International Journal of
Organizational Innovation

RAINFALL RECHARGE DRIVEN GEOTHERMAL WATER LEVEL FLUCTUATION MECHANISMS AND APPLICATIONS FOR AQUIFER MANAGEMENT IN THE BAOLAI HOT SPRING AREA

Chun-Chi Yang*
Department of Industrial Management, I-Shou University, Taiwan R. O. C.
*Corresponding author: isu11220003D@cloud. isu. edu. tw

Hsiang-Chin Hung
Department of Industrial Management, I-Shou University, Taiwan R. O. C.
seanhung@isu. edu. tw

Abstract

Geothermal water-level dynamics in tectonically active regions are highly sensitive to rainfall-driven recharge processes. This study focuses on the Baolai Hot Spring area in Liugui District, Kaohsiung City, Taiwan, to quantify how seasonal precipitation patterns and fractured lithologies jointly influence geothermal aquifer behavior. Using high-resolution hydroclimatic data from 2017 to 2023, we applied trend detection, cross-correlation, and multiple regression analyses to examine the temporal coupling between rainfall and water-level response. Results show a pronounced bimodal fluctuation pattern, with peaks in Q1 and Q3 driven by monsoonal rainfall, terrace/alluvial infiltration, and fault-guided vertical flow. Recharge consistently lags rainfall by one quarter, indicating multi-stage transmission across permeable fracture networks. Moreover, groundwater levels exhibit a long-term declining trend at −0.093 m per quarter, reflecting an imbalance between natural recharge and extraction. These findings provide a scientific basis for adaptive aquifer regulation and geothermal resource sustainability under climate change, especially in structurally complex mountainous environments.

Keywords: Baolai Hot Spring Area, Rainfall Recharge, Geothermal Water Level Dynamics, Aquifer Management

Introduction

Geothermal energy, as a stable and low-carbon renewable resource, plays a pivotal role in the global energy transition (Lund, Freeston, & Boyd, 2010). The Baolai Hot Spring area in Liugui District, Kaohsiung City, Taiwan, hosts highly mineralized thermal waters that not only ensure a reliable local heat supply but also offer significant potential for geothermal power generation and direct-use applications. However, the sustainable exploitation of this geothermal aquifer critically depends on a thorough understanding of its recharge mechanisms. Climate change–driven alterations in rainfall patterns and intensity pose unprecedented challenges to natural groundwater recharge rates (Taylor et al., 2013). Under these circumstances, quantifying the effects of rainfall recharge processes—namely infiltration, subsurface transport, and return flow—on geothermal aquifer water levels is essential to secure long-term reservoir stability and energy supply reliability. Studies in large catchments and aquifers have demonstrated that climatic variability exerts a significant control on recharge volumes and time lags, while topography, lithology, and catchment structure jointly regulate recharge efficiency (Berghuijs, Woods, Hutton, & Sivapalan, 2017). In the Baolai Hot Spring area, the interplay between typical mudstone lithologies and mountainous catchment recharge yields unique water-level dynamics (Maity et al., 2011). Investigating the seasonal recharge responses and associated lag effects in this region will provide the theoretical foundation for optimizing monitoring network design and withdrawal scheduling strategies, thereby balancing sustainable geothermal development with ecological conservation. Driven by the dual imperatives of global energy transition and sustainable water resource management, quantifying rainfall-recharge–driven geothermal water-level fluctuation mechanisms and applying these insights to aquifer management carries profound scientific and practical significance. This study not only fills a critical research gap concerning geothermal recharge processes in Southern Taiwan but also furnishes essential support for the resilient and efficient utilization of geothermal resources.

