GIS-AHP-Based Mapping of Groundwater Potential Zones and Evaluation of Water Infrastructure Locations

A Case Study in Tagum City, Philippines

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ABSTRACT

Groundwater, an essential resource, is largely governed by subsurface hydrogeology. However, despite the importance of groundwater, its potential value has not been studied in Tagum City, Philippines. This study assessed the alignment of current groundwater wells with potential areas using a Multi-Criteria Decision-Making (MCDM) methodology, integrated with Geographic Information System (GIS) techniques and Analytic Hierarchy Process (AHP). The analysis indicates that 16.81% (3,063.78 ha) of the areas studied demonstrate extremely high potential, accommodating 19 wells, while 43.76% (7,973.66 ha) exhibit good potential with 33 wells. Moderate potential zones constitute 37.66% (6,863.8 ha), encompassing 46 wells, whereas only 1.77% (322.12 ha) is designated as poor, containing one well. Significantly, the high-potential regions contain comparatively fewer wells, suggesting an opportunity for strategic well positioning to enhance resource utilization. These findings establish an evidence-based framework for groundwater management, directing well development and promoting sustainable water resource planning in the studied areas.

Keywords- groundwater potential zone; AHP; MCDM; GIS; water wells; Tagum city; Philippines

I. INTRODUCTION

In areas without centralized water infrastructure, groundwater obtained from wells contributes to public health and environmental sustainability [1]. However, urban expansion, overextraction, and contamination [2], coupled with climate-induced precipitation variability, increasingly compromise aquifer recharge and water quality [3-5]. Challenges, such as limited infiltration caused by built-up areas [4], disrupted recharge in semi-arid basins [6], saline intrusion in coastal zones [7], fractured aquifer constraints in mountainous regions, and the difficulty of managing fractured aquifers in mountainous regions [8], highlight the importance of carefully delineating groundwater zones to meet human needs while safeguarding ecological systems.

Traditional approaches, such as geological mapping, soil analysis, and borehole drilling, provide localized aquifer insights, yet their high cost, labor intensity, and geographic constraints limit broader applicability, particularly in remote or post-conflict regions [9, 10]. Data scarcity from published studies and datasets further reduces the reliability of these methods, requiring geospatial alternatives, like Geographic Information Systems - Analytic Hierarchy Process (GIS-AHP), which enhance coverage and accuracy [9]. These limitations stress the need for scalable tools, such as GIS and Remote Sensing (RS), to evaluate thematic layers.

Geospatial technologies, particularly GIS and RS, provide systematic approaches to groundwater assessment by integrating multi-layered datasets into zonation maps [6, 8]. RS complements this by detecting vegetation and thermal anomalies indicative of subsurface water [11] and by identifying recharge zones through indices such as Sentinel-2 vegetation measures. In data-limited regions, the Quantum GIS-AHP framework utilizes open-source datasets to address gaps in field observations [10], enhancing scalability while maintaining analytical precision [12].

Combining GIS and RS with MCDM methods, such as the AHP, supports structured groundwater zonation by weighing key factors such as geology, slope, and land use through pairwise comparisons [8, 13]. Hybrid models, including AHP integrated with Shannon Entropy (SE) or Multi-Influencing Factors (MIF), refine parameter prioritization and improve accuracy in heterogeneous terrains [14]. These approaches balance the quantitative and qualitative dimensions [12], strengthening groundwater mapping across diverse conditions [6, 8].

Despite progress, geospatial applications in rapidly urbanizing, mixed-terrain settings remain underexplored. In Tagum City, Philippines, with a population of 296,202, only 5 of the 23 barangays consistently have access to safe water [15], which illustrates the need for scalable groundwater solutions. Conventional and geospatial methods alone cannot fully address pressures from industrial expansion, saline intrusion in coastal zones, and the 20 % of wells. This study integrates GIS-AHP with field validation to delineate Groundwater Potential Zones (GWPZ) and evaluate the alignment of existing wells, providing adaptive strategies for well placement, recharge protection, and sustainable demand management.

To investigate this approach, the current study focuses on Tagum City, Philippines, a representative case of a rapidly urbanizing area with mixed terrain and significant water access challenges.

