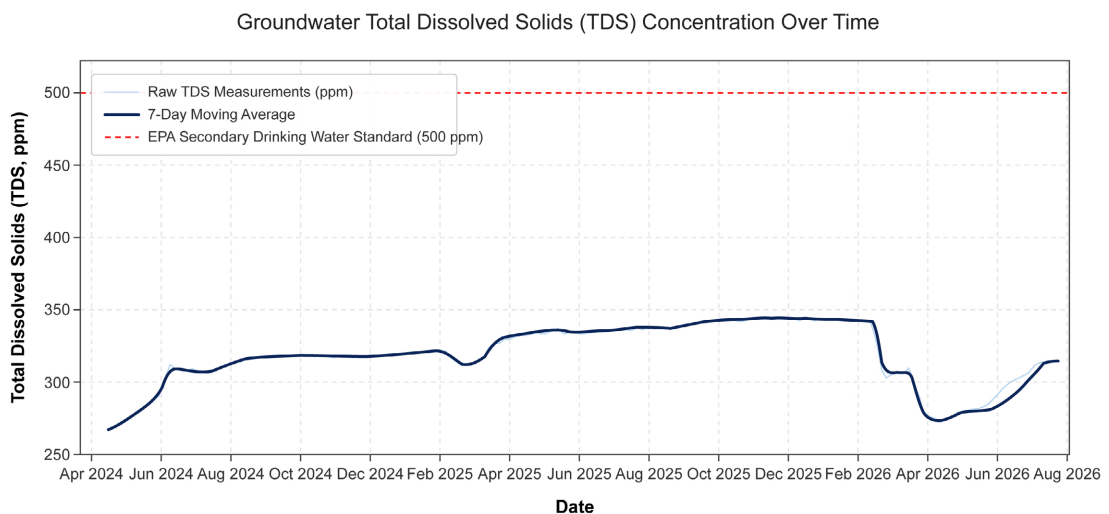


Figure 12. Total Dissolved Solids (TDS) concentrations (measured in ppm) from April 2024 through August 2026.

4. Conclusions

4.1. Seasonal Hydrodynamics and Antecedent Memory Effects

The continuous, multi-year telemetry record at Kfardane establishes that piezometric behavior in the deep Northern Bekaa carbonate aquifer is governed by strong seasonal hydraulic forcing. The consistent sequence of spring-summer drawdown and autumn-winter recovery across 2024, 2025, and 2026 mirrors the local agricultural calendar, where groundwater extraction intensifies during the dry season to meet high crop evapotranspiration demand.

A fundamental hydrogeological insight revealed by the full dataset is the control exerted by antecedent hydraulic baseline on seasonal stress extremes. Although the largest single-season magnitude occurred during summer 2024 ($\Delta h = 19.1$ m), the absolute deepest water level was recorded in July 2025 (233 m b.g.l.). This record low occurred because the system entered the 2025 irrigation season from a severely suppressed recovery baseline (218.58 m b.g.l. in March 2025), driven by the anomalously dry 2024-2025 rainy season (126 mm total rainfall).

Conversely, the higher rainfall during the 2025-2026 wet season (311 mm) drove a 17 m hydraulic recovery by April 2026, which buffered the aquifer during the subsequent 2026 irrigation season. Even after 11.2 m of summer drawdown in 2026, the August 2026 water level (226.4 m b.g.l.) remained 7 m above July 2025 absolute minimum. This contrast emphasizes that single-year drawdown metrics alone are insufficient to diagnose aquifer health; annual water table minimum is heavily governed by multi-year antecedent storage memory.

4.2. Decoupling Hydraulic Head Recovery from Volumetric Replenishment

The dramatic recovery observed between July 2025, and April 2026 highlights a critical nuance in interpreting monitoring-well hydrographs. Water level rises in heavily the observation well reflect two combined mechanisms:

In fractured carbonate aquifers, piezometric head can rebound rapidly upon pumping cessation (pumping from other wells for irrigation in the same aquifer) due to pressure equilibration within high-permeability conduit networks, even before matrix storage is fully replenished. Consequently, water-level recovery in a single monitoring well must not be directly equated with an equivalent volumetric increase in basin-scale groundwater storage.

Converting local head change (Δh) to extracted or recharged water volume requires accurate estimates of aquifer storage parameters alongside an established hydrogeological boundary model. Early analytical methods that multiplied drawdowns by assumed geometric radii of influence overestimate storage depletion by failing to account for well-bore storage, localized skin effects, and boundary conditions.

4.3. Advective Recharge vs. Geothermal Control

The high-frequency downhole temperature record provides crucial physical in-

sights into subsurface transport processes. The dampening of an atmospheric air temperature range exceeding 40°C down to a narrow 0.7°C range in groundwater (15.8 - 16.4°C) demonstrates strong thermal insulation provided by the ~200 m thick unsaturated zone.

