Groundwater Resource Potential in Table Mountain Forest, Manokwari, West Papua: A Hydrogeological Review for Conservation

Rosalina Mirino [1*], *Roni* Bawole[2], *Agustinus* Murdjoko[1], and *Richard* Lewerissa[1]

[1]Physics Department, Faculty of Science, Papua University, Manokwari, West Papua Province, Indonesia
[2]Professor *of Coastal and Marine Management,* Department of Marine Science, Faculty of Fisheries and Marine Science, University of Papua, Manokwari, West Papua Province, Indonesia.
[3]Professor of Forest Resource Conservation, Forest Faculty, Papua University, West Papua Province, Indonesia.

Abstract. This study evaluates the groundwater resource potential in Table Mountain Forest, Manokwari, West Papua, through comprehensive hydrogeological analysis for conservation planning. The 462-hectare protected forest area contains 44 active springs within a karst aquifer system that supplies 10.30% of Manokwari's municipal water demand. Using a systematic literature review methodology integrating geological, climatological, and ecological data from 2015 to 2024, this research employed multi-criteria analysis weighting geological factors (40%), climatological conditions (30%), topographical features (20%), vegetation cover (10%) and geoelectric surveys to assess groundwater potential. The application of the multi-criteria analysis framework produced a groundwater potential map of Table Mount as a high potential area zone. The geoelectric surveys identified shallow unconfined aquifers at 0.854-4.36 m depth with optimal conditions in survey lines 1, 2, and 5. The bedrock typically begins at a depth of approximately 6-9 m with resistivity values exceeding 13,000 Ωm, indicating an impermeable basement rock that prevents deeper groundwater circulation. However, developmental pressures present significant conservation challenges. The study recommends ecosystem-based management with three conservation zones: core (300 ha), buffer (100 ha), and transition (62 ha), alongside monitoring networks, 50-meter spring protection buffers, and climate adaptation strategies.

1 Introduction

Table Mountain Forest in Manokwari, West Papua, is a strategic conservation area that performs a dual function as a biodiversity habitat and a critical water catchment zone for the urban area of Manokwari. This Nature Tourism Park covering 462.16 hectares is located at coordinates 134°03'17"--134°04'05" East Longitude and 0°51'29"--0°52'59" South Latitude, with elevations ranging from 16-210 meters above sea level [3]. The hydrogeological significance of Table Mountain has been recognized since the Dutch colonial era, when this area was designated as a protected forest in 1957, with the primary objective of protecting hydrological functions. The natural spring system of this area has provided a clean water supply to Manokwari City for more than 65 years, contributing 10.30% of the total water supply of PDAM Manokwari through 44 active springs scattered throughout the area [12].

West Papua faces complex groundwater conservation challenges due to a combination of population growth, mining activities, and land-use changes. The province, which declared itself as Indonesia's first Conservation Province in 2015, has committed to protecting a minimum of 70% of its territory as conservation areas through the 2018 Manokwari Declaration [13, 14]. In this context, research on the groundwater potential of Table Mount is crucial for developing conservation models that can be replicated in similar areas [5].

Groundwater in tropical forest ecosystems plays a fundamental role in maintaining ecosystem productivity, regulating river flow during the dry season, and providing hydrological ecosystem services [4,7]. Global research shows that tropical forests with optimal tree cover can maximize groundwater recharge by up to 47 mm/year, increase soil hydraulic conductivity, and reduce surface runoff [5,6]. Groundwater conservation issues in West Papua include threats from deforestation due to industrial mining activities, infrastructure development pressures, and climate change impacts on precipitation patterns [10]. Recent research has identified Indonesia as being responsible for 58.2% of tropical deforestation caused by industrial mining, with significant implications for regional groundwater systems [13,14].

* Corresponding author: r.mirino@unipa.ac.id

2 Literature Review

2.1 Hydrogeological Theory and Tropical Aquifer Characteristics

Hydrogeological systems in tropical environments exhibit unique characteristics that are influenced by a combination of high rainfall, consistent temperatures, and intensive weathering processes. Ilstedt et al. [7] in Scientific Reports demonstrated that intermediate tree cover can maximize groundwater recharge in seasonally dry tropical regions, with optimal recharge achieved at a density of 10 trees/hectare producing 47 mm/year. Aquifers in Indonesia's tropical environment are classified based on their productivity into highly productive, moderately productive, and less productive aquifers.