II. STUDY AREA

The study was conducted in Tagum City, Davao del Norte, situated at 7°26'53.6"N and 125°48'33.9"E (Figure 1). The city is primarily situated on flat land with gentle slopes in the northern area. The Hijo and Tagum Libuganon rivers define the area, alleviating highland and urban runoff. Tagum is composed of 23 barangays, including 9 urban and 14 rural areas, with a population of 296,202. However, only 5 barangays (22%) have full access to clean water, while another 5 (22%) experience limited access. Urbanization and industrial activity increase the demand for water, placing strain on the city's limited supply.

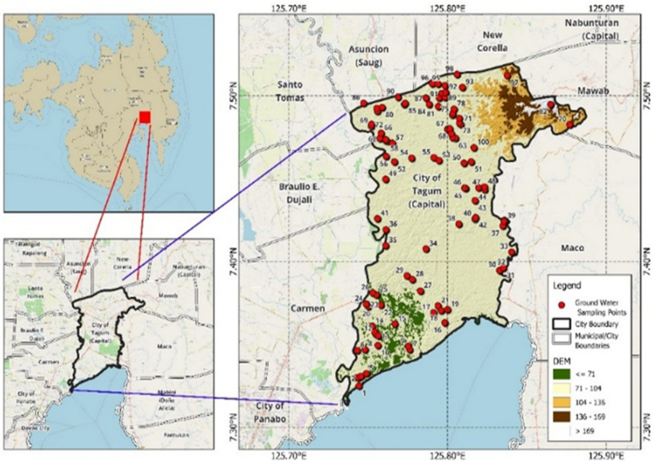

Fig. 1. Map of the study area.

III. METHODOLOGY

The study was conducted in collaboration with the Tagum City Water Section to identify 100 wells constructed between 2015 and 2024, with the aim of assessing groundwater availability. Local government personnel assisted in geotagging the well locations to speed up the process. The workflow is illustrated in Figure 2. After gathering the key parameters, the data were analyzed using the MCDM approach, integrating the AHP and GIS to generate thematic maps [16, 17].

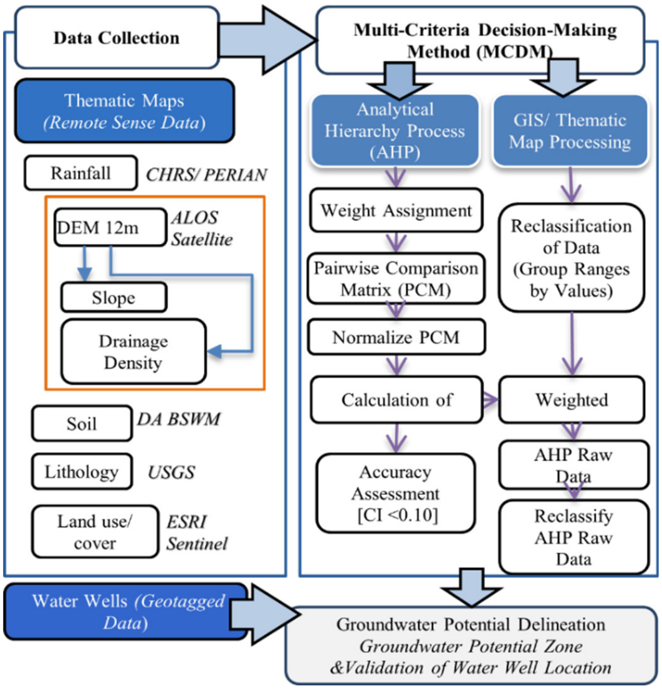

Fig. 2. Conceptual flow.

A. *Criteria and Thematic Layer Processing*

In order to map the potential groundwater zones and groundwater potential, seven parameters were evaluated in this study: slope, rainfall, drainage density, lithology, soil type, and Land Use and Land Cover (LU/LC). Slope influences infiltration; that is, gentle slopes enhance percolation compared to steep slopes [6, 8]. Rainfall supports recharge by increasing water availability [9, 11], whereas drainage density affects runoff, with lower values promoting infiltration [10, 18]. The soil type determines the recharge rate, with permeable soils facilitating faster water movement [4, 14]. Lithology controls groundwater storage and flow [8]. LU/LC influences the permeability. Specifically, vegetation favors infiltration, whereas impervious surfaces restrict it [4, 19]. The data sources listed in Table I include DEM, PAGASA, CHIRPS [20], NAMRIA [21], DA-BSWM [22], USGS [23], and classification [24]. The thematic layer weights were determined using values from the literature and expert reviews via the AHP. A summary of the literature considered in the analysis is provided in Table II, and the assigned layer weights are listed in Table III, respectively.

