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Optimization of Groundwater Well Discharge Capacity Using Step Drawdown Test Post-Earthquake in Biromaru, Sigi District, Central Sulawesi

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ABSTRACT

The effectiveness of groundwater wells in tectonically active regions remains insufficiently understood due to the lack of integrative hydrogeological evaluations. This study aims to characterize the hydraulic performance of five groundwater wells in Biromaru District, Sigi Regency, an area affected by the 2018 Central Sulawesi earthquake. A combination of the Neuman method and the Hantush-Bierschenk approach was employed to evaluate key aquifer parameters, including transmissivity, storativity, specific yield, and well loss coefficients. Step drawdown tests and time-drawdown data were analyzed to determine aquifer responses under controlled pumping conditions. The results show a clear variation in transmissivity and storativity among wells, indicating heterogeneous subsurface characteristics possibly influenced by post-seismic compaction. Wells 1 and 3 demonstrated high transmissivity and efficiency, supported by C values below 0.5, signifying well integrity and optimal construction. Conversely, well 2 exhibited low hydraulic performance, suggesting lithological constraints or structural deficiencies. The combination of analytical methods provided a robust framework for interpreting aquifer-well interactions in a post-disturbance setting. This study contributes to a deeper understanding of groundwater behavior in seismically disturbed regions and emphasizes the importance of incorporating multi-method approaches in hydrogeological assessments. The findings can serve as a reference for groundwater resource planning, well rehabilitation, and adaptive water management in vulnerable areas like Sigi Regency.

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1. INTRODUCTION

The increasing demand for clean water, coupled with rapid population growth, has exerted significant pressure on groundwater resources, particularly in areas with limited surface water infrastructure, such as Biromaru, Sigi District, and Central Sulawesi. Groundwater is a primary source for domestic, agricultural, and industrial purposes in this region. However, the recharge rate of groundwater is generally low, and unregulated extraction threatens long-term sustainability. The 2018 earthquake further exacerbated these vulnerabilities, significantly diminishing the groundwater well performance in the area. Understanding aquifer characteristics is crucial for effective groundwater management, as evidenced by several studies that emphasize the importance of transmissivity and storativity in determining aquifer capacity and resilience (Xiong et al., 2022; Jenifer & Jha, 2022). To evaluate these parameters, previous research has utilized methodologies such as the Neuman method and step drawdown tests, which have proven to be effective in assessing aquifer performance and informing groundwater management strategies (Benaafi et al., 2022).

Despite the strategic importance of groundwater in the Biromaru area, there is a paucity of empirical assessments concerning the conditions and performance of its wells. The decline in groundwater productivity following the 2018 seismic event underscores the urgent need for scientific evaluation and optimization of well capacities (Shandilya et al., 2022). The lack of reliable data impedes the development of sustainable extraction strategies that are consistent with aquifer capacity. A potential solution to this challenge involves the application of well-established hydrogeological testing methods to accurately determine aquifer properties (Kim et al., 2023). Among these methods, the step drawdown test is particularly effective for evaluating well performance under varying discharge conditions. Integrating such empirical data with analytical models facilitates informed decisions on groundwater utilization, considering both resource availability and the impacts of extraction (Pech & Asadi, 2022).

The step drawdown test is a widely used single-well technique for assessing drawdown behavior under incremental discharge rates. It has been effectively employed to evaluate well efficiency and aquifer response, providing insights into both linear and nonlinear head losses (Chen et al., 2022; Méité et al., 2023). This method assumes a constant pumping rate at each stage and is conducted in sequential steps to facilitate the analysis of drawdown stabilization and associated losses. Hantush further developed this approach by incorporating the superposition principle to model the transient flow under variable discharge, resulting in the Hantush-Bierschenk method (Ahmadi et al., 2022). This method enables the separation of aquifer loss and well loss coefficients B and C, thereby offering a more detailed understanding of well hydraulics (Paradis et al., 2022). It has been instrumental in distinguishing drawdown components related to aquifer behavior from those related to well construction and operation. Additionally, the Eden-Hazel method enhances the analysis of well performance by estimating drawdown components across varying flow rates and accounting for lithological differences and aquifer heterogeneity. This is particularly essential in regions with complex subsurface conditions, thereby providing robust frameworks for optimizing well functionality and aquifer sustainability.