Rather than indicating surface thermal contamination, the temporary down-hole cooling spikes observed in February-March 2025 ($\Delta T = -0.34^\circ\text{C}$) and March 2026 ($\Delta T = -0.51^\circ\text{C}$) note that while the cooling trend is consistent with cold-water recharge, localized mixing within the open borehole column remains a possible contributor. Meltwater from high elevation snowpacks and cold winter rainfall enter preferential conduit pathways, temporarily overriding the geothermal background [33] [34]. Once recharged subsides and summer abstraction resumes, thermal conduction from the surrounding rock matrix rapidly restores water temperature to its geothermal equilibrium (~16.2 - 16.4°C).

Because the 400 m observation well is uncased throughout its open interval, measured thermal ($\Delta T = -0.51^\circ\text{C}$) and hydrochemical ($\Delta\text{TDS} = -64.8$ ppm) transients may partially reflect localized water-column mixing and vertical crossflow within the borehole rather than purely regional aquifer flow paths. Ambient head differences between shallow alluvial (qta) and deep karstic (c4) units can induce vertical flow along the open borehole, which can blend ambient geothermal matrix water with rapid conduit recharge.

4.4. Implications for Regional Management and Telemetry Integration

While these findings align with regional remote-sensing assessments showing widespread groundwater stress across the Bekaa Plain [5] [6], this single-well hydrograph provides site-scale temporal resolution that regional satellite models cannot capture.

From a water governance perspective, real-time piezometric telemetry enables adaptive management. Monitoring the rate of spring drawdown ($\Delta h/\Delta t$) allows regional water authorities to anticipate seasonal stress, enact adaptive abstraction quotas, and identify years where winter recovery is insufficient to support full-scale irrigation.

4.5. Study Limitations and Future Research

These hydrogeological conclusions, future monitoring efforts in the Northern Bekaa Valley should address four main limitations: Expanded Observation Network: Instrumentation must be expanded to include dedicated, unpumped observation wells outside active cones of depression to separate regional head trends from localized pumping drawdown. Abstraction Metering: Metered abstraction logs should be integrated with telemetry to directly correlate extracted volumes with head response. Aquifer Parameterization: Controlled pumping tests are required to quantify transmissivity and storage parameters. Geochemical Tracing: Stable isotope and geochemical sampling should be paired with temperature series to

confirm the origin, elevation, and travel times of snowmelt-derived recharge. This study presents a high-frequency telemetry record of groundwater-level and temperature dynamics from a deep borehole in Kfardan, Northern Bekaa Valley, Lebanon. The continuous dataset provides new insight into seasonal groundwater responses in a semi-arid agricultural region where irrigation demand strongly influences groundwater conditions. The monitored borehole exhibited a consistent seasonal pattern, with groundwater levels declining during the warm irrigation period and partially recovering during cooler and wetter months. The largest recorded decline occurred between spring and summer 2025, when groundwater depth reached 233 m below ground level. A subsequent recovery of approximately 17 m occurred by April 2026, demonstrating substantial seasonal hydraulic variability at the monitoring location. Differences between hydrological years highlight the importance of antecedent conditions. The relatively dry 2024–2025 wet season resulted in limited recovery before the following irrigation period, whereas the wetter 2025–2026 season was associated with stronger groundwater-level recovery and reduced summer hydraulic stress. These results demonstrate that seasonal groundwater conditions depend on the interaction between precipitation variability, previous groundwater status, and irrigation demand. Groundwater temperature measurements revealed strong thermal buffering at depth, with groundwater temperature remaining within a narrow range compared with large atmospheric variations. Short-term cooling events during wet periods provide evidence of dynamic groundwater movement and are consistent with the influence of colder recharge water; however, additional hydrochemical and isotopic investigations are required to confirm recharge sources and pathways. The findings demonstrate the value of high-frequency telemetry for identifying seasonal groundwater stress and recovery processes in data-limited semi-arid regions. The Kfardane record provides important site-scale information on how deep groundwater systems respond to irrigation pressure and climatic variability. Overall, continuous groundwater monitoring represents an important tool for improving groundwater management in the Northern Bekaa Valley by providing timely information on seasonal stress, recovery potential, and the need for adaptive water-use strategies.

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Author Contributions

Ihab Jomaa: Conceptualization, study design, methodology, overall coordination, data analysis, and primary drafting of the manuscript. Simone Mereu: Assistance in data analysis. Matteo Funaro: Telemetry integration, and critical revision of the text. Marta Debolini: Hydrogeological framing. Randa Massaad: Gathering relevant hydrogeological and regional references. Sleiman Skaf: Briefing references for the introduction, and manuscript editing.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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