TABLE I. DATA LAYERS AND DATA SOURCE

Parameter	Data source	Data format	Spatial resolution
Slope	Digital elevation model 12.5,	Spatial raster (*.tif)	12 m resolution
Rainfall	PAGASA, CHRS, PERSIAN	Spatial raster (*.tif)	30 m resolution
Drainage density	Stream length / city area / NAMRIA	Spatial raster (*.tif)	10 m resolution
Soil	Mines and Geosciences Bureau (MGB)	Spatial vector (.shp)	None/vector shape
Lithology	USGS geology	Spatial vector (.shp)	None/vector shape
LU/LC	ERSI Sentinel 2, supervised land classification	Spatial raster (*.tif)	10 m resolution

Spatial analysis and mapping were performed in QGIS. To maintain consistency in the analysis, all thematic layers, including the two original vector layers, were converted to raster format. The resolution of each parameter was evaluated (Table I) before all data were projected to the UTM Zone 43 with the WGS datum and resampled to a uniform 30-m cell size.

TABLE II. FACTOR RELATIONSHIPS FROM THE LITERATURE FOR GWPZ LAYER WEIGHTING

Reference	Method	Factor relationships considered (influence of → on)
[4]	AHP, GIS	Slope → Soil, Slope → Slope
[8]	AHP	Rainfall → Soil
[9]	AHP	Slope → Slope
[18]	AHP, GIS. SE, FR	Slope → Lithology, Slope → Soil Rainfall → Lithology Drainage density → Lithology
[10]	AHP	Slope → Rainfall
[6]	AHP	Soil → LULC
[14]	AHP, MIF, GIS	Lithology → LULC Drainage density → Soil
[19]	AHP, GIS	Slope → LU/LC
[11]	AHP, GIS	Drainage density → Soil

B. *Analytic Hierarchy Process*

The AHP methodology, depicted in Figure 2, structures the decision problem into a hierarchy of criteria and sub-criteria, which are evaluated through pairwise comparisons to determine their relative importance [16, 17]. Weights were derived from these comparisons to represent the influence of each parameter on the groundwater potential. The consistency of the judgments was quantified using the Consistency Index (*CI*) and Consistency Ratio (*CR*):

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (1)$$

$$CR = \frac{CI}{RI} \quad (2)$$

where λ_{max} is the maximum eigenvalue, n is the number of criteria, and *RI* is the Random Consistency Index. A *CR* of ≤ 0.1 indicates acceptable consistency. The weighted parameters were then combined in GIS using a weighted overlay approach:

$$GWPI = \sum_{i=1}^{n} w_i \cdot x_i \quad (3)$$

where w_i is the weight of criterion i, and x_i is its standardized raster value. The resulting thematic maps support spatial analysis and assessment of groundwater potential based on groundwater characteristics, recharge potential, and land use.

IV. RESULTS AND DISCUSSION

The combination of thematic layers, weight assignments, and pairwise comparisons is essential for evaluating the factors influencing groundwater potential and maintaining a systematic and reproducible methodology. Table III presents the weight assignments and pairwise comparisons used in the AHP analysis of the thematic layers. The results and computed values of the pairwise comparisons are displayed in Table IV.

TABLE III. PAIRWISE COMPARISON MATRIX (PCM) OF PARAMETERS FOR THE AHP PROCESS

Layer	Slope	Rainfall	DD	Soil	Lit	LU/LC
Slope	1.00	1.00	1.00	3.00	2.00	3.00
Rainfall	1.00	1.00	1.00	5.00	2.00	5.00
Drainage density	1.00	1.00	1.00	3.00	3.00	3.00
Soil	0.33	0.20	0.33	1.00	2.00	2.00
Lit	0.50	0.50	0.33	0.50	1.00	2.00
LU/LC	0.33	0.20	0.33	0.50	0.50	1.00

A. *Validation of Results*

Using (1), the *CI* was estimated to be 0.0477. To evaluate the reliability of the pairwise comparisons, the *CR* was computed using (2), which incorporates Saaty's *RI* for the corresponding matrix size (N). With *RI* = 1.24, the resulting *CR* was 0.038, which is below the acceptable threshold of 0.1. This indicates that the pairwise comparisons are consistent and reliable, thereby validating the application of the AHP methodology that was followed in this study.

