Application of Frequency Ratio analysis and GIS techniques for Groundwater Potential Zone Mapping in the ultramafic hard rock terrain of Manoligao Watershed, Dinagat Islands, Philippines

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Application of Frequency Ratio analysis and GIS techniques for Groundwater Potential Zone Mapping in the ultramafic hard rock terrain of Manoligao Watershed, Dinagat Islands, Philippines

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Abstract: *Groundwater is a vital water source in rural areas such as Sitio Manoligao, where it occurs as springs. This study used a bivariate statistical method with GIS software to map Groundwater Potential Zones (GWPZ) in an area underlain by ultramafic rocks, where groundwater occurs primarily through secondary features like fractures and joints. Six thematic factors were analyzed: geology, geomorphology, slope, drainage density, lineament density, and land use and land cover. The resulting GWPZ map showed that the watershed is mainly classified as very low (52.14%) and low (32.47%) in potential, while moderate, high, and very high zones account for 10.37%, 2.44%, and 1.64%, respectively. Validation with discharge values shows springs in high and very high zones recorded greater discharge, with Spring 3 reaching 0.011939 m³/s. These findings highlight the need to integrate groundwater assessments into watershed conservation initiatives.*

Keywords: Groundwater Potential; GIS; Frequency Ratio; Manoligao Watershed, Dinagat Islands

1. INTRODUCTION

Groundwater is a vital natural resource that supports domestic and agricultural needs, particularly in regions where surface water is limited or unreliable. In hard-rock terrains, the search for groundwater becomes more complex due to the inherently low porosity and permeability of the underlying geological formations [1] [2]. These terrains are typically composed of compact crystalline rocks, known in hydrogeology as “hard rock,” which lack the capacity to store or transmit groundwater through primary pores. Instead, groundwater occurrence in such environments is largely controlled by secondary features such as fractures, faults, and joints [2].

The Manoligao watershed, located on Dinagat Islands in the Philippines, is underlain by ultramafic rocks that are characteristically impermeable and poor in groundwater storage potential [3]. Despite this, groundwater can still be present in the area, particularly within fracture zones and other structural discontinuities. These features are often detected as lineaments in satellite imagery and serve as important pathways and storage zones for groundwater [4].

Along with lineament density, several hydrogeomorphic factors such as geology, geomorphology, slope, drainage density, and land use or land cover also influence groundwater occurrence and distribution. The integration and analysis of these factors through Remote Sensing (RS) and Geographic Information System (GIS) techniques offer an efficient and spatially-informed approach to identify groundwater potential zones [5].

In the Philippines, geospatial methods have been successfully employed in groundwater studies. For example, the Analytical Hierarchy Process (AHP) was used in the Mt. Makiling Forest Reserve to identify recharge areas [6], while the Frequency Ratio (FR) method has been applied in Cebu Island to map groundwater potential [7]. However, no existing groundwater-focused assessments have been conducted in Dinagat Islands. Recent studies in the province have concentrated on land cover characterization, water quality, and geologic or hydrologic mapping, such as in the Sambunotan watershed in the northern portion of the island [8,9], but comprehensive studies dedicated to groundwater potential are lacking. This presents a critical gap in water resource planning and watershed conservation, especially considering that the island is composed predominantly of hard-rock formations and that several portions in the communities rely on groundwater as a primary water source.

This study was conducted to address the lack of groundwater data in the Manoligao Watershed by mapping and analyzing groundwater potential using the Frequency Ratio (FR) method within a GIS framework [10]. These layers were integrated to produce a final groundwater potential map that identifies areas suitable for groundwater extraction, recharge, and protection. The study also sought to highlight vulnerable zones that may be prone to contamination or drought.

The findings of this research are significant in several ways. First, they provide the first baseline groundwater assessment for the Manoligao Watershed, supporting evidence-based water management in a region with limited hydrological data. Second, the study demonstrates the applicability of remote sensing and statistical modeling in hard-rock hydrogeology, offering a replicable method for other similar terrains in the country. Most importantly, the output groundwater potential map can serve as a decision-support tool for local planners, conservationists, and government agencies involved in the development of a comprehensive watershed management plan. It contributes to sustainable water resource planning by identifying both extraction zones and areas that require protection, ultimately enhancing water security for the local communities of Dinagat Islands.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted at the Manoligao Watershed, located in the Municipality of Cagdianao, Dinagat Islands, at geographic coordinates 10.041543° N latitude and 125.679288° E longitude. The watershed spans approximately 24.945 km², making it one of the largest on Dinagat Islands (Fig. 1) [8]. It serves as a critical water source for local communities, supporting both agricultural and domestic needs. Additionally, the watershed functions as the primary tributary for the municipalities of Cagdianao and San Jose. Sitio Manoligao, a rural area within the watershed, is accessible only via a one-hour boat ride from Sitio Cagdianao or through a one-day trek across mountainous terrain. The Dinagat Islands fall under Type II climate according to the Modified Coronas Classification, characterized by the absence of a dry season and a very pronounced maximum rainfall period from December to February. There is not a single dry month, with minimum monthly rainfall typically occurring between March and May [11]. According to the general soil map of the Philippines, the Manoligao Watershed in Cagdianao is characterized by uniform soil composition dominated by Acrisols and Alisols (Ultisols). These reddish, clayey, and acidic soils are typical of tropical uplands, hills, and ridges with good drainage, where intense weathering and leaching occur [12]. Due to the absence of spatial variability of soil, it is not included as one of the factors in this study.

