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GROUNDWATER LEVEL DYNAMICS AND ESG SUSTAINABILITY MANAGEMENT STRATEGIES UNDER THE INTERACTIVE EFFECTS OF FAULT- FOLD STRUCTURES AND CLIMATE VARIABILITY: A CASE STUDY OF GUGUAN HOT SPRING

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Abstract

This study uses the Guguan Hot Spring in Taichung City as a case study to examine how fault-fold structures and climate variability influence groundwater-level dynamics, while proposing geothermal resource management strategies aligned with ESG sustainability principles. By integrating fault-fold mapping, long-term hydrological monitoring, and climate indicators, a quantitative interaction model was developed to elucidate the relative contributions of structural and climatic factors to groundwater recharge, flow, and thermal fluid transport.

The results show that geological structures play a dominant role in regulating groundwater dynamics and thermal conditions, whereas precipitation indirectly affects hot spring temperatures through groundwater-level fluctuations. This study highlights the need for continuous high-resolution monitoring and community engagement to address challenges posed by extreme climate events and urbanization, thereby ensuring the sustainable use of geothermal resources and environmental protection. The integrated framework not only deepens the understanding of geothermal system mechanisms but also provides policy guidance for water resource management in similar geological settings.

Keywords: Fault fold structure, Climate Variability, Thermal Groundwater level, ESG Sustainability Management, Guguan Hot Spring

Introduction

This study uses the Guguan Hot Spring in Taichung City, Taiwan as a case study to investigate how the interactive effects of fault-fold structural deformation and climate variability drive groundwater-level dynamics, and to derive implications for ESG-aligned sustainable management strategies.

Groundwater resources are a critical component of natural environments, underpinning regional ecosystem health and directly influencing socio-economic activities and long-term environmental sustainability (Taylor et al., 2013). Concurrently, as climate variability and broader environmental concerns receive increasing global attention, ESG (Environmental, Social, and Governance) frameworks have emerged as essential guides for both corporate and public resource-use planning (Eccles et al., 2014). By integrating groundwater dynamic analysis with ESG principles, this research not only advances theoretical understanding in hydrogeology and structural geology, but also provides practical policy guidance for regional sustainability planning.

Groundwater systems respond to a complex interplay of geological structures and climatic forces, with their dynamic fluctuations governing recharge, flow pathways, and storage capacity (Neuman, 2005). Structural features such as faults and folds not only define the geometry and porosity of subsurface aquifers, but also dictate preferential flow channels that modulate aquifer connectivity and hydraulic gradients. Meanwhile, climate variability alters precipitation regimes and recharge conditions, inducing temporal shifts in water-table elevations. The coupled influence of these factors generates multi-scale, heterogeneous groundwater responses that challenge conventional water-resource management and necessitate novel ESG-informed governance approaches.

In this study, we synthesize detailed fault-fold mapping, long-term hydrological monitoring records, and climate variability indices to construct a quantitative interaction model that isolates the relative contributions of structural and climatic drivers to groundwater-level fluctuations in the Guguan Hot Spring area. We then evaluate the mechanistic pathways through which these drivers modulate thermal aquifer behavior and spring discharge. Drawing on these insights, we propose a suite of sustainable management measures grounded in ESG principles that are tailored to geothermal-rich regions, emphasizing adaptive recharge enhancement, structural informed zoning, and stakeholder engagement.

Given the mounting pressures of climate change and escalating demands on groundwater resources, this research articulates an actionable, ESG-compliant groundwater management framework that explicitly incorporates the co-influence of tectonic deformation and climate variability. By deepening scientific understanding of these coupled processes and translating them into practical governance instruments, our findings offer a replicable blueprint for sustainable groundwater stewardship in analogous geologically complex regions.

Literature Review

Conduct a literature review on fault fold tectonic, climate variability, thermal groundwater level, ESG Sustainability Management, and the Guguan Hot Spring, integrating these topics with the study's overall research objectives.