Recent international investigations into aquifer recharge and water-level response have placed considerable emphasis on both time-domain and frequency-domain analytical approaches. Guillaumot et al. (2022) applied frequency-domain analysis to reveal how intense rainfall events and the thickness of overlying mud layers control recharge rates and ensuing water-level oscillations, identifying soil layer thickness as a key regulator of short-term fluctuations. Turkeltaub and Bel (2023), in turn, used long-term precipitation and evapotranspiration statistical descriptors as independent variables to systematically assess the sensitivity of recharge estimates to evapotranspiration parameterization in semi-arid regions. Furthermore, global-scale modeling studies have demonstrated that infiltration variability across multiple temporal scales can induce cyclic recharge patterns and have elucidated the coupled mechanisms linking evapotranspiration, surface runoff, and aquifer recharge processes.

Although the aforementioned studies encompass a wide range of geomorphic and hydrological settings, most have concentrated on freshwater aquifers in agricultural or arid regions, leaving topic-specific quantitative analyses of geothermal systems largely insufficient. Mueller et al. (2023) observed that aquifer water levels worldwide often exhibit accelerated declines in agricultural areas, yet investigations into recharge–evaporation balance characteristics and seasonal mismatches in geothermal zones remain sparse. Furthermore, the interplay between regional geological structures, geothermal fluid convection patterns, and rainfall infiltration distributions still lacks a comprehensive explanatory framework that integrates in-situ measurements with numerical modeling (Xu, Li, Wang, & Zhang, 2023).

To fill this research gap, the present study employs the Baolai Hot Spring area as a case study, utilizing high–temporal- resolution monitoring data to quantitatively elucidate the mechanisms by which rainfall recharge drives water-level fluctuations in the geothermal aquifer and to develop targeted hydrogeological management strategies. The findings are expected to support geothermal water-level forecasting, intelligent aquifer operation scheduling, and the optimization of long-term monitoring networks, thereby providing a robust scientific foundation for the sustainable exploitation of geothermal resources and ecological risk management (Pan, Zhang, Liu, & Wang, 2024).

Literature Review

Conduct a literature review on Baolai hot spring Area, rainfall recharge, Geothermal Water Level Dynamics, Hydrogeology, Aquifer management and in relation to the research topic and objectives.

Geological Settings

Baolai Hot Spring is located on the southwestern foothills of Taiwan, marking the frontal zone of the Central Range formed by the collision between the Eurasian and Philippine Sea plates. The area is bounded to the west by the active Chaozhou reverse fault, which delineates the western foothill belt from the metamorphic core of the Central Range. Of particular importance is the Meilongshan Fault, a branch of the Chaozhou Fault: geophysical surveys have shown that deep-seated hydrothermal fluids ascend along both flanks of this fault, supplying the discharge of shallow hot springs. Most Baolai springs emerge on the upthrown block of the Meilongshan Fault, where deep hydrothermal waters are guided toward the surface by fault impermeability, whereas the downthrown block conceals deeper geothermal reservoirs. Rapid uplift and erosion associated with plate collision have reduced the basement depth in the Baolai area to approximately 3–5 km, resulting in an elevated regional geothermal gradient. This tectonic setting explains the existence of Baolai’s hot springs: abundant high-elevation precipitation infiltrates through fracture networks, interacts with shallowly buried, high–geothermal-gradient metamorphic bedrock and fault conduits, and generates subsurface thermal water that ultimately discharges at the surface. Elucidating the mechanisms of rainfall-

recharge–driven geothermal water-level fluctuations in Baolai is essential for assessing the stability of spring resources under climate change and provides critical scientific foundations for sustainable aquifer management and geothermal energy development.
The characteristic geothermal spring network in Baolai results from the synergistic interaction of high- permeability lithologic recharge units, structurally controlled fracture networks, and a persistent regional hydraulic gradient: concentrated recharge → deep heating → rapid ascent along fault conduits → emergence at structural and lithologic interfaces. Fault architecture Shallow hydrological circulation and geothermal fluid migration are chiefly governed by the region's principal fault zones and subsidiary splays. High-angle reverse fault (Chaozhou Fault): Shown as black dashed lines, this NE–SW-trending, left-lateral reverse fault marks the boundary between the western foothill belt and the lightly metamorphosed core of the Central Range.

