Groundwater System Characteristics of Soe Area, East Nusa Tenggara, Indonesia: The Role of Rock Properties and Structural Geology

Muhammad Gazali Rachman[1], Nanda Ajeng Nurwantari[2], Eko Wibowo[3]
Faculty of Mineral Technology and Energy, UPN "Veteran Yogyakarta, DIY

Email: [1]muhammad.gazali@upnyk.ac.id, [2]nandajengn@gmail.com, [3]eko.wibowo@upnyk.ac.id

Received: 2025-08-27 Received in revised from 2025-09-03 Accepted: 2025-09-10

Abstract

Groundwater is the primary source of freshwater for communities in Soe Regency, located in the highland of West Timor Island, where surface water resources are limited. This study aims to characterize the groundwater system and assess its sustainability through an integrated approach combining geological mapping, hydrogeological observations, pumping tests, and hydrochemical analyses. Geological mapping identified two dominant lithological units: Quaternary coral limestone, functioning as the main aquifer, and the underlying Noele Formation, where marl layers act as an impermeable base. Hydrogeological surveys revealed four types of spring settings—rock unit contact, fracture-controlled, perched aquifer, and gravel contact springs—demonstrating the role of both karstification and structural controls in groundwater discharge. Groundwater level measurements show that recharge occurs in the northern highlands (elevations up to 1050 m), with flow directed southward and westward towards the Noelmina River. Pumping test results indicate discharge rates ranging from 1 to 11 L/s, with higher productivity in the southern areas. Hydrochemical analysis of 41 water samples shows TDS values of 261–500 mg/L, electrical conductivity of 400–1000 nS/cm (with a localized anomaly of 1200 nS/cm in Hane Village), and pH values of 6.6–8.5, all within safe standards for human consumption.
Based on these findings, the Soe groundwater basin is classified into three aquifer productivity zones: moderate, low, and rare. The system is dominated by shallow unconfined aquifers, which remain sufficient in both quality and yield for current needs. However, population growth and urban development pose risks to long-term availability. Therefore, conservation of the northern recharge area is essential, alongside regulation of groundwater abstraction, infrastructure improvements, and exploration of deeper confined aquifers to secure future water resources. This study contributes a comprehensive framework for groundwater system characterization in structurally complex karst environments, providing critical guidance for sustainable water management in semi-arid highland regions.

Keywords: *Aquifer productivity; Groundwater flow; Hydrogeology; Karst system; Water quality*

1. Introduction

Groundwater is a vital component of global freshwater supply, providing essential resources for domestic, agricultural, and industrial purposes. Its role is particularly critical in regions where surface water is scarce or unreliable, making groundwater the primary source of water security for millions of people [1], [2]. In Indonesia, groundwater supports community livelihoods across diverse climatic and geological settings. In semi-arid and highland regions such as East Nusa Tenggara (NTT), where rainfall is highly seasonal and river discharge is limited, groundwater serves as the most reliable water source for local populations [4], [5].

The availability and distribution of groundwater are strongly controlled by geological and structural conditions. In karst environments, aquifers are highly heterogeneous, with water stored and transmitted through complex networks of fractures, dissolution conduits, and bedding planes [9], [10]. This complexity often results in uneven distribution of groundwater resources and highly variable productivity between wells or springs. The situation becomes more intricate in tectonically active regions such as Timor, where deformation and faulting significantly influence aquifer geometry and flow patterns [6]–[8]. Understanding how lithological characteristics and structural geology interact to shape groundwater occurrence is thus essential for effective groundwater resource management in these areas.

Recent research has emphasized the value of integrated approaches in hydrogeological studies, combining geological mapping, hydrogeological surveys, pumping tests, and hydrochemical analyses [11], [12]. Such approaches not only characterize aquifer properties but also provide insights into recharge mechanisms, groundwater flow dynamics, and water quality. In karst aquifers of Java, for example, hydrogeological and geochemical studies have revealed the importance of linking structural geology with hydrochemical variability to evaluate water resource sustainability [3], [10]. Similarly, investigations in Timor have highlighted the role of lithological heterogeneity and structural control in determining groundwater potential, though most studies remain regional in scale [4], [5], [7].

Despite the critical importance of groundwater for Soe Regency in West Timor, detailed site-specific studies remain limited. Previous investigations have provided regional overviews of groundwater potential [4], [5], but the interaction between lithology, tectonic structures, aquifer productivity, and water quality has not been comprehensively addressed. This knowledge gap creates uncertainty in both scientific understanding and water management planning, especially in a region where population growth and climate variability are intensifying water demand.

To address these issues, this study integrates geological mapping, groundwater level measurements, pumping tests, and hydrochemical analyses to provide a holistic characterization of the groundwater system in Soe. The objectives are to (i) determine the lithological and structural controls on aquifer development, (ii) assess groundwater flow and productivity, and (iii) evaluate water quality in relation to national standards. This research contributes to advancing the understanding of groundwater systems in structurally complex karst environments and provides practical insights for the sustainable management of water resources in semi-arid highland regions of East Nusa Tenggara.

1.1. Regional Geology of Soe Area

The Soe area, located in the highlands of West Timor Island, is characterized by a diverse stratigraphic sequence reflecting the island’s complex tectonic and depositional history (Fig. 1). The oldest units comprise Jurassic–Cretaceous siliciclastic formations deposited in deep marine environments, representing the passive continental margin prior to the collision between the Australian and Eurasian plates [6]. Overlying these successions are extensive Eocene–Miocene carbonate platforms and reefal limestones, deposited in shallow marine settings. These limestones form one of the most important aquifers in the region due to their high secondary porosity and permeability resulting from dissolution processes.