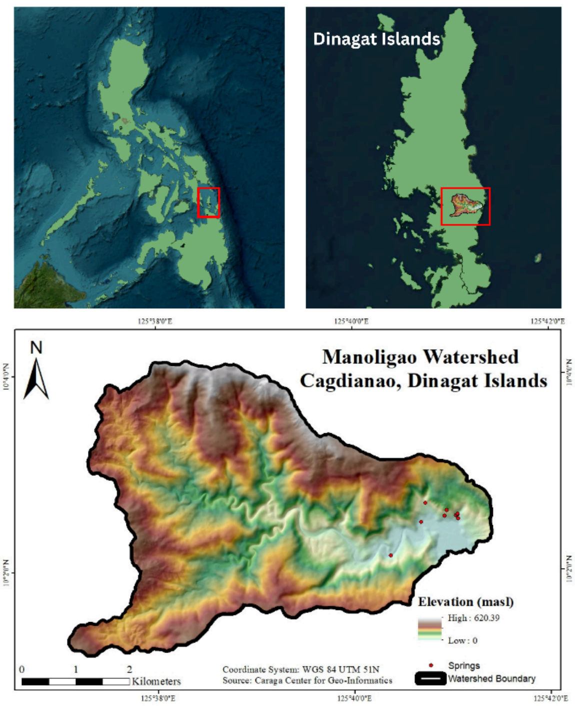


Fig. 1. Map of the study area in Cagdianao, Dinagat Islands, Philippines, including the validated spring location.

2.2 Frequency Ratio (FR) Model

Frequency Ratio (FR) is a bivariate statistical approach used to determine the probability of groundwater potential areas based on the relationship between observed dependent variables (in this study, springs) and independent variables (groundwater-influencing factors). Many researchers have successfully applied FR models for groundwater potential mapping [10,13,14]. The FR value attributed to each class of groundwater-related factors can be effectively calculated using Eq. 1:

$$FR = \frac{\frac{S}{TS}}{\frac{A}{TA}} = \frac{\%Springs}{\%Area} \qquad \text{Eq. 1}$$

where FR is the frequency ratio for a given class of a factor, S is the number of springs in each class, TS is the total number of springs in the study area, A is the area in each thematic class, and TA is the total area in the study area. The Frequency Ratio and Weighted Sum tools in ArcMap 10.4 are applied to develop the model. Groundwater Potential or GWPZ for each pixel can then be determined according to Eq. 2:

Eq. 2

$$GWPZ_{FR} = \sum_{i-1}^{n} (G_{FR} + GM_{FR} + LULC_{FR} + DD_{FR} + LD_{FR} + SL_{FR})$$

$GWPZ_{FR}$ represents the Groundwater Potential Zone frequency ratio for a given area. The summation incorporates several key parameters that influence groundwater potential, including the frequency ratios of geology (G_{FR}), geomorphology (GM_{FR}), land use/land cover ($LULC_{FR}$), drainage density (DD_{FR}), lineament density (LD_{FR}), and slope (SL_{FR}). By evaluating and summing these factors across the study area, the model provides an integrated assessment of areas with high groundwater potential [10].

2.3. Factors Affecting Groundwater Potential

In general, mapping groundwater potentiality depends on a variety of conditioning factors, which depend on data available in the study area and also as to what type of terrain is present [15]. In the present study, six groundwater-influencing factors are used.