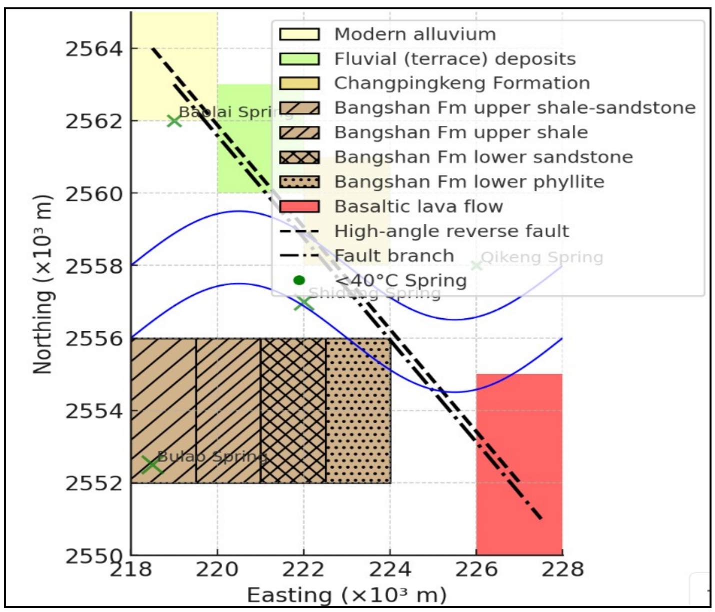

Figure 1. Schematic plan view of the geological framework and groundwater–geothermal system in the Baolai area.

Deep hydrothermal fluids preferentially ascend along its highly fractured damage zone.

Fault branches: Depicted by black dot-dashed lines, these secondary fracture splays diverge from the main fault, channeling groundwater into specific stratigraphic horizons. At intersections between the main fault and its branches, permeability is maximized, giving rise to clustered spring vents. An overlying, dense basaltic caprock to the east impedes vertical flow, diverting fluids laterally along fracture corridors at the caprock margin and producing locally elevated spring temperatures.

Hydraulic head contours:
Two blue lines show head contours deflected at fault crossings. Head decreases from NW to SE, indicating net flow toward the southeastern thermal reservoir.

Spring distribution:
• × (green): Major high-temperature springs (Baolai, Qikeng, Shiding, Bulao).
• ● (green): Low-temperature springs (< 40 °C).
All align with faults or splays, confirming fractures as primary fluid pathways; emergence shifts to fracture margins beneath the basalt cap.
Lithologic units:
• Modern alluvium (pale yellow): Western high-permeability recharge.
• Fluvial terraces (pale green): Adjacent recharge aquifer.
• Changpingkeng Fm (light brown): Moderate permeability sedimentary rocks.
• Bangshan Fm: Four subunits (shale–sandstone, shale, sandstone, phyllite).
• Basaltic lava (red): Dense, fractured caprock sealing the reservoir.

Rainfall Recharge

Rainfall recharge refers to the process by which surface precipitation infiltrates through soil or rock fractures into geothermal aquifers. In the Baolai Hot Spring area, the average annual precipitation is approximately 3,500 mm (mostly between May and September), which rapidly recharges the aquifers: water percolates downward, is heated at depth, and then rises as hot springs under structural control. Hydrochemical and isotopic investigations in the Xiamen region confirm that mountainous geothermal waters are primarily sourced from rainfall (Wang et al., 2022), while δ^2H–$\delta^{18}O$ data from Indonesia's Ulubelu field quantify the depths of fracture-guided recharge (Iqbal et al., 2023). Chen et al. (2024) introduced a thermal-pulse tracking model that links temperature differentials to flow velocities and thermal-signal attenuation, providing a robust scientific framework for aquifer management in Baolai.

Geothermal Water Level Dynamics

Geothermal water level denotes the elevation of groundwater within geothermal reservoirs or spring aquifers, reflecting subsurface pressure and storage capacity, and is primarily sustained by atmospheric precipitation recharge.