Although the step drawdown test and its derivatives have been widely utilized across diverse hydrogeological settings to quantify well losses and determine aquifer properties, their systematic application in post-seismic contexts, such as the Sigi District, remains underexplored. In regions recently affected by tectonic activity, aquifers often experience complex structural changes, including compaction, fault reactivation, and permeability alterations, which standard methods may fail to adequately capture. Pumping tests in such environments have shown potential in revealing transient aquifer responses to stress and recovery; nonetheless, the absence of integrated multi-method approaches—combining time-drawdown analysis, loss coefficient quantification, and structural assessments—limits the comprehensive understanding of well-aquifer interaction (Molwalefhe & Shemang, 2023; Hamad & Tubagus, 2021).

The restricted use of both the Hantush-Bierschenk and Eden-Hazel methods in comparative research constrains a broader comprehension of the dynamic interplay between engineered well components and aquifer systems, particularly under variable stress conditions commonly found in tectonically active regions (Zhang et al., 2023; Illien, 2022). When applied independently, these analytical approaches often overlook the compounding effects of well geometry, casing integrity, and lithological heterogeneity, which are crucial for accurately diagnosing well performance degradation. Additionally, existing literature offers insufficient insight into the operational efficiency and resilience of groundwater wells in areas affected by faulting and seismic activity. There is a clear lack of practical frameworks or design protocols to optimize well productivity and ensure long-term aquifer sustainability in post-disturbance scenarios, thereby limiting the ability of local authorities and engineers to respond effectively to hydrogeological challenges following geological disturbances.

The aim of this study was to assess and enhance the debit capacity of groundwater wells through the application of the step drawdown test, utilizing the Hantush-Bierschenk and Eden-Hazel analytical methods in Biromaru, Sigi District. This research seeks to quantify aquifer transmissivity, storativity, and well loss coefficients to facilitate precise classification of well efficiency and aquifer sustainability. The novelty of this study resides in its dual-method approach for post-seismic groundwater evaluation, integrating both the Hantush and Eden-Hazel models to yield comprehensive insights into well performance under diverse geological influences. The scope encompasses hydrogeological testing of five wells, data analysis, and interpretation of aquifer parameters to support sustainable groundwater utilization policies in seismically active regions.

2. METHOD

2.1. Materials

This study was conducted in Lolu Village, Sigi Biromaru Sub-District, Sigi District, Central Sulawesi Province, Indonesia. The area is located at coordinates 0° 57' 0" - 0° 58' 0" South Latitude and 119° 54' 0" - 119° 55' 0" East Longitude, approximately 12 km from Palu City, accessible within 30 min by motorbike. The study area was selected based on the high utilization of groundwater wells by the local population for domestic and agricultural purposes, particularly after the 2018 earthquake, which impaired the functionality of several wells. The location of the research is shown in Figure 1.