Fault Fold Structure

Tectonic deformation creates fault zones that form high-permeability conduits, accelerating groundwater flow and causing localized water level anomalies (Chen & Hu, 2010). Folding modifies stratigraphic dip angles and thicknesses, affecting groundwater storage distribution. In the Guguan Hot Spring region, the interplay between faulting and folding produces a heterogeneous groundwater system that is closely linked with hydrothermal circulation. Recent studies indicate that fault fracture zones act as primary pathways for rapid groundwater transport (Wang, Zhang, & Chen, 2020), while climate variability—especially precipitation changes—strongly influences groundwater recharge in these structurally controlled settings (Li et al., 2021). Consequently, geological structures not only dictate subsurface flow dynamics and aquifer characteristics but also affect water quality distribution. Additionally, research by Scannell and Gifford (2020), Fronzi et al. (2021), Pradhan et al. (2022), Reinecke et al. (2021), and Zhou and Kuang (2024) further emphasizes that understanding the combined effects of tectonic deformation and climate forcing is critical for ESG-oriented sustainable water management.

Climate Variability

Climate variability alters recharge, evapotranspiration, and subsurface flow, causing groundwater declines of ~0.5 m per year in semi-arid aquifers under RCP4.5/RCP8.5 (Fallahi et al., 2023). Under RCP4.5, major aquifers could see a 7–11% reduction in water table depths by 2050 (Costantini et al., 2023). Gumuła Kawęcka et al. and Khadim et al. (2023) found that drought in northern Poland reduces recharge in shallow glacial aquifers—similar to effects seen in geothermal systems—while in Ethiopia, climate-driven depletion lowers baseflow and heightens seasonal spring discharge variability. Moreover, Ndehedehe et al. (2023) showed that tropical and temperate geothermal aquifers are highly sensitive to interannual climate oscillations, with recharge elasticity exceeding 0.6. In Texas, Yang and Bertetti (2023) reported that a 10% annual precipitation drop leads to a 6% decrease in groundwater levels in fault-controlled aquifers, and Diancoumba et al. (2023) observed that extreme wet-dry cycles in Mali increase intra-annual water table fluctuations by over 25%. Bresinsky et al. (2023) projected that, under the SSP5-8.5 scenario (Hausfather & Peters, 2024), thermal spring discharge in Mediterranean karst aquifers could drop by 9–14% by 2050. Overall, these studies underscore that changes in precipitation and temperature significantly affect geothermal groundwater levels. For sustainable ESG management of Guguan Hot Springs, integrating high-resolution climate projections with fault/fold mapping and real-time monitoring is essential to guide water strategies, protect resources, and enhance resilience.

Thermal Groundwater Level

In geothermal settings, the "thermal groundwater level" is the elevation of the saturated zone in the main aquifer that supplies hot spring water. It marks where pore water pressure equals atmospheric pressure and is controlled by climate (precipitation and recharge), geological conductivity, and human withdrawals. While several aquifer layers may exist, this term refers only to the extensive, continuously saturated layer that actively delivers geothermally heated water, which is essential for resource management. Against the backdrop of accelerating climate change and urbanization, groundwater resource variability has emerged as a critical concern in hydrology, geology, and environmental management. Groundwater level in geothermal zones a key indicator of hot-spring resource availability is governed not only by hydrological drivers (precipitation, aquifer permeability, pumping) but also by regional geologic structures (faults and folds). The combined influence of fault-fractured zones and folding produces pronounced stratification and heterogeneity in groundwater flow, presenting elevated demands on spring water quality, hydrothermal dynamics understanding, and resource governance. As Environmental, Social, and Governance (ESG) principles increasingly inform resource management, balancing sustainable utilization with environmental protection and social benefit constitutes a new challenge—and opportunity—for geothermal resource management (Yang & Li, 2025).

Recent research highlights the interplay of geologic structure and climate variability in controlling thermal groundwater levels, which is vital for ESG-based sustainability management. Yang and Bertetti (2023) showed that fault-folding in Texas aquifers creates high-permeability conduits that trigger localized water table anomalies, emphasizing the need for structural controls in groundwater governance. Fallahi et al. (2023) found that shifts in precipitation seasonality can reduce recharge by up to 0.5 m/year in semi-arid aquifers, stressing geothermal resources. In Mediterranean karst regions, Bresinsky et al. (2023) projected that under the SSP5 8.5 scenario, declining precipitation could lower hot spring discharge by 9–14% by mid-century. Eccles, Ioannou, and Serafeim (2021) argue that integrating environmental stewardship into resource planning enhances long-term resilience, while case studies by Li, Zhang, and Wang (2022) and Chen, Wang, and Lee (2024) demonstrate that combining structural mapping with climate forecasts can optimize geothermal resource allocation and adaptive management.