Precipitation infiltrates the subsurface, is heated at depth, and reemerges as springs; consequently, fluctuations in geothermal water level are intrinsically tied to rainfall recharge. Serianz et al. (2025) performed a hydrogeological analysis of a low-temperature geothermal aquifer in the Julian Alps of Slovenia, demonstrating that topographic forcing and geological structures jointly regulate the vertical rise and spatial distribution of thermal waters. Picourlat et al. (2025) developed the AquaVar decision-support system—an integrated hydrological, hydraulic, and hydrogeological modelling framework—to simulate the impact of extreme precipitation events on groundwater levels; its application to the Mediterranean Var watershed in southern France showed that scenario-based recharge simulations can accurately predict groundwater responses, thereby informing sustainable geothermal resource management. Chen et al. (2024) introduced a thermal-tracking method that leverages temperature differentials induced by rainfall to estimate lateral groundwater velocities, elucidating the mechanistic link between precipitation events and geothermal water-level dynamics.

Aquifer Management

Aquifer management Aquifer management is fundamentally based on mechanistic analysis, aiming to optimize the configuration of monitoring networks and the development of groundwater level regulation strategies to support the sustainable utilization of geothermal resources. Effective management helps prevent issues such as abrupt groundwater drawdown caused by overextraction. In geothermal systems, this requires maintaining a balance between groundwater withdrawal and natural recharge to ensure stable water levels and the sustained discharge of geothermal wells and hot springs. In geothermally active regions such as the Baolai Hot Spring area, aquifer management strategies are especially critical. Hałaj et al. (2022) demonstrated that Aquifer Thermal Energy Storage (ATES) can be effectively implemented even in low-permeability formations, provided that appropriate injection and extraction techniques are employed.

Sufyan et al. (2024) investigated Managed Aquifer Recharge (MAR) as a sustainable groundwater management approach, emphasizing the integration of water rights frameworks, interdepartmental coordination, dynamic scheduling mechanisms, and indicator-based performance evaluation systems. Aquifer Recharge (MAR) as a sustainable groundwater management approach, emphasizing the integration of water rights frameworks, interdepartmental coordination, dynamic scheduling mechanisms, and indicator-based performance evaluation systems. Sloan et al. (2023) reviewed the application of MAR in the mining sector and found Sloan et al. (2023) reviewed the application of MAR in the mining sector and found that subsurface injection and infiltration basins can effectively manage surplus water and mitigate the impact of pumping on aquifer systems. Formulating aquifer management strategies that subsurface injection and infiltration basins can effectively manage surplus water and mitigate the impact of pumping on aquifer systems. Serianz et al. (2025) further highlighted the necessity of incorporating topographic and geological considerations

Methods

To quantify the mechanisms by which rainfall recharge governs groundwater-level fluctuations in the Baolai geothermal aquifer and to formulate effective management strategies, this study employs a three-tiered methodology:

1. Literature Review
Compile and synthesize existing hydrogeological and meteorological monitoring studies of geothermal spring areas.

2. Time-Series Alignment & Quality Control Acquire hourly precipitation records (2017–2024) from the Baolai Hot Spring regional meteorological station. Concurrently process well water-level time series by removing outliers and linearly interpolating data gaps ≤ 6 h to construct a continuous, reliable surface-recharge flux dataset.

3. Statistical Analysis
Trend Detection: Apply the Mann–Kendall test and Sen's slope estimator to quantify long-term trends and rates of change in both water levels and rainfall. Correlation & Regression: Use multiple linear regression to assess the contributions of daily and weekly cumulative rainfall to water-level dynamics, and employ cross-correlation functions to reveal temporal lags between recharge events and aquifer responses. This integrated framework rigorously quantifies the hydro-thermodynamic behavior driven by rainfall recharge and provides a solid scientific basis for aquifer- management decision making.