2.3.1 Geology

The spatial distribution, occurrence, and quality of groundwater are significantly influenced by the type of lithology present in the study area. Dinagat Island is largely underlain by the Dinagat Ophiolite, and in the Manoligao Watershed, the mantle section is exposed, consisting primarily of harzburgite with minor occurrences of dunite (Fig. 2) [3]. Although there are two lithologies, both are classified as peridotites, commonly referred to as hard rocks. This limited variation in geology means it does not significantly influence the groundwater potential map as a thematic layer. Both lithologies are types of ultramafic rocks that, in hydrogeological terms, exhibit secondary porosity. In these rocks, groundwater primarily moves through fractures, in contrast to sedimentary rocks, which typically have better primary porosity and permeability. Field mapping did not reveal the physical contact between the two lithologies, but the blocky harzburgite observed in the area commonly displays jointing and fractures.

2.3.2 Geomorphology

Geomorphology refers to the study of landforms and surface processes that influence groundwater movement. In this study, geomorphological classification was based on a modified approach by ACER OMEGA-PHIVOLCS, using elevation and slope gradient derived from DEM data [16]. The area was divided into five geomorphic units: plains (elevation below 5 meters), upper plains (5–50 meters), low slopes, denudational slopes, and highlands (above 500 meters), located in the northern portion of the watershed (Fig. 2). Denudational slopes cover the largest portion of the study area.

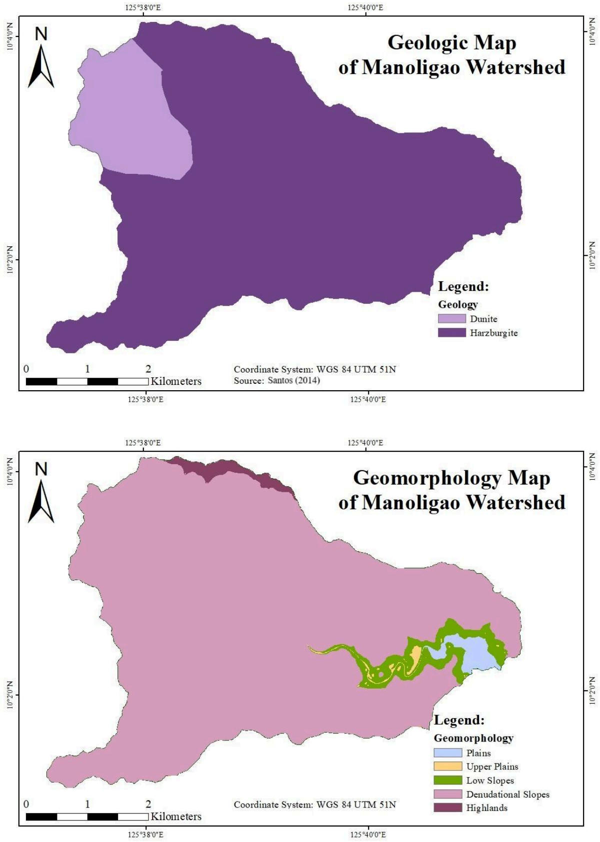


Fig. 2. Geologic (top) and geomorphology (bottom) maps of the Manoligao watershed.

2.3.4 Land Use and Land Cover (LULC)

The land use and land cover (LULC) map classifies the watershed into several categories: closed forest, open forest, shrubs, grassland, cropland, perennial crops, barren areas, built-up zones, mangroves, and water bodies. Closed forest covers the largest area, accounting for 44.03% of the watershed, followed by shrubland at 30.35% and open forest at 10.74%. Grasslands cover 7.97%, while cropland (0.26%), perennial crops (0.23%), and built-up areas (0.16%) occupy smaller portions. Water bodies account for 1.78%, and mangroves cover 0.75%. Built-up areas are mainly located near the river delta, where coastal communities are concentrated (Fig. 3). This map was produced by the Caraga Center for Geo-Informatics.

2.3.5 Slope

Slope is a key factor affecting surface runoff and infiltration. Steeper slopes promote rapid runoff, while gentler slopes allow more infiltration. In flat areas, the velocity of water flow is slow, and thus water stays longer, as a result, more water infiltrates the ground [17]. For this study, slope values were categorized into five classes: 0–9.82% (dark green), 9.82–16.58% (light green), 16.58–23.13% (yellow), 23.13–30.76% (orange), and 30.76–55.64% (red). The spatial distribution indicates a mix of gentle and steep terrain within the watershed (Fig. 3). Steeper slopes are concentrated in the central and northern parts, while gentler slopes are more common in the southern and western areas.