ESG Sustainability Management

ESG sustainability management is critical for water resource strategies, emphasizing long-term groundwater protection (Golovina et al., 2021). Golovina et al. propose an integrated legal, technical, and participatory approach for transboundary aquifer management. Climate change strongly influences groundwater recharge and water table stability; Reinecke et al. (2021) highlight high uncertainty in recharge projections under warming scenarios, and Döll et al. (2020) show that human extraction and reservoir operations amplify groundwater storage fluctuations. Effective ESG strategies also require stakeholder participation and risk assessment, as demonstrated by Kneier et al. (2023) and Herbert and Döll (2021), who identify the heightened vulnerability of transboundary aquifers. Finally, model uncertainty analyses by Reinecke et al. (2024) and high-resolution observations by Yang et al. (2025) underscore the need for cautious interpretation of groundwater models in sustainable water resource management.

Collectively, these studies indicate that ESG sustainability management strategies should: (1) integrate multi- model projections with field observations in a comprehensive monitoring system; (2) foster cross-sectoral collaboration and participatory risk assessment; (3) establish flexible management targets that explicitly account for uncertainty; and (4) reinforce policy and regulatory frameworks to ensure long-term groundwater availability. Future research should prioritize model validation, data transparency, and innovative financial and social mechanisms to operationalize ESG principles in groundwater sustainability.

Guguan Hot Spring

Geological Settings.

In the Guguan area, hot spring recharge is primarily derived from precipitation: rainfall infiltrates deeply into the subsurface, is heated by the regional geothermal gradient, and then gradually ascends to the surface to emerge as hot springs. The spatial distribution of geothermal flow paths is constrained to the structural corridor defined by the Guguan Fault and its subsidiary minor faults (Figure 1), with geothermal reservoirs occurring at depths of approximately 60–600 m below ground surface. Drilling records further indicate that practical well depths range from 70 to 550 m (Figure 2), representing the technically feasible interval for exploitation. Based on historical spring emergence patterns and current withdrawal practices, the 60–600 m depth interval is therefore identified as the primary target zone for geothermal resource development in the Guguan hot spring area.

Figure 1. The ellipse denotes the primary conduit for geothermal fluids, which is tightly constrained by the Guguan Fault and its subsidiary minor faults. The observed spring discharge area lies centrally within this fault corridor, demonstrating that these structurally weakened zones not only facilitate vertical migration of heated groundwater but also locally focus its emergence. When combined with literature identifying a 60–600 m depth interval as the target reservoir zone, it can be inferred that The fractured fault zone within this depth range provides the principal porosity and permeability for hot-spring storage and transport. The aerial view further reveals a narrow, north–south–trending network of folds and faults along the Dajia River valley, serving as an efficient ascent pathway for deep-heated groundwater.

Figure 2 presents a geological cross-section with the hot spring well at about 700 m elevation. Four sedimentary units are present—from top to bottom: siliceous sediment, siliceous sandstone–shale, Triassic sandstone–shale interbeds, and a lower siliceous layer. The Guguan Fault fracture zone, outlined by dash-dot lines, features intensely fractured rock that forms a high-permeability pathway for geothermal fluids, with the well positioned at its base. An eastward principal fault juxtaposes different stratigraphic blocks and controls lateral groundwater flow, collectively confining geothermal fluids until they discharge at the well (Water Resources Agency, Executive Yuan, 2002).