Results

Figure 2 demonstrates:

1. Season al Bimodal Fluctuations
Groundwater levels in the Baolai geothermal aquifer show a seasonal bimodal pattern, peaking at 404–407 m in Q1 and Q3, and dropping to 398–399 m in Q2 and Q4. This reflects a delayed recharge process via high-permeability terrace/alluvial layers. The response is shaped by surface permeability, fault conduits, and monsoonal rainfall patterns.

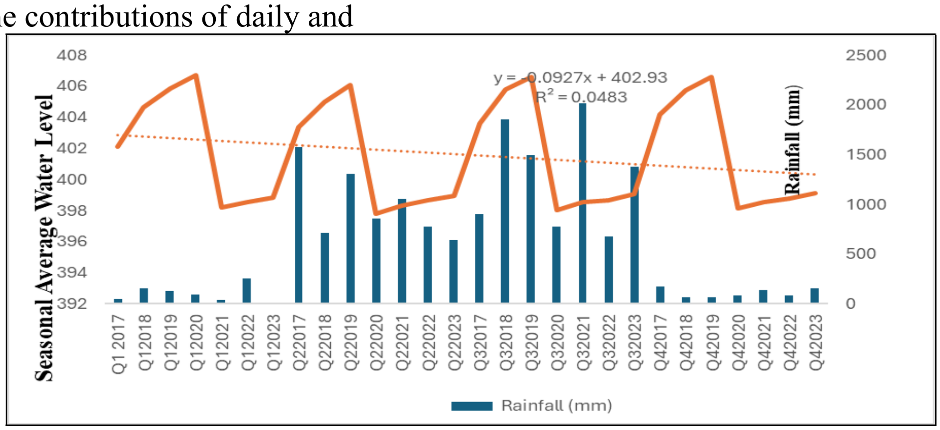

Figure 2. Table of Historical Seasonal Average Water Levels and Rainfall at the Baolai Hot Spring Area from Q1 2017 to Q4 2023

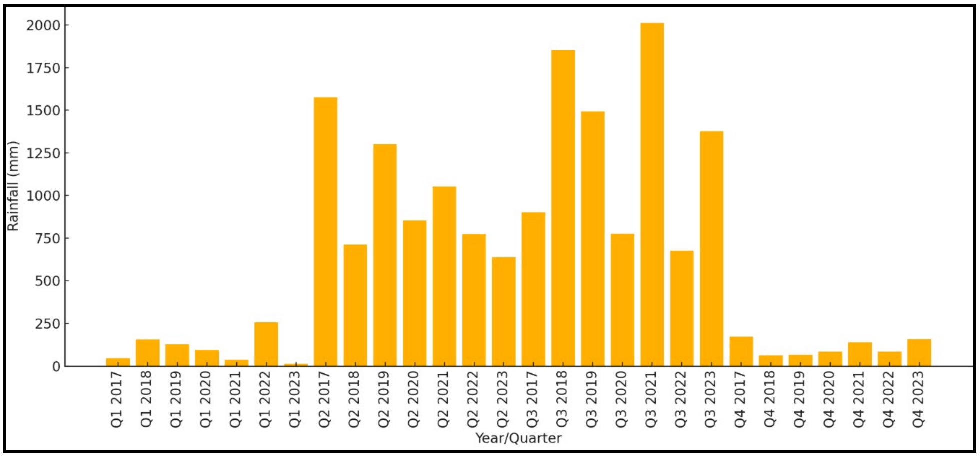

Figure 3. Quarterly Rainfall Statistics for the Baolai Hot Spring Area (Q1 2017–Q4 2023)