Volcaniclastic and tuffaceous deposits of Miocene–Pliocene age are interbedded with carbonates, recording the influence of contemporaneous arc volcanism [7]. These rocks contribute to hydrogeological heterogeneity by providing localized permeability along fractures and weathered zones. Quaternary deposits of alluvium and colluvium are also present in valleys and depressions, forming shallow aquifers that often host local springs and domestic water sources. The combination of carbonate, volcanic, and alluvial units creates a mosaic of aquifers with variable hydrogeological characteristics.

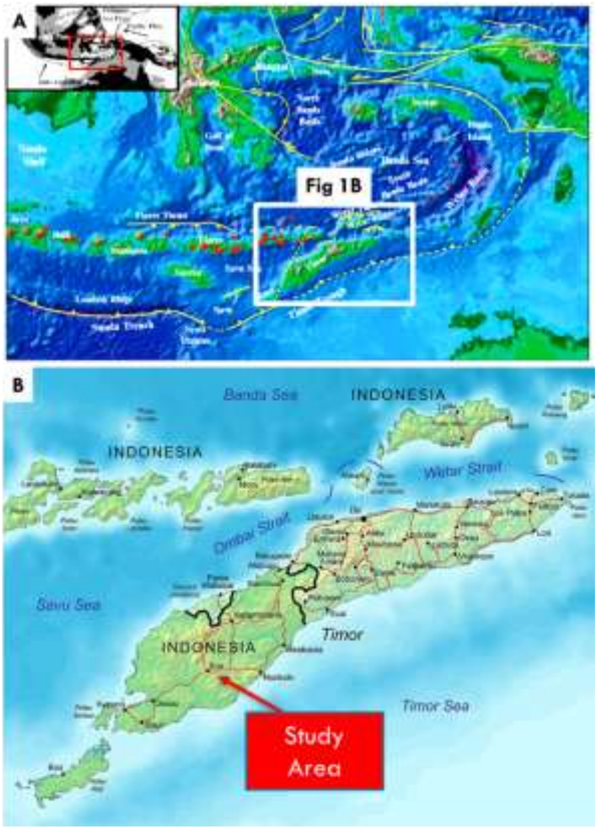

Figure 1. Location of the study area in Soe District, South Central Timor Regency, East Nusa Tenggara Province. Figure 1A is modified from [8].

The tectonic framework of West Timor, including the Soe area, is governed by the active collision between the Australian continental margin and the Banda Arc system [6]–[8]. This collision produced intense folding, thrusting, and faulting, forming a regional fold-and-thrust belt with imbricate sheets and duplex structures. These features compartmentalize aquifers, creating marked spatial variability in groundwater potential over relatively short distances. At the same time, normal faults and extensional fractures enhance vertical and lateral groundwater movement, facilitating recharge and discharge pathways.

Karst processes exert an equally important influence on aquifer properties. The uplifted Quaternary limestones in the Soe area exhibit well-developed karstification, including dissolution conduits, cavities, and enlarged fractures, which significantly increase permeability and control spring distribution [9], [10]. Structural features such as thrusts and normal faults intersect these karst systems, enhancing aquifer connectivity and providing preferential flow pathways [7], [8].

Taken together, the Soe groundwater system reflects a hybrid hydrogeological model. Aquifer properties are jointly controlled by (i) lithological characteristics of highly karstified Quaternary limestones and older carbonate platforms, and (ii) structural deformation associated with the Banda Arc–Australian continental margin collision. This interplay between karst development and tectonic structures governs groundwater occurrence, recharge dynamics, and the spatial variability of aquifer potential across the Soe region.

2. Method

This research employed an integrative approach to characterize the groundwater system of Soe Regency by combining geological, hydrological, and hydrochemical investigations.

Geological survey. Detailed geological mapping was carried out to identify lithological units, stratigraphic relationships, and structural features, including fractures and faults that control groundwater occurrence and flow. The mapping results were compiled into a new geological map of the Soe area, which served as the fundamental basis for hydrogeological interpretation.

Groundwater level measurement. Depth-to-water measurements were taken at 47 hand-dug wells (Fig. 2A) and 33 springs using a water level meter. These data were corrected to ground elevation and interpolated into a groundwater level contour map, from which flow directions were derived.

Aquifer testing. Pumping tests were performed at 13 representative hand-dug wells (Fig. 2C). Step-drawdown and constant-rate pumping were conducted following standard hydrogeological procedures [2]. Drawdown data were analyzed using the Cooper–Jacob approximation of the Theis equation to estimate aquifer transmissivity (T) and hydraulic conductivity (K). Recovery data were also used to evaluate aquifer storage properties and recharge potential. This approach follows established methods for karst and fractured aquifers, where well test data are commonly applied despite aquifer heterogeneity [11], [12].

Water quality assessment. A total of 41 water samples were collected from both wells and springs (Fig. 2B). Field parameters measured in situ included temperature, pH, electrical conductivity (EC), and total dissolved solids (TDS).

Integration of datasets. The geological, hydrological, and hydrochemical results were integrated to produce a holistic characterization of aquifer properties, groundwater flow, and water quality. This methodological framework builds on previous hydrogeological investigations in karst and structurally complex terrains [3], [11], [12], and aligns with approaches applied in Nusa Tenggara for groundwater exploration and management [4], [5].

Figure 2. Fieldwork documentation: (A) measurement of groundwater table in hand-dug wells, (B) water quality measurements including TDS, electrical conductivity (DHL), and pH, and (C) pumping test measurement to determine groundwater discharge.

3. Results and Discussion

3.1. Rocks Unit of Soe Area

The geology of the Soe area is dominated by two primary lithological units of Quaternary age, both of which are closely related to the regional groundwater system. The uppermost unit consists of Quaternary limestone (Fig. 3), primarily coral limestone deposits composed of coral fragments, mollusk shells, and gastropod fossils that reflect a shallow marine depositional environment. This unit, referred to as the Coral Limestone Member, exhibits significant secondary porosity due to karstification and structural fracturing, making it the principal aquifer in the study area.