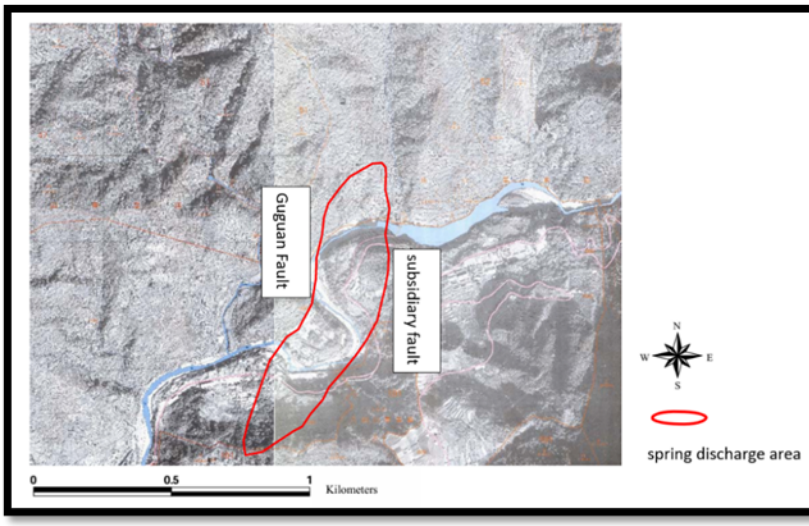

Figure1: Structural control and flow-path

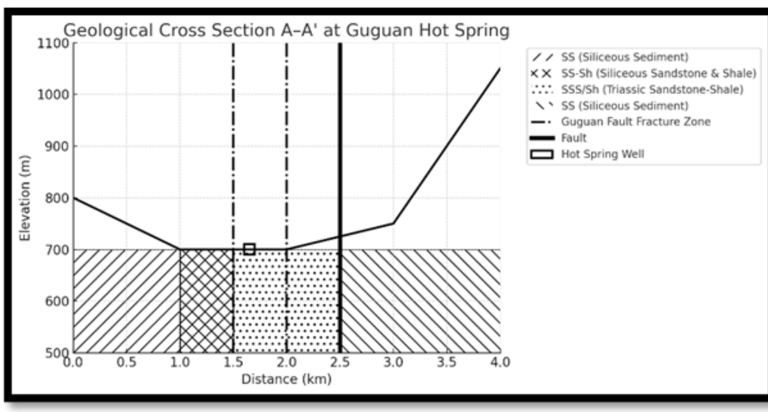

Figure 2: presents the detailed geological cross section along the A–A′ transect through the Guguan Hot Spring area.

The geothermal water storage capacity in the Guguan area was estimated using the volumetric method. The storage capacity is calculated by multiplying the volume of the geothermal flow zone by its effective porosity, according to the following equation:

$Q = V \times N$

- Q:geothermal water storage capacity (m^3)
- V:volume of the geothermal flow zone (m^3)
- n : effective porosity (%)

The geothermal conduit in the Guguan area encompasses an area of approximately 1.4 km² (1.4 × 106 m²). Assuming a reservoir thickness of 300 m (based on geological cross-sections) and an effective porosity of 5%, The estimated geothermal water storage capacity is approximately 21 million cubic meters (21 × 106 m³).

Methods

Hot spring monitoring is a critical approach to elucidating the dynamic internal changes within hot spring regions. This study aims to investigate the interactions between groundwater levels and precipitation factors in the Guguan hot spring area,as well as the regulatory effects of faults and folds on groundwater movement. Drawing on principles from geology, hydrology, and ESG theory, an integrated management strategy is developed to promote the sustainable development of hot spring resources. Procedural Steps Data Collection (2022–2024): Groundwater levels are acquired from monitoring wells in Guguan, and long-term precipitation records are obtained from the Meteorological Agency of the Ministry of Transportation. Ensuring Temporal and Spatial Representativeness: The raw data are scrutinized and organized to ensure completeness and reliability. Data Analysis: Trend Analysis (Time Series): Quantify the temporal trends in groundwater level changes. Correlation Analysis: Assess the statistical relationship between precipitation and groundwater levels.

Multiple Regression Modeling.

Employ precipitation and geological structure parameters (e.g., faults, folds) as independent variables, with groundwater level changes as the dependent variable, to quantitatively evaluate the contributions and interactions of each factor. Quantitative Evaluation and Validation of Fault and Fold Effects: Model results are used to ascertain the regulatory influence of faults and folds on groundwater movement, providing a basis for subsequent management of hot spring resources.