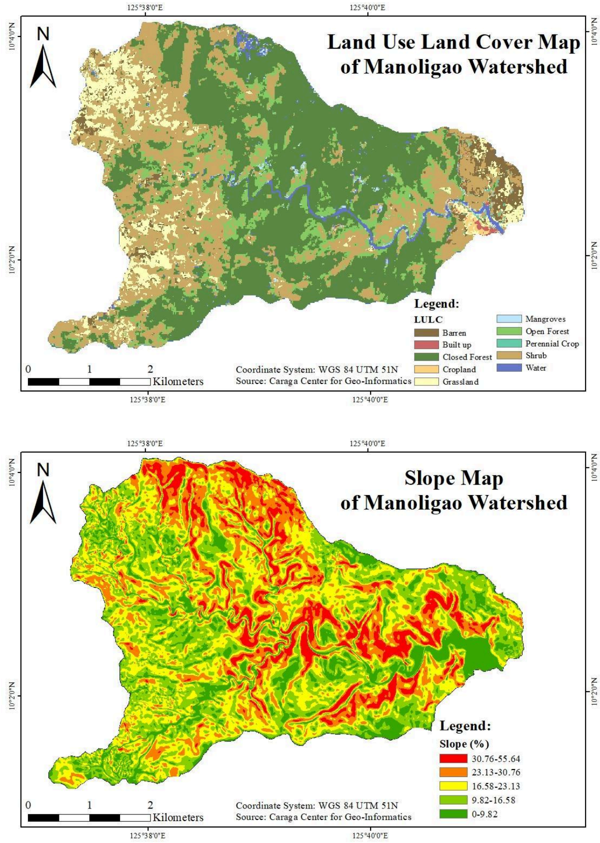


Fig. 3. LULC (top) and slope (bottom) maps of the Manoligao watershed.

2.3.6 Drainage Density (DD)

Drainage density (DD) is an important indirect indicator of groundwater potential, as it is inversely related to infiltration capacity and permeability [18]. Higher DD values suggest increased surface runoff and reduced infiltration, indicating low groundwater potential [5]. Conversely, lower DD values are associated with higher infiltration and, therefore, greater potential for groundwater recharge [19]. In this study, the drainage network was extracted from DEM data provided by the Caraga Center for Geo-Informatics. The data were classified into five classes, ranging from 51.95 to 470.67 (Fig. 4).

2.3.7 Lineament Density (LD)

Faults and joint systems play a crucial role in the occurrence and local recharge of groundwater. Lineaments are structurally controlled linear features that indicate zones of faulting and fracturing [1]. These features are typically associated with increased porosity and permeability due to localized weathering. As such, they are valuable indicators of groundwater movement and storage and serve as important guides for groundwater exploration [2]. The LD was produced using a line density tool. In the study area, lineament density ranges from 0.00 to 22.44 and is classified into five classes (Fig. 4). Areas with high lineament density, especially near the main river network, are considered potential recharge zones. In contrast, lower lineament density corresponds to reduced groundwater potential [4].

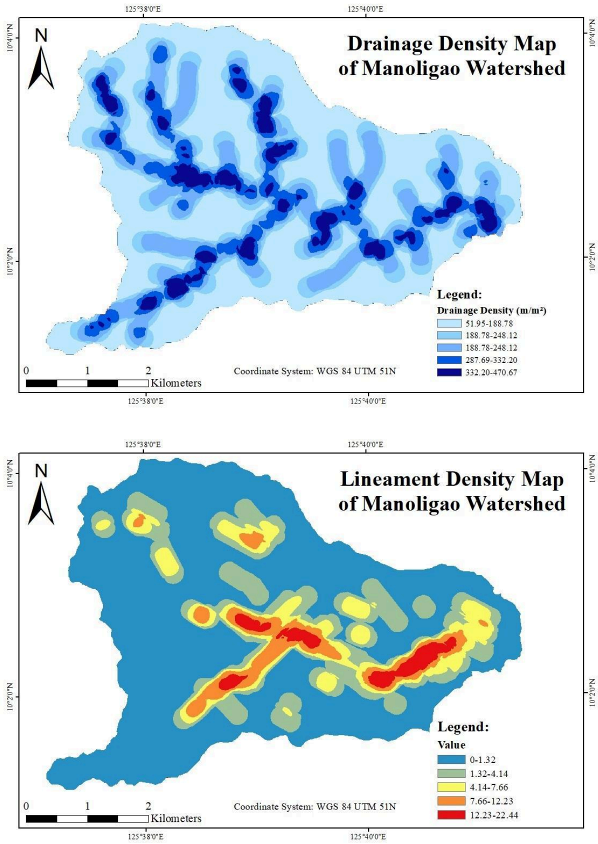


Fig. 4. Drainage density (top) and lineament density (bottom) maps of the Manoligao watershed.