Figure 3. Outcrop and close-up photographs of the Quaternary Coral Limestone unit showing characteristic karstified features.

Beneath the limestone lies the Quaternary clastic carbonate sequence, known as the Noele Formation, composed of interbedded carbonate sandstone and marl (Fig. 4). The carbonate sandstone layers, with fine- to medium-grained textures, show evidence of bioturbation and abundant fossil content, indicating deposition in a shallow marine setting. Importantly, the marl layers within the Noele Formation act as an impermeable base layer, effectively confining the aquifer system developed in the overlying coral limestone. This stratigraphic arrangement establishes a composite hydrogeological framework in which the karstic limestone serves as the productive aquifer, while the marl functions as an aquitard that limits downward groundwater flow and maintains groundwater storage within the system.

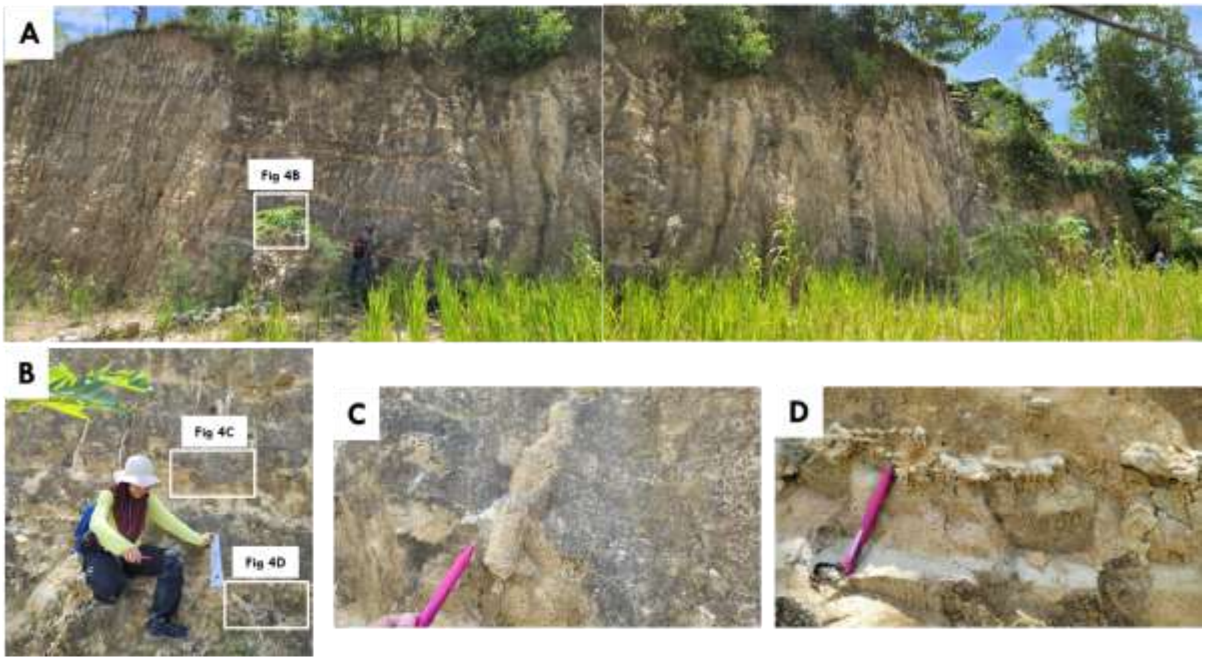

Figure 4. Outcrop of the Noele Formation consisting of interbedded very fine calcarenite and marl, displaying abundant vertical (C) and horizontal (D) burrows.

3.2. Structure Geology of Soe Area

The structural framework of Soe Regency is characterized by two dominant fault systems that exert a strong influence on both regional morphology and groundwater occurrence. The first system consists of north–south trending sinistral faults with oblique movement, expressed locally as normal faulting. The second system is composed of northeast–southwest trending dextral faults, which intersect with the north–south structures and collectively shape the geomorphology of the region (Fig. 5). The interaction of these fault systems has produced a rugged highland terrain, with fault-bounded ridges and valleys that strongly dictate surface morphology.

In addition to their geomorphic expression, these structural features exert a primary control on hydrogeological processes. Springs in several locations, such as Oelbubuk, emerge at the intersections of fault zones, demonstrating the role of fractures and fault conduits in directing groundwater flow. The structural control observed in Soe is consistent with regional tectonic models of West Timor, where collision between the Australian continental margin and the Banda Arc has produced a complex fold-and-thrust belt overprinted by strike-slip and oblique faulting [6, 8]. These tectonic structures not only compartmentalize aquifers but also provide secondary permeability pathways that enhance groundwater storage and discharge in an otherwise heterogeneous carbonate environment.