B. *Results Analysis by Parameter*

1) *Slope*

Slope ranked third among the most relevant elements for groundwater potential, with a weight of 0.2259 (Table IV). As shown in Figure 3(a), gentle inclines facilitate recharging via infiltration, but steeper inclines enhance runoff. In Tagum City, the inclines are predominantly mild. Classification indicates that angles between 0° and 12.5° are the most advantageous (reclass value 5), whereas angles beyond 50° are the least advantageous (reclass value 1) (Table III).

2) *Rainfall*

Rainfall is as significant as slope and drainage density. The predominant factor possesses a weight of 0.2723 (Table IV). Increased precipitation improves the recharge capacity, with urban measurements varying from 94.96 to 138.26 mm/year (Figure 3(b)). The precipitation is categorized into four classifications: less than 95 mm/year, which is considered the least favorable (reclass value 1), and greater than 140 mm/year, which is considered the most favorable (reclass value 5).

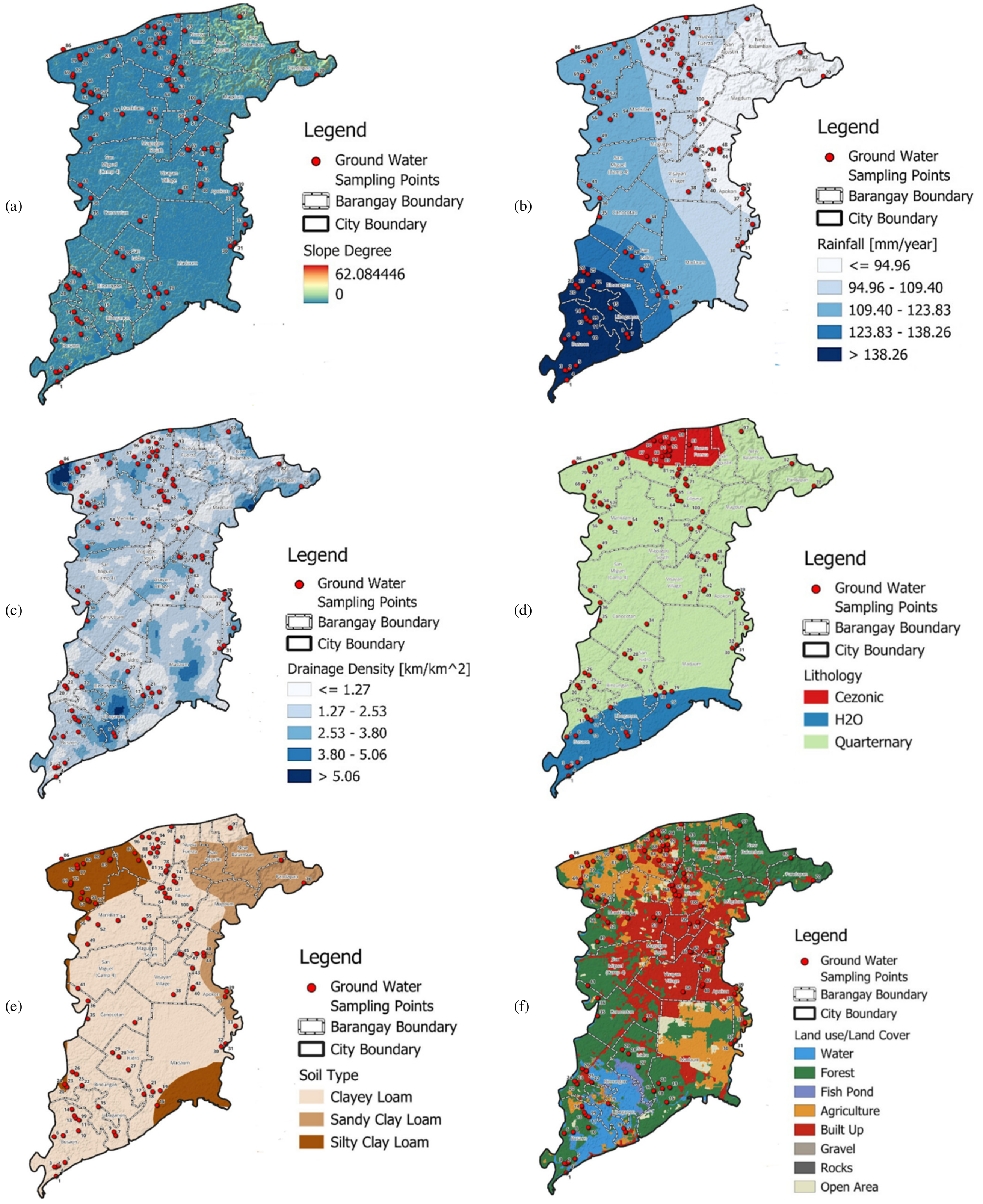

Fig. 3. Thematic layers for the GWPZ study: (a) slope, (b) rainfall, (c) drainage density, (d) lithology, (e) soil map, and f) LU/LC.

TABLE IV. PAIRWISE COMPARISON RESULTS AND VALUES FOR AHP

Parameters	Weighted values	Ranges and values	Reclass values for AHP
Slope	0.2259	0 - 12.5	5
		12.5 - 25.0	4
		25.0 - 37.5	3
		37.5 - 50	2
		> 50.0	1
Rainfall (mm/yr)	0.2723	< 95	1
		95.0 - 110	2
		110 - 125	3
		125 - 140	4
		> 140	5
Drainage density (km/km^2)	0.2417	0 - 1.2	5
		1.2 - 2.4	4
		2.4 - 3.6	3
		3.6 - 4.8	2
		> 4.8	1
Soil	0.1012	Clayey loam	2
		Sandy clay	4
		Silty clay loam	3
Lithology	0.0984	Cenozoic	3
		H20	5
		Quaternary	4
LU/LC	0.0605	Water	3
		Fishpond	3
		Forest	5
		Agriculture	4
		Built-Up	1
		Gravel	2
		Rocks	1
		Open area	3

3) *Drainage Density*