Results

Figure 3 demonstrates a low correlation ($R^2 = 0.0148$) between monthly rainfall and average monthly groundwater level, indicating that the groundwater level in this region does not exhibit an immediate response to rainfall variations. This limited sensitivity may be attributed to factors such as aquifer depth, geological structure, and recharge pathways.

Figure 4 shows a high correlation ($R^2 = 0.9238$) between average monthly groundwater level and average monthly hot spring water temperature, suggesting that as groundwater levels gradually rise, hot spring water temperature increases concurrently.

These findings imply that hot spring water temperature is more sensitive to fluctuations in groundwater levels, likely due to mixing processes of hot and cold waters within the geothermal system and the dynamics of geothermal fluid recharge. From a hot spring resource management perspective, understanding this strong coupling relationship is crucial for predicting temperature trends and devising appropriate recharge strategies and conservation measures.

Conclusion

Our study in the Guguan Hot Spring area revealed key interactions among rainfall, groundwater levels, and hot spring temperatures. Figures 3 and 4 indicate a weak correlation between rainfall and groundwater levels—suggesting a delayed response due to aquifer depth, complex geological structures, and recharge pathways. In contrast, a strong positive correlation exists between groundwater levels and hot spring temperatures, indicating that the thermal regime is mainly governed by groundwater dynamics. This underscores the pivotal role of geological structures, particularly fault-fold zones, in regulating geothermal systems. Although rainfall affects groundwater recharge, its impact on hot spring temperature is primarily indirect through groundwater fluctuations that drive water mixing and energy exchange.

From an ESG sustainability perspective, these interactions pose challenges for geothermal resource management amid extreme climate events and shifting rainfall patterns. To mitigate risks, further research on fault-fold permeability and continuous, high-resolution monitoring of groundwater levels and hot spring temperatures is necessary, along with active engagement of local communities and stakeholders to develop resilient management strategies.

In summary, our study establishes a robust framework that clarifies the intrinsic coupling between groundwater dynamics and hot spring temperatures, offering a replicable model for sustainable geothermal management under climate variability and urbanization pressures.

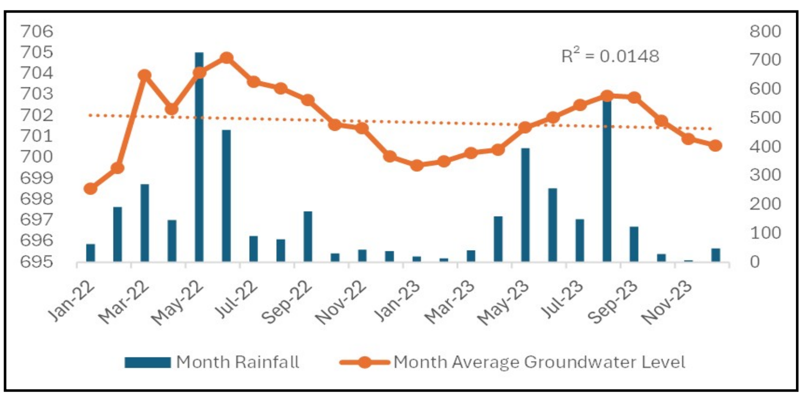

Figure 3: Monthly Rainfall and Average Groundwater Level Trends from January 2022 to December 2023

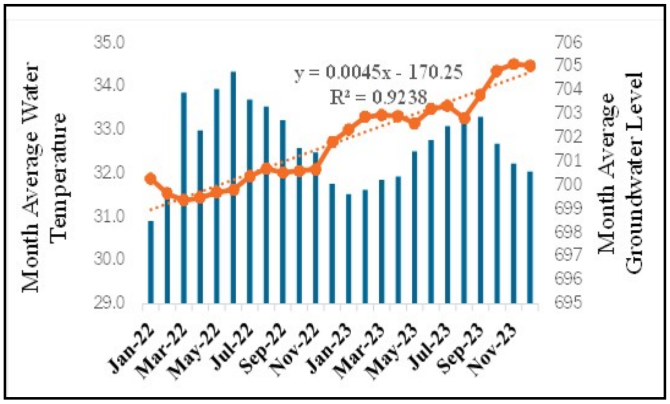

Figure 4: Monthly Average Groundwater Level and Monthly Average Hot Spring Water Temperature Trends from January 2022 to December 2023

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