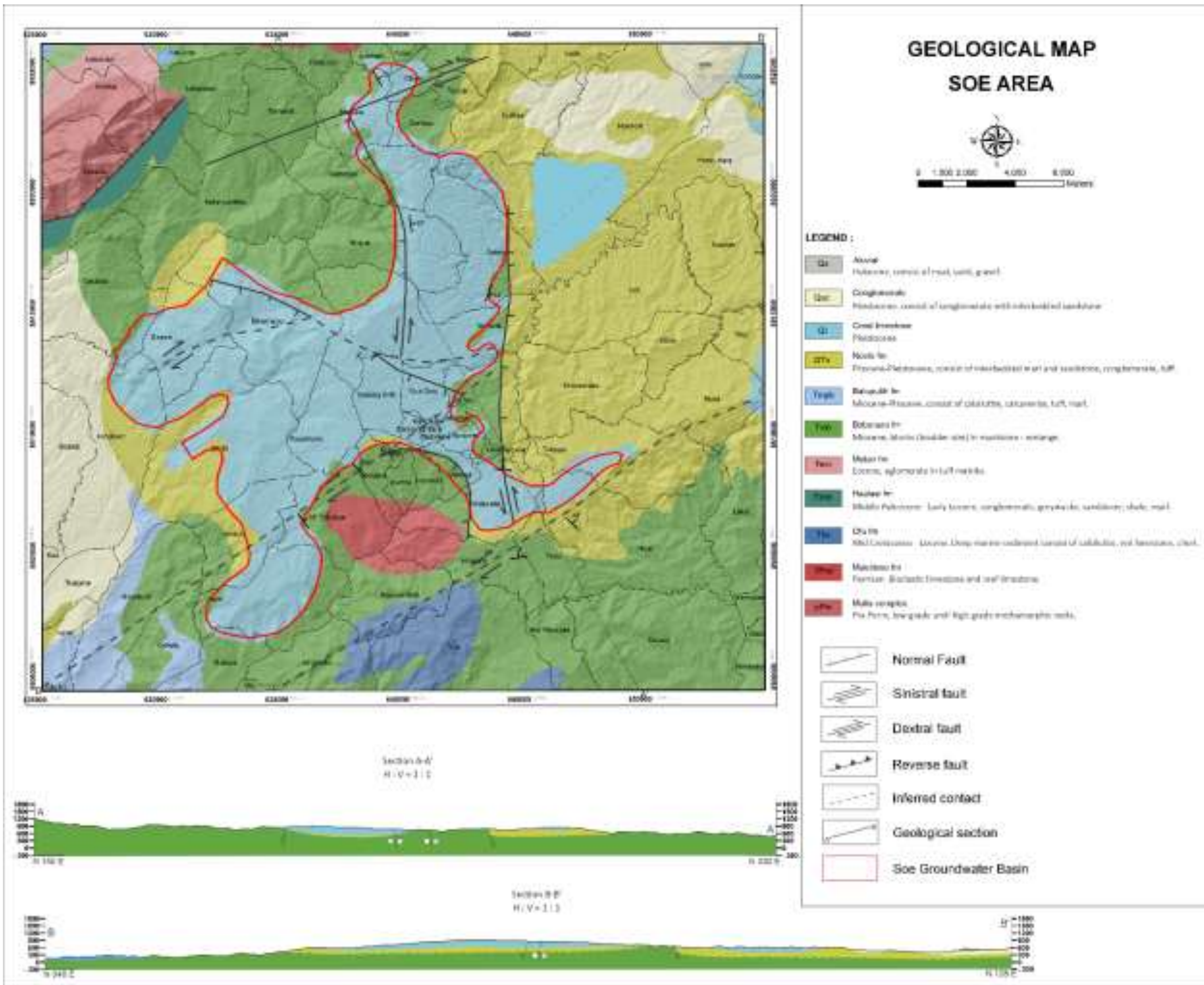

Figure 5. Geological map of the Soe area produced in this study. The Soe groundwater basin, outlined in red, is dominated by Quaternary Coral Limestone.

3.2.1. Hydrogeology of Soe Area

3.2.2. Springs

The occurrence of Springs in the Soe area reveals that groundwater discharge occurs through several types of springs, which can be classified into four main hydrogeological settings: (1) rock unit contact springs, (2) fracture-controlled springs, (3) perched aquifer springs, and (4) gravel contact aquifer springs. This classification reflects the diverse geological and structural conditions that influence groundwater flow and emergence in the study area.

The most significant discharge is observed at Kobelete Spring (Fig. 6A), where water emerges with a large volume at the contact between karstified limestone and the marl of the Noele Formation. A similar setting is also noted at Oenoko Spring, which records a discharge of approximately 2 liters per second, further confirming the role of lithological contacts as major groundwater outlets. Fracture-controlled springs are exemplified by Oelbubuk Spring (Fig. 6D), which is spatially associated with the intersection between a north–south and an east–west trending fault system. The structural control at this location highlights the importance of tectonic deformation in facilitating groundwater movement.

In addition, a perched aquifer spring is identified at Puames Spring (Fig. 6B), where groundwater accumulates above a relatively impermeable layer, creating a localized reservoir that discharges at the surface. Finally, a gravel contact aquifer spring is recognized at Fatukoko Spring (Fig. 6C), where groundwater emerges along the contact between coarse clastic deposits and underlying finer-grained sediments. Despite the hydrogeological significance of these springs, facilities at each location remain underdeveloped, limiting their potential to serve local communities effectively. Improving the infrastructure and utilization of these spring resources is therefore necessary to maximize their contribution to water supply in the Soe area.

Figure 6. Locations of selected observed springs (A–D) with corresponding index map showing spring distribution.

3.2.3. Groundwater level

The measurement of groundwater levels across 47 wells in Soe Regency demonstrates a clear spatial variation in groundwater table elevation. The highest groundwater levels are recorded in the northern part of the study area, reaching elevations of approximately 1050 meters above sea level, particularly in the villages of Netpala, Oelbubuk, Binaus, Oelakam, Noinbilla, Karang Sirih, and Kesetnana. In contrast, groundwater levels in the western and southern regions are significantly lower, ranging between 600 and 900 meters above sea level, as observed in villages such as Bikekneno, Bisene, Biloto, Benlutu, and Hane (Fig. 7).

The distribution pattern of groundwater levels indicates that the northern highlands act as the primary recharge area, where rainfall infiltration is concentrated due to the presence of permeable karstified limestones. From these elevated zones, groundwater flows downgradient towards the south and west, following the regional topographic gradient. The flow system ultimately discharges into the Noelmina River, a major surface water body located to the west of Soe town. This hydrogeological configuration highlights the strong topographic and geological controls on groundwater occurrence, with recharge–discharge dynamics reflecting both lithological permeability contrasts and structural guidance.