Drainage density, with a weight of 0.2417 (Table IV), is comparable in importance to slope [6] and rainfall [10]. This layer dominates a wide area of the city (Figure 3(c)), promoting recharge by reducing runoff and allowing infiltration. Values below 1.2 km/km^2 are the most favorable (reclass value 5), while those above 4.8 km/km^2 are the least favorable (reclass value 1).

4) *Lithology*

Lithology (Figure 3(d)), weighed at 0.0984, plays a balanced role in recharge, comparable to drainage density, soil, and LU/LC (1.00). Permeable quaternary formations are the most favorable (reclass value 4), Cenozoic formations provide moderate potential, and water bodies are the least favorable.

5) *Soil*

Soil, weighed at 0.1012, works with lithology to influence infiltration and water retention, although it is less critical than slope, rainfall, and drainage density [18]. Clayey loam (reclass value 2) is the least permeable, sandy clay (reclass value 4) allows higher flow, and silty clay loam (reclass value 3) offers moderate permeability. The soil thematic layer is shown in Figure 3€.

6) *Land Use/Land Cover*

LU/LC (Figure 3(f)), with the lowest weight of 0.0605, affects water movement. Forested areas (reclassification value 5) enhance recharge through high infiltration, whereas built-up areas (reclassification value 1) restrict it. Agricultural land, water bodies, and open spaces show moderate potential. Impervious urban surfaces limit infiltration, whereas forests and green spaces support recharge, underscoring the role of LU/LC in groundwater management.

C. GIS Processing of the Thematic Layers and Spatial Analysis

Figure 4 shows the GWPZ of Tagum City with existing well locations, generated through GIS-AHP integration. The zones were classified as "Very Good", "Good", "Moderate", and "Poor" based on intervals from 2.3266 to 4.9258. This provides a systematic basis for evaluating groundwater availability and suitability. Table V presents the classification breakdown of the GWPZ.