West Papua falls into the highly productive aquifer category along with South Kalimantan, East Sumatra, and South Sulawesi, with Indonesia's total groundwater potential exceeding 300 billion m³ from 471 identified hydrogeological basins [8]. Krishnaswamy et al. [9] developed the "infiltration-evapotranspiration trade-off" hypothesis for humid tropical forest ecosystems, showing that forests can increase groundwater recharge under specific conditions through increased infiltration rates and reduced surface runoff.

2.2 Karst Aquifer Characteristics in Tropical Regions

Karst aquifer systems exhibit complex hydrogeological characteristics with flow patterns through networks of fractures, conduits, and matrix porosity. Research in South Java by Adyasari et al. [1] demonstrated groundwater-surface water interactions in tropical karst systems with significant seasonal variability in land-sea nutrient fluxes. Karst formations in Indonesia generally develop on Miocene-Pliocene carbonate rocks with progressive dissolution processes, thereby creating cave systems and spring networks. The Table Mount Karst system is categorized as a young karst with limited cave development (19 natural caves identified) but has a highly productive spring system.

2.3 Groundwater Conservation Methods in Tropical Forests

Groundwater conservation approaches in tropical forests integrate nature-based solutions with MAR techniques. Effective conservation strategies include:
Forest buffer zones: Protection of riparian forests and catchment areas as natural filtration and recharge systems. **Parkland agroforestry**: Sustainable management systems balancing agricultural productivity with groundwater conservation. **Integration of local knowledge**: Combining traditional water management practices with formal regulatory frameworks.

3 Methodology

3.1 Literature Study Approach

This research employed a comprehensive literature study methodology with a systematic review approach to integrate secondary data from academic, governmental, and international sources. Literature searches were conducted through peer-reviewed academic databases, Indonesian scientific publications, and government technical reports focusing on the 2015-2024 period to ensure relevance and data currency.

The inclusion criteria were (1) research on Papua hydrogeology/similar tropical regions, (2) tropical forest groundwater conservation studies, (3) geological and climatological data from Manokwari, (4) Papua Forest ecosystem research, and (5) Indonesian water management regulatory frameworks. The exclusion criteria included non-peer-reviewed literature without scientific validation and data with limited geographical relevance.

3.2 Data Sources

The primary data source is the geoelectric measurement data with the dipole-dipole configuration at Mount Table. The secondary data source consists of: Geological and Geomorphological Data: Manokwari Quadrant Geological Map 1981 [11], Indonesian Geological Agency surveys, and Bird's Head Peninsula geological structure research. Climate and Hydrological Data: BMKG (Meteorology, Climatology, and Geophysics Agency) data [2], Ministry of Public Works and Housing (water resources data), international climate databases, and regional Papua hydrological studies.

Ecological and Biodiversity Data: Ministry of Environment and Forestry data, Papua conservation organizations, West Papua biodiversity research, forest and satellite monitoring data, and local conservation initiatives. Regional Hydrogeological Data: Regional hydrogeological mapping, aquifer surveys.

3.3 Analytical Methods Applied

Spatial Analysis: Geographic data integration using overlay approaches to identify potential groundwater zones based on combinations of geological factors, topography, vegetation cover, and rainfall patterns. Multi-Criteria Analysis: Application of a multi-criteria analysis framework to evaluate groundwater potential with weighting of geological factors (40%), climatological (30%), topography (20%), and vegetation cover (10%) based on regional literature. Analysis of geoelectric measurement results: Resistivity values associated with rock types and aquifers.

4 Results and Discussion

4.1 Geographical and Topographical Characteristics of Table Mountain

Table Mountain occupies a strategic position 2.5-3 km north of Manokwari city center with a total area of 462.16 hectares. This area exhibits topographic variation from flat to gently undulating in the eastern part, continuing to heavily undulating terrain from east to west with maximum elevation of 210 meters at Bonay Peak. Moderate relief with karst hills and karst topography creates a unique landscape of limestone cliffs, natural caves (19 caves identified with 4 large caves), and karst springs. These geomorphological characteristics indicate progressive karst development with complex underground drainage systems. The geographical position at coordinates 134°04' East Longitude and 0°52' South Latitude places the area 52 minutes (0.87 degrees) south of the equator, resulting in equatorial tropical climate conditions with minimal temperature variation throughout the year.