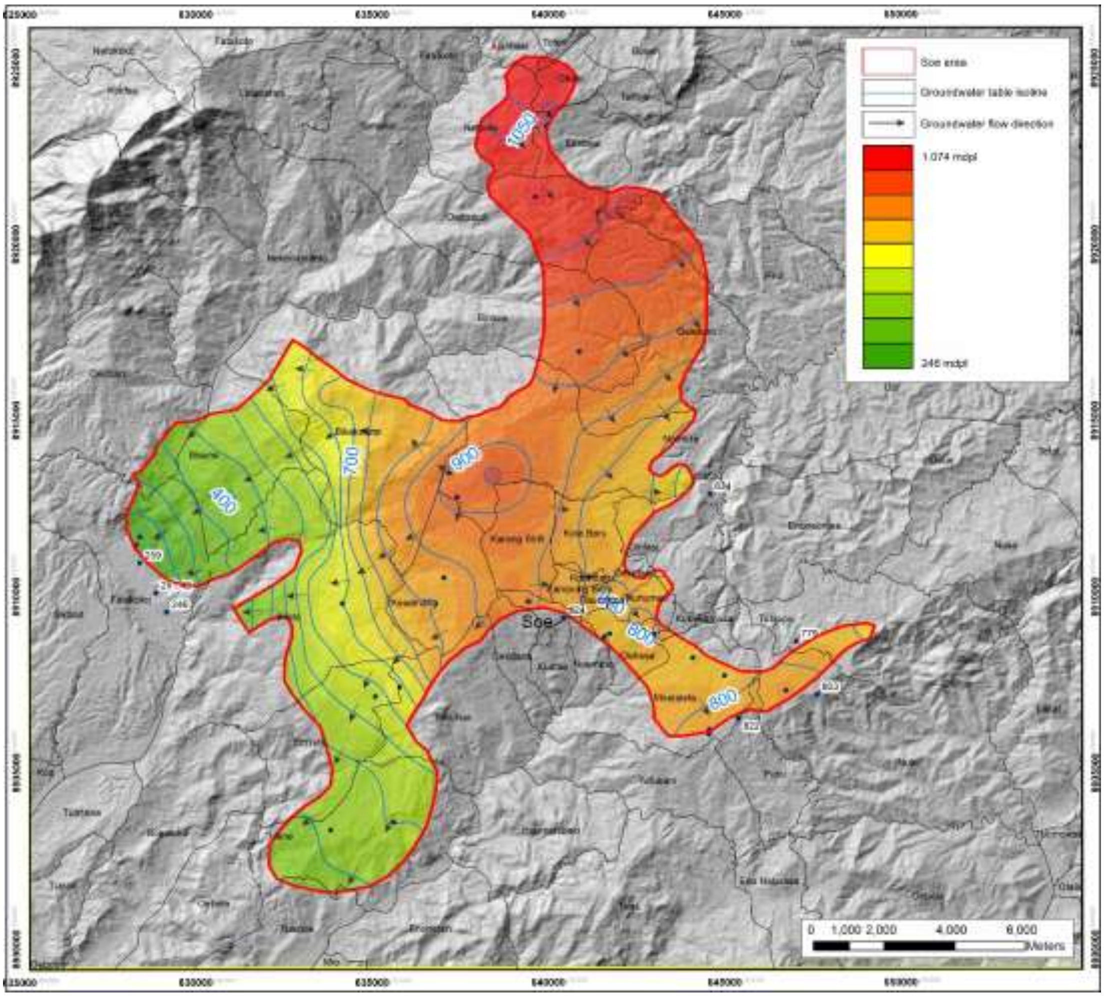

Figure 7. Groundwater elevation map illustrated with blue contour lines. Red colors indicate higher groundwater table elevations, whereas green colors indicate lower elevations. Black arrows represent groundwater flow directions.

3.2.4. Groundwater Discharge

Pumping test analyses conducted on 13 hand-dug wells in the Soe area reveal that groundwater discharge rates vary considerably, ranging from 1 to 11 liters per second. This variation reflects the heterogeneity of aquifer properties, which are influenced by both lithological characteristics and structural controls. The highest discharge values are observed in the southern part of Soe, particularly in the villages of Kesetnana, Biloto, and Hane (Fig. 8). These locations coincide with areas of relatively low groundwater table elevation and represent zones of concentrated groundwater flow and storage.

The spatial pattern of discharge obtained from the pumping test results corresponds closely with the groundwater flow mapping. Both datasets indicate that groundwater movement from the northern recharge areas culminates in enhanced discharge capacity in the southern regions. This correlation between groundwater level distribution and well productivity underscores the reliability of the integrative methodological approach applied in this study, while also providing a robust hydrogeological basis for groundwater resource management in the Soe area.