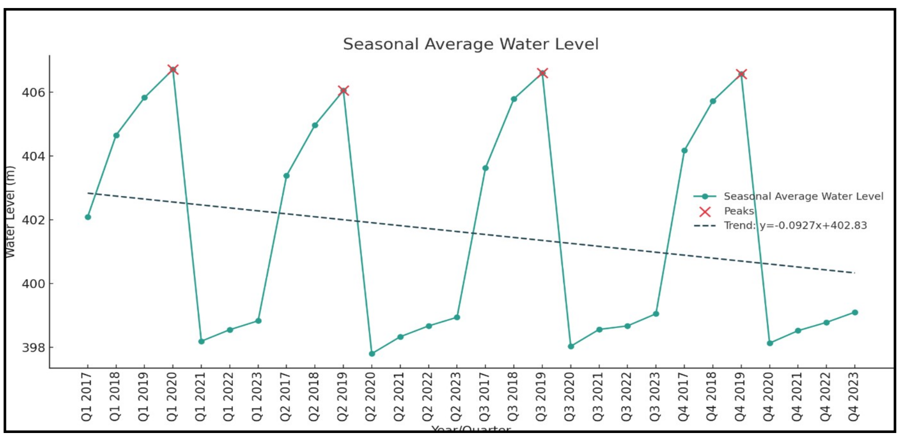

Figure 4. Seasonal Average Water Level Trends in the Baolai Hot Spring Area (Q1 2017– Q4 2023)

Figure 3 illustrates the pronounced seasonality of rainfall in the Baolai area, with Q2 and Q3 representing the primary wet seasons and Q1 and Q4 corresponding to drier periods. Rainfall infiltrates through terrace and alluvial deposits and typically reaches the geothermal aquifer with a one-quarter lag, resulting in a distinct recharge delay. In certain years, such as 2020 and 2022, below-average rainfall during Q2/Q3 may have led to insufficient groundwater recharge, highlighting a potential imbalance between recharge and extraction in the geothermal system.

2. Recharge Lag Phenomenon

Groundwater level peaks lag rainfall maxima by about one quarter, reflecting a multi-stage recharge process involving surface infiltration, lateral flow, and fault-guided vertical migration. This delay highlights the phased hydrologic response to seasonal rainfall.

3. Long-Term Decline in Groundwater Levels
A linear water-level decline of –0.0927 m/quarter ($R^2 = 0.0483$) has resulted in a >2 m drawdown over six years. This trend indicates persistent over-extraction relative to natural recharge, signaling potential depletion and the need for sustainable aquifer management.

Figure 4 illustrates the green solid line of water levels with a deep blue dashed linear trend, and red "×" marking biannual peaks:

1.Biannual Cycle
Water levels peak in Q1 and Q3 (~404–407 m), lagging one season behind rainfall in Q4 and Q2.
Troughs in Q2 and Q4 (~398–399 m) reflect reduced recharge during drier periods.

2.Recharge Lag
Peak levels lag rainfall by one quarter, e.g., Q2 rains raise Q3 levels.

3.Long-Term Decline
Trendline ($y = -0.0927x + 402.83$, $R^2 = 0.0483$) shows a slow decline (~0.093 m/quarter), totaling over 2 m drop in 6 years, suggesting recharge–extraction imbalance.

Conclusion

Our analysis of the Baolai geothermal aquifer revealed three key dynamics:

1. Seasonal Bimodal Fluctuations
Groundwater levels peak at 404–407 m in Q1 and Q3 and drop to 398–399 m in Q2 and Q4, driven primarily by recharge through terrace/alluvial deposits, fault conduits, and monsoonal rainfall.

2.Recharge Lag
Peak water levels lag peak rainfall by one quarter, reflecting a multi-stage transmission process involving shallow infiltration and fault-guided vertical flow.

3.Long-Term Decline Trend
Water levels have been declining at –0.0927 m per quarter (approximately 2 m over six years), indicating that extraction continues to exceed natural recharge.