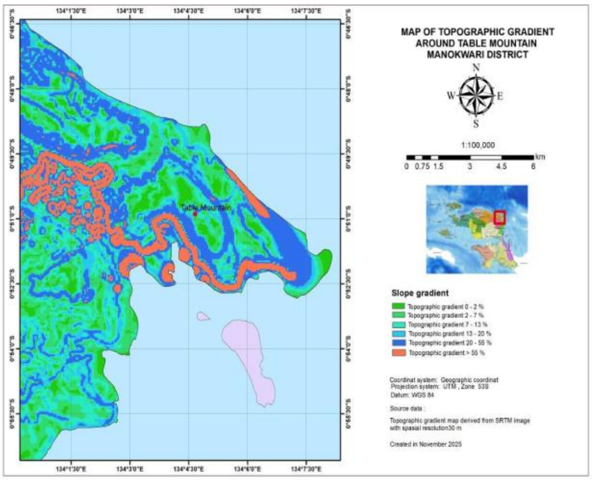

Fig.1. Map of Topographic Gradient around Table Mountain

This map shows the slope and steepness of the terrain. Topography significantly influences groundwater recharge as follows: Infiltration vs. runoff: Gentle slopes allow more time for water to infiltrate the ground, while steep slopes promote rapid surface runoff. Water accumulation: Flat or depression areas are zones where water can pond and percolate slowly downward. Drainage patterns: Topography controls how water moves across the landscape. Recharge efficiency: Lower gradient areas generally have higher recharge potential. Areas with moderate to low slopes typically receive higher scores for groundwater potential, whereas steep mountainous terrain scores are lower due to limited infiltration opportunities.

4.2 Geological Conditions and Rock Structure

The Manokwari Formation dominates the geology of the area, consisting of reef limestone with biomicrite, calcirudite, and minor calcarenite of Miocene to Pliocene ages [11]. The rock composition contained algae and foraminifera fossils, indicating a shallow marine depositional environment. Regional tectonic context places the area within the Bird's Head Peninsula terrane experiencing active oblique convergence with uplift rates up to 1.28 m/ka based on uranium-series dating.

Major fault systems including the Sorong Fault Zone, Yapen Fault, and Ransiki Fault influence the regional hydrogeological structure. Dominant soil types include reddish limestone soil, alluvial deposits, clay soil, rocky soil, and coral soil with very thin topsoil depths of <30 cm. Drainage is generally good because of the limestone bedrock and the developed karst features.

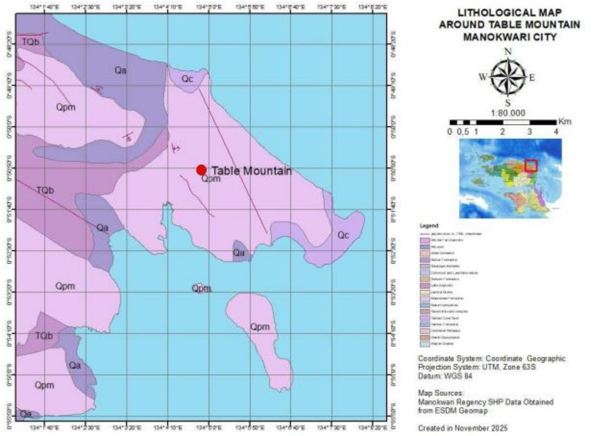

Fig.2. Lithological Map around Table Mountain

The lithological map shows the rock types and geological formations across the study area. This receives the highest weighting because rock type is the most critical factor controlling groundwater storage and movement. The different lithological units vary. Porosity and permeability: Some rocks (like sandstones, fractured limestones, and alluvial deposits) allow water to pass through easily and store significant amounts of groundwater. Fracture density: Fractured or weathered rocks create pathways for water infiltration. Aquifer potential: Certain formations act as good aquifers (water-bearing layers), whereas others are aquitards (impermeable barriers). The map categorizes rocks from high to low groundwater potential: - for example, unconsolidated sediments and highly fractured rocks would score higher than massive crystalline rocks or clay-rich formations.

4.3 Climate and Rainfall Analysis

The Manokwari area exhibits tropical rainforest climate classification (Af) with high precipitation throughout the year and a minimal dry season [2]. The total annual rainfall was 2,597 mm, with a monthly average of 216 mm and 265.74 rainy days per year (72.81% of the year). Seasonal distribution shows the wettest month in April (230.35 mm) and driest in September (114.96 mm), but even the "dry" period still receives substantial rainfall. This rainfall pattern strongly supports a continuous groundwater recharge throughout the year.