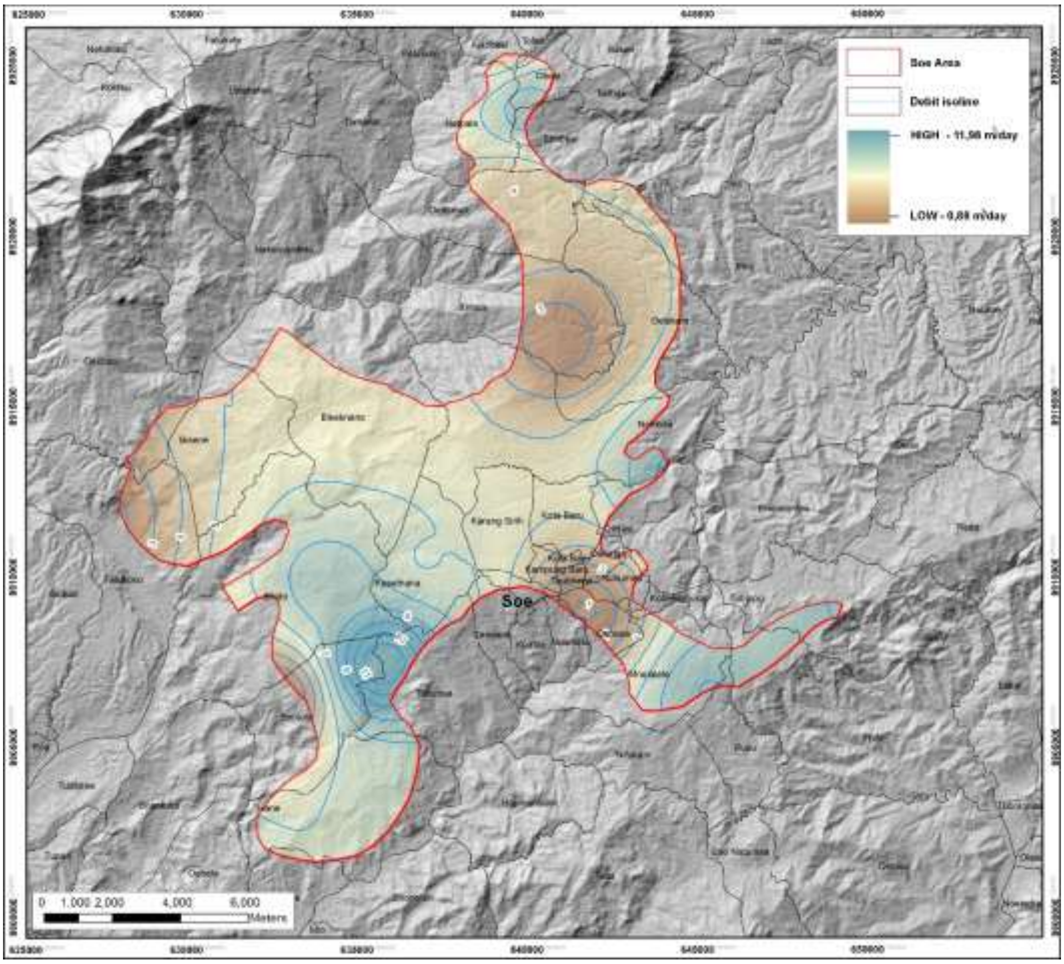

Figure 8. Groundwater discharge map of the Soe area based on pumping test results, illustrated with blue isolines. Blue-colored zones represent higher groundwater discharge, while brown zones represent lower discharge.

3.2.5. Groundwater Quality

Hydrochemical analysis provides important insights into groundwater quality, as parameters such as Total Dissolved Solids (TDS), electrical conductivity (DHL), and pH are fundamental indicators of water suitability for human consumption. TDS reflects the total concentration of dissolved minerals and salts in water, with elevated values often associated with contamination, excessive mineralization, or salinity intrusion. Electrical conductivity (DHL) is directly correlated with TDS and serves as a rapid measure of water mineralization, where anomalously high values typically suggest contamination from anthropogenic or natural sources. Meanwhile, pH values determine the acidity or alkalinity of groundwater, which strongly influences its potability and corrosive potential for water infrastructure. Together, these parameters provide a comprehensive evaluation of groundwater quality and its compliance with national and international standards.

The results of the hydrochemical tests, carried out on 41 samples from hand-dug wells and springs (Fig. 9A), show that TDS values range from 261 to 500 mg/L, classifying the groundwater into a safe quality category according to the Indonesian Ministry of Energy and Mineral Resources Regulation No. 31/2018, which sets the safe threshold at <1000 mg/L (Fig 9B). Similarly, DHL values range from 400 to 1000 nS/cm, generally indicating good water quality under the same regulation. However, a local anomaly was detected in Hane Village, where DHL reached 1200 nS/cm, suggesting localized contamination or higher mineralization (Fig. 9C). The pH values range between 6.6 and 8.5, all of which fall within the acceptable limits for drinking water as defined by the Indonesian Ministry of Health Regulation No. 492/MENKES/PER/IV/2010 (Fig. 9D).

Overall, the hydrochemical assessment indicates that the groundwater in Soe Regency is of generally good quality and safe for consumption, with only localized anomalies requiring further attention. These findings reinforce the importance of continuous monitoring to safeguard water resources, particularly in areas where evidence of contamination has been observed.