References

Berghuijs, W. R., Woods, R. A., Hutton, C. J., & Sivapalan, M. (2017). Large-scale controls on groundwater recharge: Insights from streamflow modelling. Advances in Water Resources, 102, 103–120. doi:org/10.1016/j.advwatres.2016.12.009

Chen, K., Guo, Z., Yin, M., Liang, X., Chang, Z., Yang, S., Jiang, X., & Zheng, C. (2024). Using rainfall-induced groundwater temperature response to estimate lateral flow velocity. Water Resources Research, 60(11), e2023WR036715. doi:org/10.1029/2023WR036715

Hałaj, E., Pająk, L., & Papiernik, B. (2022). Simulation study of the Lower Cretaceous geothermal reservoir for aquifer thermal energy storage. Environmental Geochemistry and Health, 44, 2253–2279. doi:org/10.1007/s10653-021-01130-7

Huang, S.-Y., Lin, L.-H., & Kuo, C.-H. (2024). Geological characteristics and exploration potential of the Baolai geothermal area. Ti-Chih (Geology), 43(1), 36–41. doi:org/10.1016/j.jvolgeores.2017.05.016

Iqbal, M., Al-Hassan, M. A., Herdianita, N. R., & Juliarka, B. R. (2023). Determining recharge area in ULUBELU geothermal field, LAMPUNG, Indonesia using stable isotope data. Applied Geochemistry, 156, 105763. doi:org/10.1016/j.apgeochem.2023.105763

Jiang, C., Wang, X., Pu, S., & Jourde, H. (2022). Incipient karst generation in jointed layered carbonates: Insights from three-dimensional hydro-chemical simulations. Journal of Hydrology, 610, 127831. doi:org/10.1016/j.jhydrol.2022.127831

Kmec, J., & Šír, M. (2024). Modeling 2D gravity-driven flow in unsaturated porous media for different infiltration rates. Hydrology and Earth System Sciences, 28, 4947–4970. doi:org/10.5194/hess-28-4947-2024

Lund, J. W., Freeston, D. H., & Boyd, T. L. (2010). Direct utilization of geothermal energy 2010 worldwide review. Geothermics, 39(3), 189–208. doi:org/10.1016/j.geothermics.2010.03.002

Maity, J. P., Liu, C.-C., Nath, B., Bundschuh, J., Kar, S., Jean, J.-S., Bhattacharya, P., Liu, J.-H., Atla, S. B., & Chen, C.-Y. (2011). Biogeochemical characteristics of Kuan-Tzu-Ling, Chung-Lun and Bao-Lai hot springs in southern Taiwan. Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering, 46(11), 1207–1217.doi: 10.1080/10934529.2011.598788.

Martín-Rodríguez, J. F., Mudarra, M., De la Torre, B., & Andreo, B. (2023). Towards a better understanding of time-lags in karst aquifers by combining hydrological analysis tools and dye tracer tests.

Journal of Hydrology, 621, 129643. doi:org/10.1016/j.jhydrol.2023.129643

Picourlat, F., Tallé, H. A., Abily, M., & Billaud, F. (2025). AquaVar decision support system for water resource management: Lessons learned from the first five years of operation. River Research and Applications, 41(2), 120–135. doi:org/10.1002/rvr2.120

Serianz, L., Markelj, A., Rman, N., & Brenčič, M. (2025). Hydrogeological analysis of topography-driven groundwater flow in a low temperature geothermal aquifer system in the Julian Alps, Slovenia. Hydrogeology Journal, 33, 237–256. doi:org/10.1007/s10040-024-02866-zSpringerLink

Sloan, S., Cook, P. G., & Wallis, I. (2023). Managed Aquifer Recharge in Mining: A Review. Groundwater, 61(4), 511–523. doi:org/10.1111/gwat.13311 ngwa.onlinelibrary.wiley.com +1ngwa.onlinelibrary.wiley.com+1

Sufyan, M., Martelli, G., Teatini, P., Cherubini, C., & Goi, D. (2024). Managed aquifer recharge for sustainable groundwater management: New developments, challenges, and future prospects. Water, 16(22), 3216. doi:org/10.3390/w16223216

Taylor, R. G., et al. (2013). Ground water and climate change. Nature Climate Change, 3(4), 322–329. doi:org/10.1038/nclimate1744

Wang, B., Li, X., & Zhang, Y. (2022). Effects of seawater recharge on the formation of geothermal reservoirs in Xiamen, China. Frontiers in Earth Science, 10, 872620. doi:org/10.3389/feart.2022.872620