2.2. Methodological Framework

Conventional data and DEM-derived datasets were acquired and processed to generate six thematic maps, including geology, geomorphology, drainage density, slope, LULC, and spring location maps (Fig. 5). Field mapping conducted by the team has identified springs that are used as training data for frequency ratio (FR) analysis. After reclassification of the thematic layers, each was converted from raster to polygon format using the raster to polygon tool. Polygons representing the same class were merged using the dissolve tool, which facilitated the aggregation and analysis of spring occurrences within each class. The spring counts per class were determined using the select by location tool. Table 1 contains the primary data collected and utilized for the analysis.

The attribute tables of these polygon layers were further enhanced with four new columns: spring count, spring percentage (number of springs per class divided by the total springs), area percentage (class area divided by total watershed area), and frequency ratio (spring percentage divided by area percentage), all calculated using the field calculator. These enhanced polygon layers were then converted back to raster format with pixel values based on the frequency ratio. Subsequently, weighted overlay analysis was done to produce a composite groundwater potential map. The continuous output raster was then reclassified into five discrete groundwater potential zones using the reclassify tool with the natural breaks (Jenks) classification method.

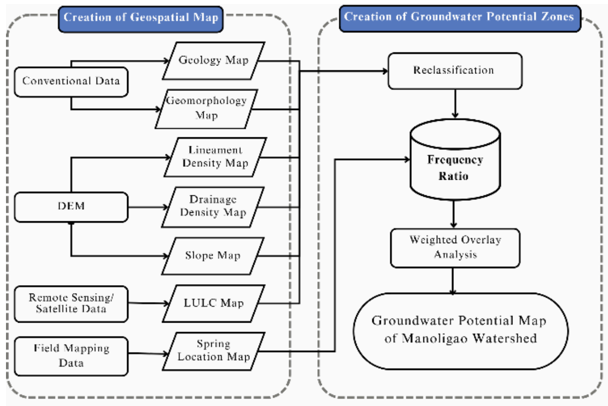


Fig. 5. Methodological framework of the study.

3. RESULTS AND DISCUSSION

3.1 Field Occurrence of Springs

The springs documented during fieldwork provide direct evidence of shallow groundwater discharge in a hard rock terrain, where water storage and movement are highly dependent on secondary features (Fig. 1). Springs emerge from fractured harzburgite outcrops (Fig. 6a), confirming that jointed ultramafic rock plays a significant role in groundwater flow. Fracture orientation was measured using a Brunton compass, and a consistent northwest (NW) orientation was observed across multiple spring locations (Figs. 6a–b). This aligns with the dominant lineament trends derived from remote sensing data (Fig. 4), suggesting that spring occurrence is structurally controlled. Figures 6c and 6d show how local residents use water pipes to collect groundwater. Man-made pool basins at the base of the springs are also covered with nets, and some cover the openings of the water pipes to filter and prevent twigs and leaves from contaminating the collected water (Figs. 6e–f).

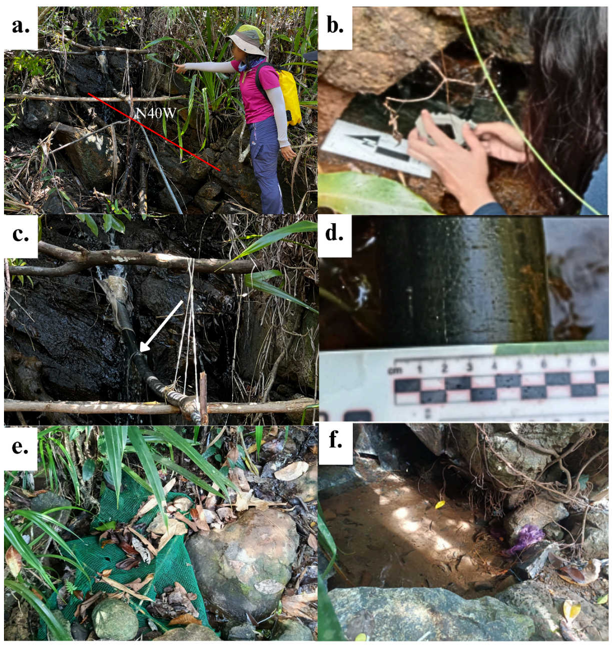


Fig. 6. Field photos of the springs

3.2 FR Groundwater Potential Zone Map

Among the two lithological units mapped in the study area, only harzburgite showed a positive association with groundwater occurrence, with an FR of 1.14 (Table 1). Both are classified as ultramafic peridotites and generally exhibit low primary porosity. However, field observations revealed that springs discharge from fractures and joints within blocky harzburgite outcrops (Fig. 6), highlighting the role of secondary porosity in groundwater storage [1][4]. In contrast, dunite, which recorded no associated springs, is primarily distributed in the western headwater portion of the watershed, an area likely less conducive to recharge due to its structural or topographic conditions (Fig. 3).