Atmospheric conditions with an average relative humidity of 78.74% and temperature variation of only 1°C throughout the year (25.67-28.01°C) create optimal conditions for hydrological processes.

Evapotranspiration is limited due to high humidity, optimizing the precipitation-to-recharge ratio. This map shows the spatial distribution of precipitation across the region. Rainfall is the primary source of groundwater recharge, making it the second-most important factor.

Key aspects include: Recharge zones: Areas with higher rainfall contribute more water to the groundwater system. Temporal distribution: The pattern and intensity of rainfall affect how much water infiltrates versus runoff. Regional variations: Mountainous areas typically receive more rainfall than lowlands. Climate patterns: The map reflects local climatological conditions that directly influence water availability. Higher rainfall zones correlate with a greater potential for groundwater recharge, assuming that geological conditions allow infiltration.

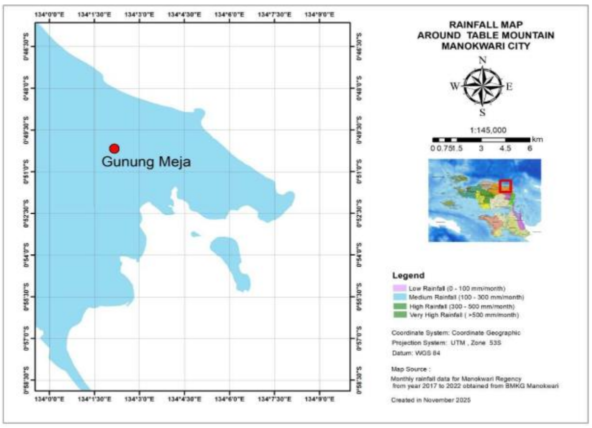

Fig.3. Rainfall Map around Table Mountain

4.4 Vegetation and Hydrology Function

Table Mountain Forest is classified as lowland tropical rainforest representative of the northern Papua coastal region. Forest structure shows typical stratification with emergent layer reaching 40 meters (especially Rainbow Tree - Eucalyptus deglupta), main canopy forming a 10-meter-thick layer, fragmented understory, and forest floor with limited vegetation. Dominant species composition included Pometia pinnata, Vitex confassus, Horsfieldia spp., Sterculia macrophylla, and various palm species including Licuala sp., Calamus aruensis, and Caryota rumphiana. Recorded biodiversity included 19 plant species, 23 bird species, and 11 animal species.

Hydrological function of vegetation is highly significant with the forest canopy intercepting ~95% of incident rainfall, regulating local evapotranspiration, and root systems facilitating deep groundwater infiltration [4]. High soil water content is indicated by wet-moist soil conditions and ideal fungal growth, showing excellent water storage capacity.

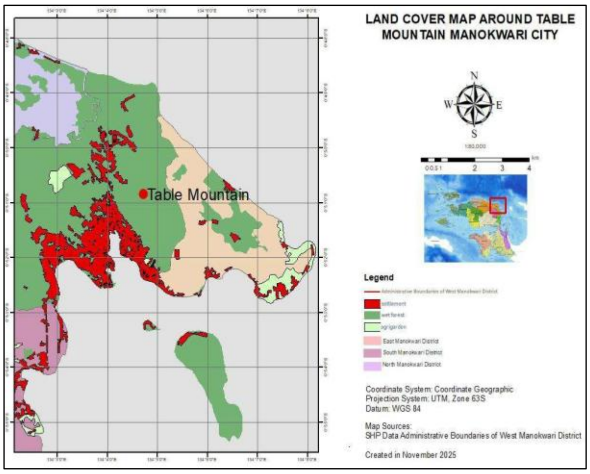

Fig.4. Land Cover Map around Table Mountain

This map depicts vegetation types and land-use patterns. At least weighted, land cover still affects the groundwater recharge. Vegetation effects: Dense vegetation can increase infiltration by slowing runoff and improving soil structure, but it also increases evapotranspiration. Soil protection: Vegetated areas reduce erosion and maintain soil permeability. Urbanization impacts: Built-up areas with impervious surfaces prevent infiltration. Agricultural lands: Different land uses have varying effects on water infiltration rates. Forested areas and natural vegetation generally favor groundwater recharge, whereas urbanized or barren lands may reduce it.