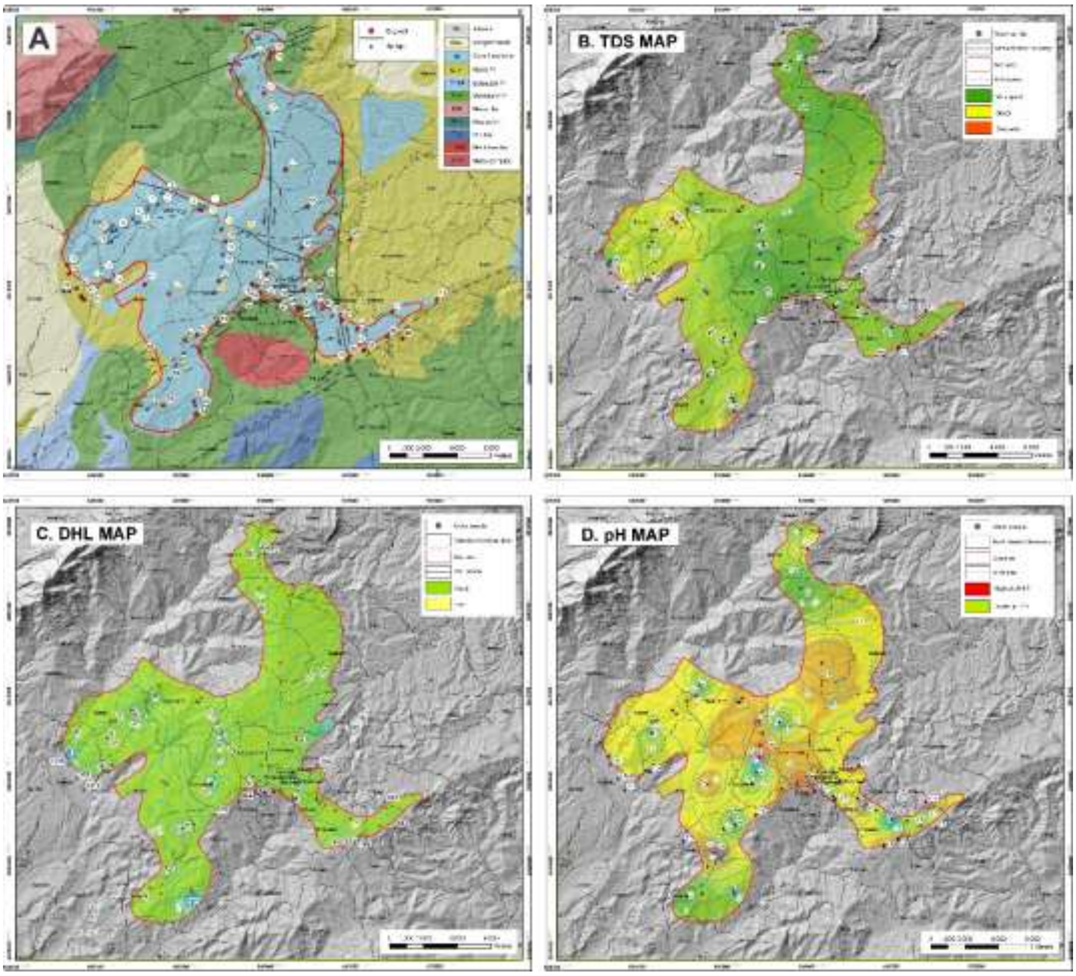

Figure 9. Hydrochemical analysis results: (A) locations of sampled wells and springs (red dots), (B) Total Dissolved Solids (TDS) distribution map, (C) electrical conductivity (DHL) distribution map, and (D) pH distribution map.

The integration of geological, hydrogeological, pumping test, and hydrochemical data provides a coherent understanding of the groundwater system in Soe Regency, establishing the foundation for further discussion on how lithological, structural, and geochemical factors collectively influence groundwater availability and quality.

3.3. Hydrogeology Map of Soe Area

The integration of geological mapping, hydrogeological observation, and pumping test results allows the classification of aquifer productivity in the Soe groundwater basin into three categories: moderate productivity aquifers, low productivity aquifers, and rare productivity aquifers (Fig. 10). Aquifers of moderate productivity are primarily characterized by fracture- and conduit-dominated systems within karstified limestone, where groundwater storage and movement are enhanced by dissolution channels and structural controls. These aquifers are found in the villages of Biloto, Benlutu, Tubuhue, Menlalete, and Nule, reflecting areas where lithological and structural conditions support sustainable yields.

By contrast, aquifers with low productivity dominate the study area, with groundwater flow occurring through a combination of fractures, joints, and minor karst conduits. This type of aquifer is widely distributed across villages such as Netpala, Eonbesi, Obesi, Oelbubuk, Binaus, Oelekum, Noinbila, Oinlasi, Kotabaru, Karangsirih, Kampungbaru, Bikekneno, Hane, and Bisene. Although these aquifers are more limited in discharge capacity, they remain a vital water source for local communities, particularly in areas without major spring development.

A more restricted category is the rare productivity aquifer, which is confined to localized zones, such as in Oebesa Village. In this setting, the limited aquifer potential reflects lithological constraints and reduced recharge capacity, thereby offering only minimal groundwater availability.

Overall, the aquifers currently utilized by the communities of Soe belong predominantly to shallow, unconfined aquifer systems developed within Quaternary limestone and clastic carbonates. Hydrochemical analyses demonstrate that water quality remains within safe thresholds for consumption, with only isolated anomalies indicating localized contamination. This suggests that current groundwater resources are both sufficient in quality and moderate in productivity to support present needs. Nevertheless, ongoing population growth and urban development pose a significant risk to the sustainability of shallow aquifer systems. To secure long-term water availability, exploration and utilization of deeper confined aquifers are necessary, as these units potentially contain larger and more resilient groundwater reserves.