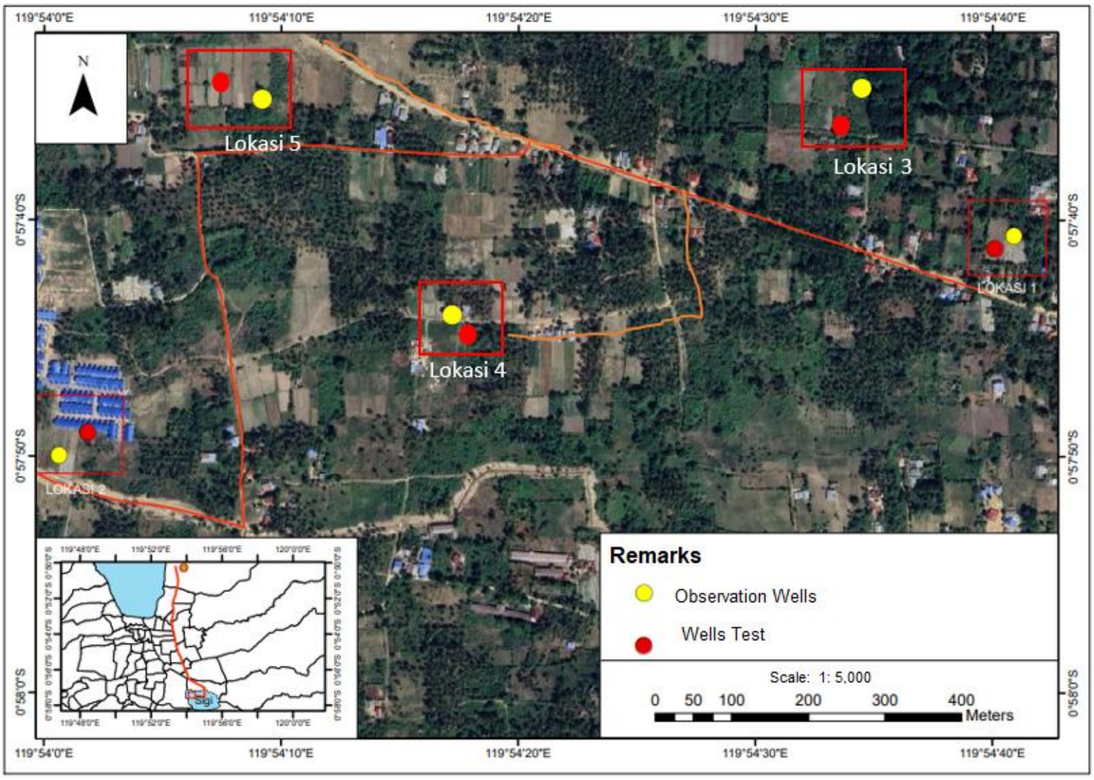

Figure 1. Map of the research location.

The primary tools used included a water level meter, flow meter, stopwatch, and submersible pump, which were essential for conducting the step drawdown test. The analytical tools used to process the data included Microsoft Excel and curve-fitting plots based on the Neuman and Hantush-Bierschenk models.

2.2. Sample Preparation

Five groundwater wells in the study area were selected for sampling. Each well was observed for physical integrity, construction specifications, and suitability for step-drawdown testing. Prior to testing, the wells were cleared of sediments and allowed to stabilize to ensure that the initial water levels reflected static conditions. Measurements such as depth, diameter, and casing length were documented. Each well was then equipped with calibrated instruments for recording the discharge and drawdown data.

2.3. Hydrogeological Testing Procedures

This study applied two key hydrogeological testing methods: the drawdown test and step drawdown test. The drawdown test involves continuous pumping from the well while recording water level changes over time to determine the transmissivity (T), storativity (S), and specific yield (Sy) using Neuman's method. The drawdown was plotted against time and analyzed using curve fitting based on theoretical Neuman curves. The step drawdown test, first proposed by Jacob (1947), measures drawdown at multiple increasing discharge rates. Each step was conducted for a constant duration (30–60 min), and drawdown stabilization was observed before switching to the next rate. The equation used in Jacob's analysis is

$$S_w = BQ + CQ^P \quad (1)$$

where ***B*** is the linear aquifer loss coefficient and ***C*** is the nonlinear well loss coefficient. To refine this, the Hantush-Bierschenk method was applied as follows:

$$S_{w(n)} = \sum_{i=1}^{n} \Delta Q_i \, B(r_{ew}, t - t_i)Q + CQ_n^2 \quad (2)$$

Assuming homogeneous, isotropic aquifers and full well penetration, the data were analyzed to derive coefficients ***B*** and ***C***.

2.4. Data Analysis

Data obtained from the step drawdown test were processed to determine the relationship between the discharge rate and drawdown using regression analysis in Microsoft Excel. The linear and quadratic components of drawdown were fitted against the discharge to determine coefficients ***B*** and ***C***. The goodness-of-fit was assessed using the coefficient of determination R^2, and residuals were examined for consistency. Variability across wells was analyzed to detect anomalies possibly linked to subsurface lithological differences or well construction factors.