The geomorphological class of low slopes recorded the highest FR (20.6), identifying it as the most favorable landform for groundwater accumulation (Table 1). Denudational slopes and hills, while occupying a large portion of the watershed (Fig. 2), had a much lower FR of 0.22. Other units, such as plains and highlands, showed negligible associations. These results support the understanding that gentle slopes encourage infiltration by allowing water to remain longer on the surface, whereas steep or rugged terrain increases runoff and limits subsurface recharge [20].

Further analysis of slope gradients confirmed that gently sloping areas (0–9.82%) and moderately sloping zones (9.82–16.58%) are most favorable for recharge, with FRs of 1.54 and 1.47, respectively (Table 1). These zones represent a balance between water retention and surface flow [5]. In contrast, slopes steeper than 23% yielded lower FRs, suggesting that increased runoff on steeper slopes reduces infiltration capacity. These findings highlight slope as a critical topographic factor influencing groundwater potential [19].

The role of lineament density was also evident, with areas having moderate to high lineament densities (4.14–7.66 and 7.66–12.23) recording high FRs of 8.04 and 3.95, respectively (Table 1). These lineaments, which represent structural features such as faults and fractures, enhance secondary porosity and permeability [2], facilitating subsurface water movement and localized storage, particularly important in hard rock environments like Manoligao.

Drainage density followed a similar pattern. Intermediate classes (248.13–287.69 and 287.70–332.20) showed relatively high FRs of 2.15 and 3.50 (Table 1), suggesting favorable recharge conditions. These areas likely represent an optimal balance between surface runoff and infiltration. Field validation supports this finding: springs and seepages were observed along riverbanks near blocky harzburgite outcrops (Fig. 6). These zones align with moderately drained areas and follow the course of the Manoligao River, which appears structurally controlled by regional lineaments (Fig. 4). The presence of fractures likely enhances both vertical infiltration and lateral subsurface flow, explaining the higher potential in these areas [4].

For land use and land cover (LULC), shrublands and river zones exhibited the highest association with groundwater occurrence (Table 1) [20]. Open forest also showed a positive, though more moderate, influence. In contrast, cropland, grassland, mangroves, and barren areas had FRs of zero. These results suggest that natural vegetation cover and proximity to watercourses support infiltration by maintaining soil structure and moisture. On the other hand, anthropogenic land uses likely inhibit recharge through surface sealing, increased runoff, or degradation of soil permeability [5].

Table 1. Statistical analysis of dependent and independent variables in the study.

Parameter	Class	A	TS	SP	AP	FR
G	Dunite	3.13	0	0	0	0
	Harzburgite	21.82	10	1	0.87	1.14
GM	Plains	0.35	0	0	0	0
	Upper Plains	0.09	0	0	0	0
	Low Slopes	0.97	8	0.8	0.04	20.6
	Denudational Slopes & Hills	23.01	2	0.2	0.92	0.22
	Highlands	0.35	0	0	0.01	0
LULC	Grassland	1.98	0	0	0.08	0
	Cropland	0.06	0	0	0.00	0
	Open forest	2.68	1	0.1	0.93	0.93
	Closed forest	10.97	1	0.1	0.44	0.23
	Shrub	7.57	7	0.7	0.30	2.31
	Built up	0.04	0	0	0.002	0.94
	Barren	0.94	0	0	0.04	0
	Perennial Crop	0.44	0	0	0.00	0
	Mangroves	0.06	0	0	0.002	0
	River	0.19	1	0.1	0.007	13.43
SL	30.76-55.64	2.35	1	0.1	0.09	1.06
	23.13-30.76	4.99	3	0.3	0.20	1.50
	16.58-23.13	7.33	0	0	0.29	0
	9.82-16.58	6.80	4	0.4	0.27	1.47
LD	0-9.82	3.30	2	0.2	0.13	1.51
	1.32-4.14	4.23	1	0.1	0.59	0.59
	4.14-7.66	2.17	7	0.7	8.04	8.04
	7.66-12.23	1.26	2	0.2	3.95	3.95
	12.23-22.44	0.66	0	0	0	0
DD	51.95-188.8	11.86	1	0.1	0.48	0.21
	188.8-248.12	3.93	1	0.1	0.16	0.63
	248.1-287.7	4.64	4	0.4	0.19	2.15
	287.7-332.20	2.85	4	0.4	0.11	3.50
	332.20-470.7	1.67	0	0	0.07	0

G=Geology, GM=Geomorphology, LULC=Land Use/Land Cover, SL=Slope, LD- Lineament Density, DD=Drainage Density, A=Area of Class, S=Springs in Class, SP= Spring Percentage. AP= Area Percentage, FR= Frequency Ratio

The FR model in this study produced Groundwater Potential Index (GWPI) values ranging from 0.222 to 48.24, which were classified into five potential classes, very low, low, moderate, high, and very high, using the Jenks natural breaks classification method (Fig. 7 & Table 2).