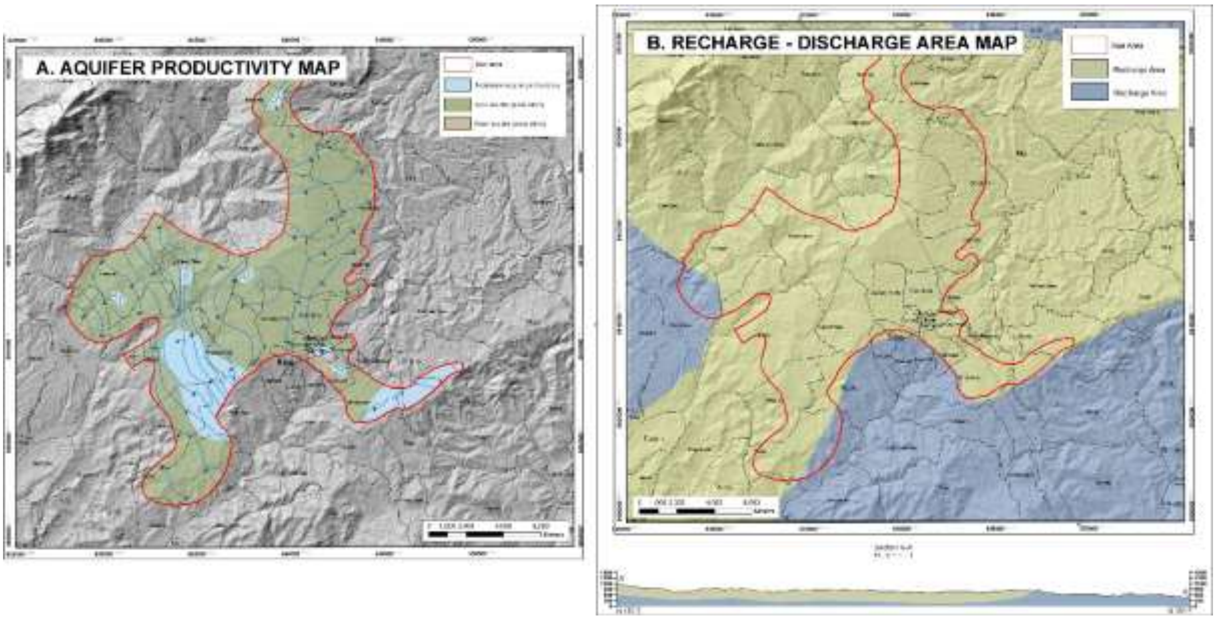

Figure 10. (A) Aquifer productivity map of the Soe groundwater basin showing spatial distribution of moderate, low, and rare productivity zones. (B) Recharge-discharge area map of Soe area

4. Conclusion

This study presents a comprehensive characterization of the groundwater system in Soe Regency, East Nusa Tenggara, using an integrated approach that combines geological mapping, hydrogeological surveys, pumping tests, and hydrochemical analyses. The results demonstrate that groundwater occurrence is primarily controlled by karstified Quaternary limestones and further influenced by fracture and fault systems associated with the regional fold-and-thrust belt. These aquifers overlie the marl-rich Noele Formation, which acts as a relatively impermeable base. Groundwater recharge originates in the northern highlands and flows predominantly southward and westward toward the Noelmina River, as confirmed by groundwater level mapping. Pumping tests show discharge rates ranging from 1–11 L/s, with the highest yields concentrated in the southern basin. Hydrochemical analyses reveal that groundwater is generally suitable for domestic use, although localized anomalies (e.g., elevated electrical conductivity) require site-specific monitoring and management.

The aquifer system of Soe can be classified into three productivity zones—moderate, low, and rare—dominated by shallow unconfined aquifers that currently sustain most community water demand. However, increasing population pressure and land-use change pose risks to long-term resource sustainability. To address this challenge, conservation of northern recharge areas, strict regulation of groundwater abstraction, and improved spring infrastructure are urgently required. Lessons from groundwater policy frameworks developed in Kupang City [13], [14], suggest that a combination of community-based monitoring, well zoning, and multicriteria policy analysis could be adapted for Soe to balance water supply, ecological integrity, and social needs. In addition, the strategic exploration of deeper confined aquifers may provide a supplementary source to reduce pressure on shallow systems.

By linking geological and hydrogeological insights with practical management implications, this study contributes both to the scientific understanding of groundwater systems in structurally complex karst environments and to the formulation of sustainable groundwater strategies for semi-arid highland regions such as Soe.

5. Discussion

Ensuring the sustainability of groundwater resources in Soe Regency requires a management framework that integrates hydrogeological characteristics, water quality preservation, and socio-economic needs. The conservation of the northern recharge area emerges as the highest priority, since this highland zone functions as the main infiltration source sustaining the entire groundwater system. Comparable cases in Central Sumba [15] and Kupang [16] demonstrate that protecting recharge areas from deforestation, land-use conversion, and contamination is critical to maintaining long-term groundwater availability.

Groundwater abstraction from shallow unconfined aquifers must also be regulated to prevent over-extraction. Establishing pumping limits based on aquifer recharge capacity, supported by continuous monitoring of water levels and spring discharge, would provide early warnings of depletion. Similar regulatory approaches have been applied in Kupang City through participatory policy frameworks [13], [14], showing that combining technical controls with stakeholder involvement can increase effectiveness.

Infrastructure improvements at major springs are also necessary to optimize water collection and reduce the risk of contamination from direct human and animal activities. Lessons from karst aquifers in Gunungkidul, Java, emphasize that inadequate spring protection often leads to local waterborne health risks [17].

Future exploration of deeper confined aquifers is recommended, as these reservoirs provide larger storage capacity and are less sensitive to seasonal variability. The application of hydrogeophysical surveys, such as resistivity methods tested in Kupang [18], [19], could support the identification of sustainable targets for drilling and abstraction. Artificial recharge techniques, including infiltration ponds and recharge wells, also present opportunities to enhance aquifer replenishment during the wet season, as demonstrated in semi-arid karst systems globally [11].

Finally, strengthening community participation remains essential. Public awareness campaigns and community-based water management programs can foster responsible water use, improve facility maintenance, and enhance collective protection of recharge zones. Studies in Mandalika, Lombok, highlight that local engagement is vital for managing hydrochemical variability and protecting aquifers from contamination risks [20].

By combining recharge protection, regulated abstraction, spring infrastructure improvements, confined aquifer development, artificial recharge, and community involvement, the groundwater resources of Soe Regency can be safeguarded for both present and future needs. This integrated approach is consistent with sustainable groundwater management frameworks being developed across Nusa Tenggara Timur [13]–[16], while contributing new insights into the interplay of karst processes and tectonic structures in semi-arid highland environments.

6. Acknowledgement

This research was conducted as a collaborative effort between Universitas Pembangunan Nasional “Veteran” Yogyakarta and the Department of Energy and Mineral Resources of East Nusa Tenggara Province. The authors would like to express their sincere gratitude to Dr. Ir. C. Prasetyadi, M.Sc., and the entire team for their invaluable support and active participation during the fieldwork and data collection phases of this study. High resolution maps presented in this paper are available by requesting to the author.

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