3. RESULTS AND DISCUSSION

3.1. Results

The calculation of aquifer parameters using the Neuman method yielded values for transmissivity (T), storativity (S), and specific yield (Sy) across the five tested wells. The highest transmissivity value was found in well 3 at 254.698 m²/day, while the lowest was in well 4 with a value of 17.68 m²/day. Specific yield values across all wells were consistently low, ranging from 5.0×10^{-5} to 5.4×10^{-4}, suggesting that the aquifers mainly consist of moderately porous sandstone formations with limited groundwater reserves.

Table 1. Aquifer characteristics by Neuman Method

Wells	T (m²/d)	S	Sy	T.rec (m²/d)
1	243.485	5.08E-05	5.0E-05	24.124
2	18.57	4.00E-03	5.4E-04	247.64
3	254.698	1.25E-04	5.0E-05	24.124
4	17.68	3.40E-02	5.4E-04	247.64
5	25.02	1.17E-03	5.0E-05	246.5

The table shows that wells 1 and 3 had the highest transmissivity values, suggesting better aquifer permeability compared to others. Well 4 displayed the highest storativity and specific yield, indicating its greater capacity for temporary water storage under pressure, which may be due to distinct lithological characteristics. Meanwhile, well 2 shows the lowest transmissivity, likely reflecting more compact or less permeable geological formations. The T.rec values remained relatively high for wells 2, 4, and 5, suggesting consistent recharge potential across these locations despite varying aquifer properties.

The results of the step drawdown test using the Hantush-Bierschenk method demonstrated the drawdown values and associated well losses with increasing pumping rates. For example, in well 1, the drawdown increased proportionally with the pumping discharge, with Swn/Qn ranging from 0.00578 to 0.00736 d/cm². These values indicate high hydraulic efficiency and minimal energy loss within the well system under increasing flow conditions.

Table 2. Step Drawdown Test Results – Hantush-Bierschenk Method

Step	Qn (l/s)	Qn (m^3/d)	ΔSw (cm)	Swn (cm)	Swn/Qn (d/cm^2)
1	1.2	103.68	0.6	0.6	0.0057866
2	2.8	241.92	0.8	1.4	0.0057870
3	3.7	319.68	0.5	1.9	0.0059434
4	4.4	380.16	0.9	2.8	0.0073653

The table illustrates a progressive increase in drawdown (Swn) with increasing discharge rate (Qn), indicating a predictable response of the well under controlled stress conditions. The Swn/Qn values remained relatively stable across the steps, highlighting the consistent hydraulic behavior and efficiency of the well throughout the varying extraction rates.

The analysis of the well loss coefficients (B and C) revealed variations in efficiency among the five wells. Well 3 exhibited the highest efficiency of 996.94, with B = 0.0184 and C = 0.0118, indicating minimal nonlinear loss. Conversely, well 2 had the lowest efficiency of 4.78, likely owing to suboptimal well design or less favorable geological conditions. Notably, all C values were below the 0.5 threshold, indicating that the wells were generally in good condition according to Walton's classification.

Table 3. Coefficients of Well Loss – Hantush-Bierschenk Method

Wells	B	C	Efficiency
1	0.0172	0.0215	969.27
2	0.00213	0.00458	4.78
3	0.0184	0.0118	996.94
4	0.00304	0.00457	6.64
5	0.0310	0.0049	904.21

The table indicates that well 3 achieved the highest hydraulic efficiency, followed closely by wells 1 and 5, reflecting its superior performance in minimizing energy loss during pumping. The B and C values in these wells suggest favorable aquifer properties and minimal well loss effects. On the other hand, well 2 had the lowest efficiency, potentially due to construction-related issues or local lithological constraints. Overall, all C values remained well below the 0.5 threshold, confirming that all tested wells are in acceptable operational conditions.

3.2. Discussion

The step drawdown and Neuman method analyses revealed significant insights into the hydrogeological behavior of the Biromaru area's unconfined aquifer. The high efficiencies observed in wells 1 and 3, reflected in C values below 0.5, demonstrated that these wells were properly designed and constructed, contributing to their high performance under pumping conditions (Hamad et al., 2023). These findings affirm the functional integrity of the wells and support their continued operation in water-supply systems. The observed variation in transmissivity across wells suggests diverse subsurface lithological and structural properties that are likely influenced by local post-seismic sediment rearrangement. Changes in permeability and compaction due to earthquake-induced shaking, as found in similar geological settings, may have played a role in the reduction of hydraulic conductivity in some wells (Marema et al., 2023). These interpretations are further strengthened when considering the spatial disparities in aquifer properties, where the depth and thickness of productive zones may vary due to the underlying tectonic and depositional history. Such heterogeneity has been noted in large-scale studies of transboundary aquifers, indicating that resource estimation may be inaccurate and potentially unsustainable without detailed characterization (Mohammed et al., 2024).