4.5 Aquifer System

Based on the geoelectric survey of five lines at Mount Table, the following results were obtained:

1. Line 1

Electrode Spacing: 5 m
Maximum Depth: ± 11 m
Resistivity Value: 57.3 – 4,900 Ωm
Error: 29.1%

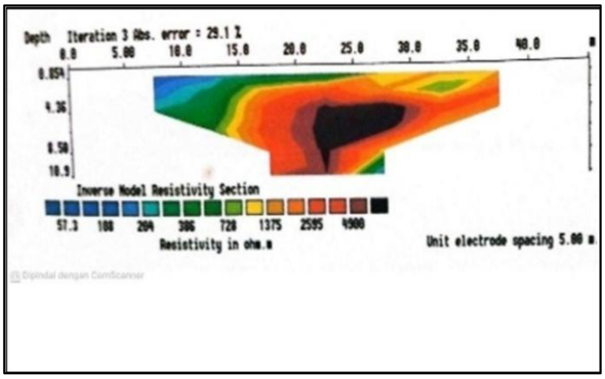

Fig.5. Geoelectric data Mount Table in line 1

2. Line 2

Electrode Spacing: 5 m
Maximum Depth: ± 11 m
Resistivity Value: 99.2 – 47,943 Ωm
Error: 19.8%

 https://doi.org/10.1051/bioconf/202621302012

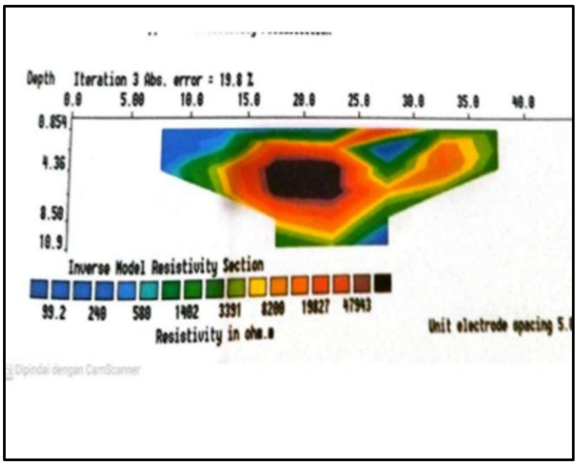

Fig.6. Geoelectric data Mount Table in line 2

Line 3
Electrode Spacing: 5 m
Maximum Depth: ± 11 m
Resistivity Value: 261 – 86,368 Ωm
Error: 13.9%

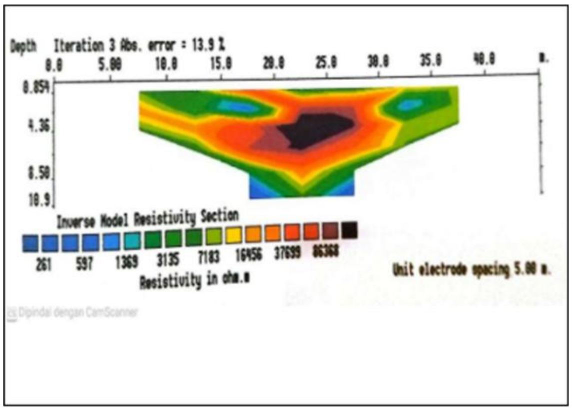

Fig.7. Geoelectric data Mount Table in line 3

Line 4
Electrode Spacing: 5 m
Maximum Depth: ± 11 m
Resistivity Value: 1,038 – 27,991 Ωm
Error: 10.0%

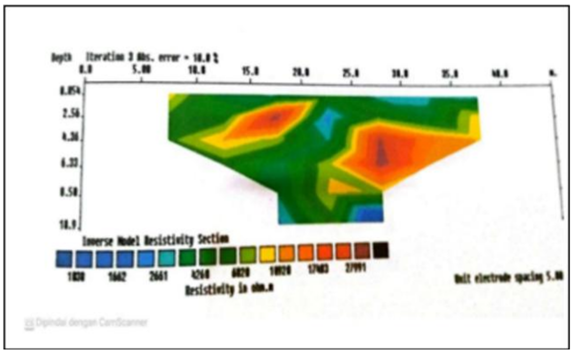

Fig.8. Geoelectric data Mount Table in line 4

Line 5
Electrode Spacing: 5 m
Maximum Depth: ± 11 m
Resistivity Value: 969 – 20,894 Ωm
Error: 1.89%