Table 2. The distribution of groundwater potential values and areas in Manoligao watershed.

GWPZ	Class	Area (km^2)	Percentage (%)
Very Low	0.22-4.36	13.03	52.14%
Low	4.36-9.07	8.12	32.47%
Moderate	9.07-19.05	2.60	10.37%
High	19.05-29.60	0.61	2.44%

Very High	20.60-48.24	0.41	1.64%

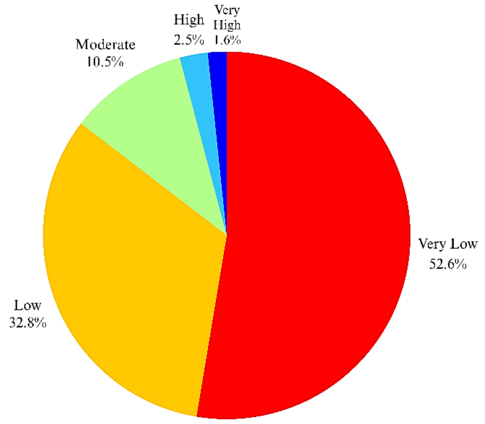


Fig 7. Percentage of groundwater potential zones in the study area.

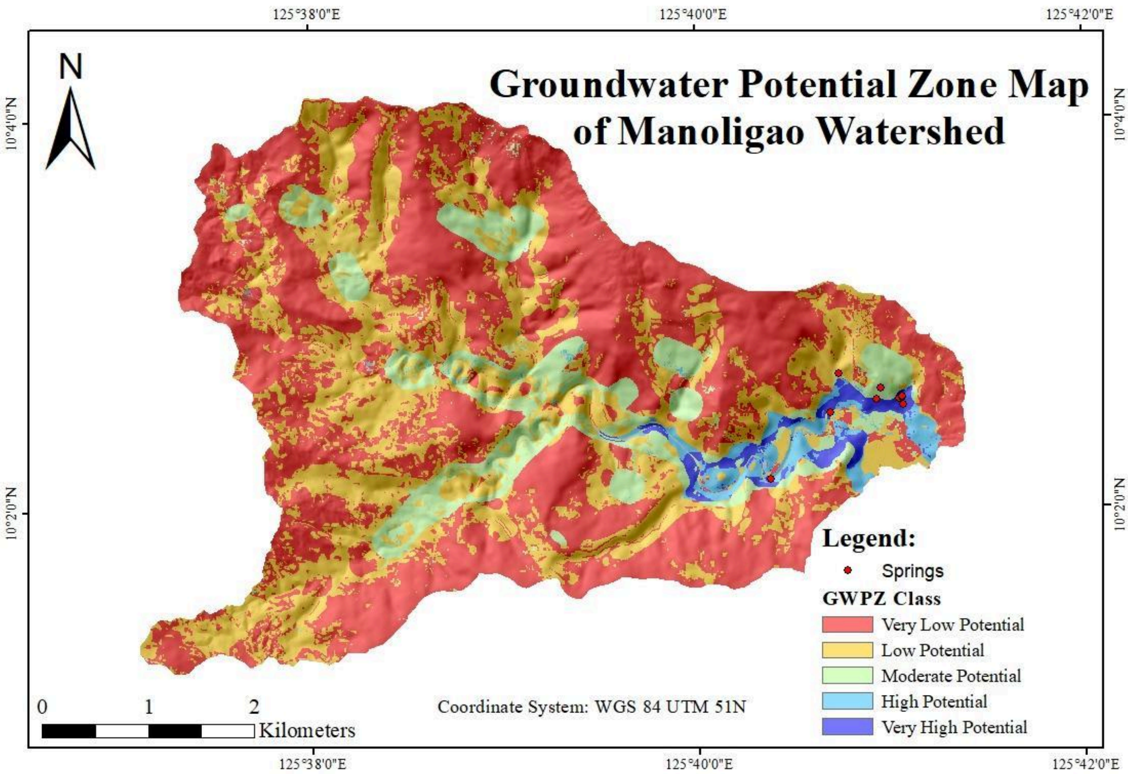
Very low to low groundwater potential zones dominate the Manoligao Watershed (Fig. 8), covering much of the upper and central areas where steep terrain limits infiltration. In contrast, moderate to high potential zones are concentrated near the central river valley and its tributaries, particularly in areas underlain by blocky harzburgite, where fractures and joints observed in the field facilitate groundwater movement (Figs. 4&6). Very high potential zones, shown in deep blue, are limited in extent but occur adjacent to, rather than directly along, the Manoligao River. These areas correspond with field-mapped springs and seepages and are likely influenced by structural lineaments that control both surface and subsurface flow. Their offset from the river channel reflects more favorable recharge conditions, as locations directly along the river are more prone to rapid runoff [5]. Despite the watershed's hard rock terrain and steep slopes, the model effectively delineates localized recharge zones where infiltration and groundwater storage are enhanced.