The drawdown characteristics and aquifer responses across the tested wells further indicate heterogeneity in aquifer-aquitard interactions. The variation in storativity values, despite relatively stable drawdowns, suggests semi-confining behavior with differing degrees of vertical leakage potential. This behavior aligns with the conceptual understanding of aquitard deformation under dynamic stress, where delayed responses in water release correlate with vertical stratification and heterogeneity (Li et al., 2023). Moreover, the presence of vertical heterogeneity in aquitard formations, such as those influenced by glacial till deposits or compacted clay layers, can significantly alter transient flow behavior, which is consistent with patterns identified in regional aquifer systems exhibiting variable recharge and leakage mechanisms (Li & Zhang, 2025). These variations further complicate efforts to model and predict aquifer responses during long-term pumping or drought scenarios, particularly in geologically complex regions. In such settings, reliance on average values for storativity and transmissivity can lead to substantial under- or overestimation of sustainable yield. Integrating more refined stratigraphic data along with time-dependent stress response models can enhance the predictive capacity and help avoid resource mismanagement during periods of critical water demand (Manewell et al., 2024).

The findings of this study have substantial scientific and operational implications. On a scientific front, the confirmation of well integrity through low C values reinforces the applicability of the Hantush-Bierschenk approach for evaluating well performance in seismically affected regions (Lasme et al., 2023). The use of transmissivity and specific capacity as diagnostic tools for identifying high-performance wells can be effectively integrated into spatial groundwater resource assessments. These insights are particularly relevant in the context of aquifers affected by tectonic disturbances, where compaction and material rearrangement can reduce permeability, leading to non-uniform well performance (Marema et al., 2023). From a practical perspective, the prioritization of high-efficiency wells, such as wells 1 and 3, for long-term utilization provides a strategic advantage in water resource planning. Conversely, the poor performance of Well 2 calls for diagnostic evaluation and potential redesign. By integrating these empirical indicators into regional groundwater governance frameworks, resource managers can implement targeted maintenance and well rehabilitation strategies in line with broader adaptive management principles aimed at sustaining groundwater access in stressed aquifer systems (Bostic et al., 2023). These adaptive strategies should also consider the vulnerability of community-level water infrastructure, especially in seismically active or geologically unstable terrains, where fluctuating aquifer dynamics and delayed responses to stress events may exacerbate water access inequities. Incorporating continuous monitoring systems and local stakeholder input into well management practices could greatly enhance the long-term sustainability and resilience of groundwater resources, ensuring equitable access even under compounded environmental and socio-economic pressures (Melo et al., 2024; Dobbin & Bostic, 2025).

4. CONCLUSIONS

This study evaluated the hydraulic performance of five groundwater wells in the Biromaru District using the Neuman and Hantush-Bierschenk methods. The results reveal that wells 1 and 3 possess the most favorable aquifer characteristics, with high transmissivity and efficiency values, whereas well 2 shows the lowest performance due to probable lithological or construction-related constraints. The calculated C values across all the wells were below 0.5, indicating acceptable construction conditions. Furthermore, the drawdown and storativity behaviors suggest that semi-confining aquifer dynamics are influenced by vertical heterogeneity and possible post-seismic compaction effects.

These findings demonstrate the applicability of combined analytical methods for assessing well and aquifer behavior in tectonically active regions. The scientific implications include improved modeling of aquifer response under stress, whereas the practical contributions involve prioritizing well maintenance and development efforts. Future research should focus on integrating geophysical surveys to refine aquifer mapping and implementing continuous monitoring systems to support adaptive groundwater resource management, particularly in earthquake-prone settings such as Central Sulawesi.

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