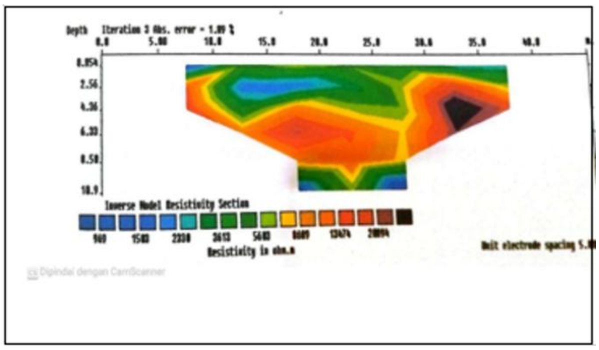

Fig.9. Geoelectric data Mount Table in line 5

4.5.1 Aquifer Types Identified

The study identified three main aquifer categories across the five survey lines: Shallow Unconfined Aquifers - Found in the uppermost layers with high porosity and permeability, primarily in topsoil, sandy clay, and alluvium. Potential Aquifers - Layers that could hold water if saturated, typically in weathered sedimentary rocks or sandstone. Non-aquifers/Aquitards: Compact rocks with very low porosity that do not store or transmit water effectively.

4.5.2 Depth Variations Across Survey Lines

The aquifer depths vary significantly depending on location: Line 1: Shallow aquifer from 0.854-4.36 m depth (resistivity 57.3-204 Ωm). Line 2: Shallow aquifer from 0.854-4.36 m depth (resistivity 99.2-580 Ωm). Line 3: Limited aquifer from 0-4.36 m depth (resistivity 261-1,369 Ωm). Line 4: Low potential aquifer from 0.854-2.56 m depth (resistivity 1,038-2,661 Ωm) - the shallowest. Line 5: Unconfined aquifer from 0.854-2.56 m depth (resistivity 969-1,603 Ωm).

4.5.3 Bedrock Layer Characteristics

The bedrock (basement) appears at varying depths with distinctively high resistivity values: Line 1: Depth 8.50-10.9 m, resistivity 2,595-4,900 Ωm (andesite, hard breccia). Line 2: Anomaly at 4.36-8.50 m, resistivity 19,827-47,943 Ωm (massive igneous rock, very hard breccia). Line 3: Depth 4.36-10.9 m, resistivity 37,699-86,368 Ωm (granite/massive andesite) - highest resistivity. Line 4: Depth 6.33-10.9 m, resistivity 17,483-27,991 Ωm (massive breccia). Line 5: Anomaly at 2.56-8.50 m, resistivity 13,474-20,894 Ωm (massive igneous rock or hard breccia).

The best aquifer potential is in lines 1, 2, and 5, where shallow unconfined aquifers exist at depths of 0.854-4.36 m. The bedrock typically begins at a depth of approximately 6-9 m with resistivity values exceeding 13,000 Ωm, indicating an impermeable basement rock that prevents deeper groundwater circulation. The maximum investigation depth across all survey lines was approximately 11 m. Table Mount aquifer system exhibits extraordinary productivity with 44 active springs classified as 7 government-managed springs, 1 military spring (Korem 1703), and 36 springs utilized by communities. Spring discharge varies with some springs producing up to 5 liters/second [15]. Recharge zones are facilitated by forest cover, which provide natural recharge for the groundwater system with discharge points through natural springs indicating good groundwater circulation.

4.6 Factors Affecting Groundwater Potential

By overlaying the maps above with weighting of geological factors (40%), climatological factors (30%), topography (20%), and vegetation cover (10%), a groundwater potential map was produced. The resulting map typically shows groundwater potential zones in Table Mountain classified as high potential areas where favorable lithology (permeable rocks), high rainfall, gentle slopes, and suitable land cover all coincide suitable for groundwater development with good yields.