3.3 Validation

Due to the limited number of available springs (Fig. 1), all mapped springs were necessarily used as the training dataset for the Frequency Ratio (FR) analysis, which precludes the use of independent statistical validation techniques such as receiver operating characteristics-area under the curve (ROC-AUC). Instead, cross-validation was performed in the field by measuring the manual discharge of springs and comparing these values with the GWPZ map classification. This is comparable to validating the output using well yield data [2]. Spring discharge values show a strong spatial correspondence with the predicted groundwater potential zones (Table 3): springs in very high potential classes (e.g., Springs 1, 2, 3, and 7) exhibit notably higher discharge rates, with Spring No. 3 recording the highest at 0.011939 m³/s. Springs in high potential zones (Springs 4 and 5) demonstrated moderate discharge, while Spring 10 in a moderate zone yielded the lowest discharge of 0.000006 m³/s. This pattern of increasing discharge with higher classified potential zones provides field-based support for the model's reliability despite the dataset limitations.

Table 3: Summary of spring discharge values.

SP	Lat (°N)	Long (°E)	Discharge m^3/s	GWPZ Class
1	10.041472	125.67803	0.000595	Very High
2	10.042052	125.68433	0.00012	Very High
3	10.042609	125.68399	0.011939	Very High
4	10.042523	125.68203	0.000025	High
5	10.044741	125.67875	0.000285	High
6	10.035792	125.6729	no data	Very High
7	10.042728	125.68425	0.000126	Very High
8	10.042791	125.68427	no data	Very High
9	10.042789	125.68424	no data	Very High
10	10.04347	125.68238	0.000006	Moderate



3.4. Groundwater Use and Risk Implications based on the Potential Zones

The spatial distribution of groundwater potential zones in the Manoligao watershed reveals distinct areas for recharge, extraction, and vulnerability (Fig. 8). Recharge is favored in the central to southeastern portion, where moderate to very high potential zones coincide with fractured harzburgite, gentle slopes, and natural vegetation. Springs are clustered in the southeastern region, aligning with high potential zones and representing key extraction points that rely on upstream recharge. However, these spring areas, especially near settlements or disturbed land (Fig. 3), are also prone to contamination and require protective land use policies. In contrast, the western and northern parts of the watershed, dominated by very low to low potential classes, face higher drought risk due to steep slopes, poor infiltration, and limited spring presence. These areas may benefit from supplemental measures such as rainwater harvesting or managed aquifer recharge to improve water availability.

4. CONCLUSION & RECOMMENDATION

Ultramafic rocks, as part of a hard rock terrain, typically have low primary porosity and rely on fractures and joints for groundwater movement. In rural, data-scarce areas like the Manoligao watershed, the Frequency Ratio method within a GIS framework proved effective in delineating zones with high groundwater potential despite a limited number of mapped springs. The resulting map shows that most of the watershed falls under very low to low potential due to steep slopes, high runoff, and limited infiltration. However, moderate to very high potential zones were identified, especially adjacent to the Manoligao River, in areas where blocky harzburgite outcrops with visible fractures were observed. These zones align with moderate lineament and drainage density, gentle to moderate slopes, and natural land cover, all of which support groundwater recharge.

The output map can guide spring development programs and protection of recharge areas for communities reliant on groundwater. Similarly, extraction points must be managed alongside contamination-prone areas, near settlements, to ensure a safe water supply through proper land use planning and sanitation control. Further work may include water quality sampling of identified springs, seasonal monitoring, or geophysical validation to improve accuracy. The Frequency Ratio method can also be applied to other watersheds on Dinagat Islands to support broader groundwater conservation and planning efforts.

5. ACKNOWLEDGEMENTS

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