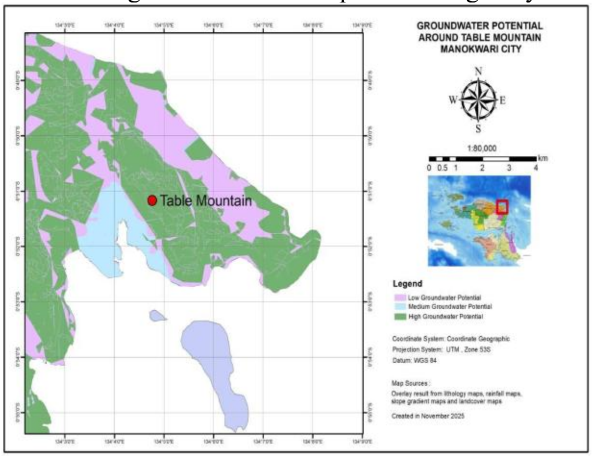

Fig.10. Groundwater Potential Map around Table Mount

4.7 Aquifer Potential and Sustainable Development Goals (SDGs) Implications

4.7.1 Water Resource Management (SDG 6)

Based on Water Resource Management (SDG 6) results: 1. High Aquifer Potential Zones: Line 1 (0.854-4.36 m): shallow unconfined aquifer with high porosity, - suitable for community wells. Line 2 (0.854-4.36 m): shallow unconfined aquifer with alluvial deposits, - excellent for water supply. Line 5 (0.854-2.56 m): Unconfined aquifer in sandy clay formation, - inaccessible groundwater source. 2. Moderate Aquifer Potential: Lines 1, 2, and 5 show the potential at intermediate depths (4.36-8.50 m) when water is saturated.

Recommendations for Sustainable Water Management: Prioritize shallow aquifer development (0.85-4.36 m depth) for community water supply. Implement monitoring systems to prevent over-extraction and maintain aquifer sustainability. Protect recharge areas to ensure long-term groundwater availability. Consider managed aquifer recharge (MAR) strategies in high-potential zones.

4.7.2 Geological Insights for Land Conservation (SDG 15)

Based on Geological Insights for Land Conservation (SDG 15) results: 1. Subsurface Structure: Surface layer (0-4.36 m): Weathered sediments and alluvium supporting soil development and vegetation. Intermediate layer (4.36-8.50 m): Mixed sedimentary rocks with varying permeability. Deep layer (8.50-10.9 m): Basement rocks (andesite, granite, and breccia) forming geological foundation. 2. Ecosystem Support Functions: Shallow aquifers provide baseflow to springs and streams, supporting riparian ecosystems. Weathered rock layers facilitate root penetration and nutrient cycling for terrestrial vegetation.

Groundwater-surface water interactions maintain wetland habitats and biodiversity. Land Management Recommendations: Protect shallow aquifer recharge zones from land degradation and contamination. Integrate hydrogeological data into spatial planning for conservation areas. Monitor groundwater levels to detect early signs of ecosystem stress. Promote land use practices that enhance natural infiltration and aquifer recharge.

The Mount Table groundwater conservation strategy requires an ecosystem-based management approach that integrate biodiversity conservation and hydrological function protection. The conservation framework should apply ridge-to-reef management principles that connect forest catchment zones with aquifer systems and coastal discharge zones. Conservation zonation is recommended with a core zone of 300 ha for strict protection of springs and primordial vegetation, a buffer zone of 100 ha for research and limited access, and a transition zone of 62 ha for sustainable use and community engagement.

5 Conclusions and Recommendations

5.1 Conclusions

Table Mount Forest demonstrates high groundwater resource potential with unique hydrogeological characteristics that make it strategic for regional groundwater conservation. The application of multi-criteria analysis framework produces a groundwater potential map of Table Mount as a High Potential Area zone. The Manokwari Formation dominated by Miocene-Pliocene reef limestone provides a karst aquifer system with a significant storage capacity [11, 15]. Geoelectric surveys identified shallow unconfined aquifers at 0.854-4.36 m depth with optimal conditions in survey lines 1, 2, and 5. The study recommends ecosystem-based management with three conservation zones: core (300 ha), buffer (100 ha), and transition (62 ha), alongside monitoring networks, 50-meter spring protection buffers, and climate adaptation strategies.

5.2 Recommendations

5.2.1 Further Research Recommendations

Priority hydrogeological research includes comprehensive aquifer characterization using geophysical methods (resistivity and, seismic), detailed groundwater flow modeling with numerical simulation, and climate change impact assessment of groundwater recharge patterns using downscaled climate models. Ecosystem services valuation to quantify economic benefits from groundwater services, carbon sequestration, and biodiversity conservation to support payment for ecosystem services schemes. Traditional ecological knowledge documentation to integrate indigenous water management practices with scientific approaches. Long-term monitoring programs have established automated systems for continuous data collection, remote sensing integration for landscape change detection, and community-based monitoring protocols for sustainable management. Comparative studies with similar karst systems in Indonesia have developed best practices [1].

5.2.2 Implementation of Recommendations

Immediate actions include the establishment of a comprehensive monitoring network, implementation of spring protection protocols with 50-meter protection radius, and an invasive species control program for 39 identified invasive plants. Legal framework development through local regulations for groundwater protection with clear enforcement mechanisms [13]. Medium-term strategies focus on integrated watershed management with a multi-stakeholder governance structure, sustainable extraction limit implementation based on safe yield calculations, and climate adaptation measures to enhance forest resilience and water storage capacity.

Long-term vision toward a conservation model that can be replicated in similar areas across Papua with the successful integration of biodiversity protection, groundwater conservation, and sustainable community development [14]. Regional cooperation with research institutions, government agencies, and international organizations for knowledge sharing and capacity building. Policy implications for the West Papua Conservation Province strategy with Mount Table as a demonstration site for integrated ecosystem management [14]. Scaling up successful conservation approaches to achieve 70% conservation targets under the Manokwari Declaration with emphasis on the groundwater-forest-biodiversity nexus [13].

References

1. Adyasari, D., Pratama, M. A., Santoso, A. B., & Teguh, N. A. (2018). Groundwater-surface water interactions in tropical karst systems: Hydrochemical evidence from South Java, Indonesia. *Hydrogeology Journal*, 26(4), 1435-1451.
2. Badan Meteorologi, Klimatologi, dan Geofisika (BMKG). (2024). *Data Iklim Manokwari 2015-2024*. Stasiun Meteorologi Rendani Manokwari.
3. Balai Konservasi Sumber Daya Alam Papua Barat. (2019). *Rencana Pengelolaan Taman Wisata Alam Table Mountain 2020-2029*. Manokwari: BKSDA Papua Barat.
4. Bruijnzeel, L. A. (2004). Hydrological functions of tropical forests: Not seeing the soil for the trees? *Agriculture, Ecosystems & Environment, 104*(1), 185-228. https://doi.org/10.1016/j.agee.2004.01.015
5. Ellison, D., Morris, C. E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., ... & Sullivan, C. A. (2017). Trees, forests and water: Cool insights for a hot world. *Global Environmental Change*, 43, 51-61.
6. Filoso, S., Bezerra, M. O., Weiss, K. C., & Palmer, M. A. (2017). Impacts of forest restoration on water yield: A systematic review. *PLoS ONE, 12*(8), e0183210. https://doi.org/10.1371/journal.pone.0183210
7. Ilstedt, U., Bargués Tobella, A., Bazié, H. R., Bayala, J., Verbeeten, E., Nyberg, G., ... & Malmer, A. (2016). Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. *Scientific Reports*, 6, 21930.
8. International Groundwater Resources Assessment Centre (IGRAC). (2020). *Indonesia Country Profile: Groundwater Resources and Management*. UN-IGRAC, Delft.
9. Krishnaswamy, J., Bonell, M., Venkatesh, B., Purandara, B. K., Rakesh, K. N., Lele, S., ... & Braun, J. J. (2013). The groundwater recharge response and hydrologic services of tropical humid forest ecosystems to use and reforestation: Support for the "infiltration-evapotranspiration trade-off hypothesis". *Journal of Hydrology*, 498, 191-209.
10. Mausio, K., van der Ploeg, J., & Wollenberg, E. (2022). Understanding the impacts of gold mining on livelihoods and food security in Papua, Indonesia. *Extractive Industries and Society, 10*, 101076. https://doi.org/10.1016/j.exis.2022.101076
11. Nana, R., & Robinson, G. P. (1981). *Peta Geologi Kuadran Manokwari, Irian Jaya*. Pusat Penelitian dan Pengembangan Geologi, Bandung.
12. PDAM Manokwari. (2022). *Laporan Tahunan PDAM Kabupaten Manokwari 2021*. Manokwari: PDAM Kabupaten Manokwari.
13. Pemerintah Provinsi Papua Barat. (2018). *Deklarasi Manokwari: Komitmen Konservasi Papua Barat*. Manokwari: Pemerintah Provinsi Papua Barat.
14. Rayadin, Y., & Snoep, M. (2021). Conservation province in practice: A case study from West Papua, Indonesia. *Land, 10*(11), 1163. https://doi.org/10.3390/land10111163
15. Siahaya, M. E., Hutauruk, T. R., & Aponno, H. S. E. S. (2021). Evaluasi kualitas air mata air Table Mountain sebagai sumber air baku PDAM Manokwari. *Jurnal Penelitian Kehutanan Wallacea, 10*(1), 13-2