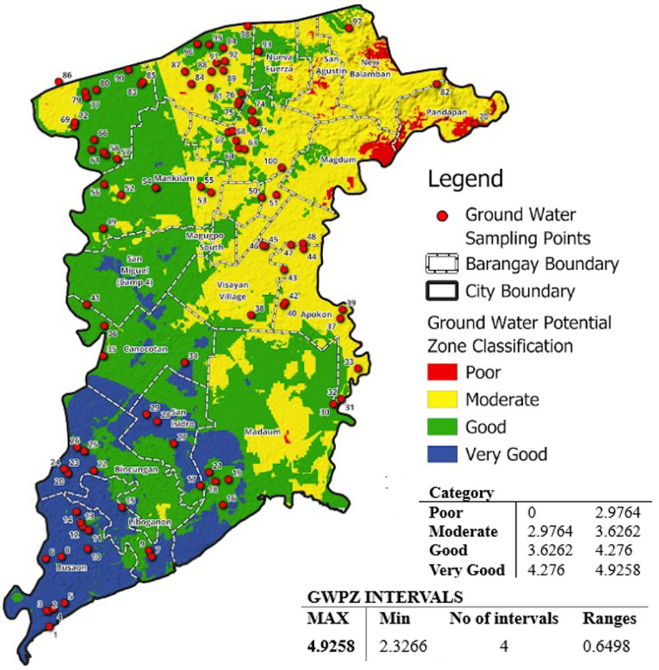

Fig. 4. Water wells and GWPZS in Tagum City.

TABLE V. CLASSIFICATION AND AREA DISTRIBUTION OF GWPZS

Class	Area (ha)	Percentage	No. of wells
Very good	3063.78	16.81%	19
Good	7973.66	43.76%	33
Moderate	6863.8	37.66%	46
Poor	322.12	1.77%	1
Others			1
Total	18223.36	100.00%	100

The "Very Good" zone (3,063.78 ha, 16.81%) comprises 19 wells, primarily located in the south, near rivers and coastal areas. Favorable land cover and high rainfall enhance recharge; though, coastal proximity increases the risk of salinity and elevated EC. Monitoring and setback measures are essential for maintaining a long-term supply.

The "Good" zone (7,973.66 ha, 43.76%) contains 33 wells across eight barangays, while the "Moderate" zone (6,863.8 ha, 37.66%) holds 46 wells in nine barangays, nearly half of the city's total. Together, these two zones account for more than 80% of the city's area, highlighting their dominant role in groundwater provision. The higher well concentration in the moderate zone reflects the reliance on local wells due to the absence of a centralized water supply. Sustainable management requires regulating withdrawal, spacing wells appropriately, and supporting recharge initiatives.

The "Poor" zone (322.12 ha, 1.77%) has only one well in the mountainous area, while the other categories represent a single well outside city limits with negligible influence. Overall, the classification and mapping of GWPZs provide useful guidance for groundwater management, helping to prioritize high-potential areas and point out zones where other solutions are needed.

V. CONCLUSIONS

This case study assessed Tagum City's groundwater potential using Geographic Information Systems (GIS) and the Analytic Hierarchy Process (AHP), integrating data on rainfall, slope, soil type, lithology, drainage density, and land use. Four Groundwater Potential Zones (GWPZs) were delineated: the "Good" zone (7,973.66 ha, 33 wells) is the most reliable, while the "Moderate" zone (6,863.8 ha, 46 wells) indicates stress due to higher well density. The "Very Good" zone (3,063.78 ha) faces potential risks of salinity and contamination due to its coastal proximity, while the "Poor" zone (322.12 ha, 1 well) highlights infrastructural and geographic limitations in mountainous areas.

This study demonstrated several replicable methods. The GIS-AHP framework provides a systematic approach to combine multiple thematic layers and weight factors based on their influence on the recharge potential. Overlaying water well locations on the GWPZs enabled the assessment of the alignment between groundwater potential and the extraction practices. Classification into "Very Good", "Good", "Moderate", and "Poor" zones informs evidence-based planning, guiding well placement, protecting recharge areas, and identifying low-potential regions that require alternative solutions. These methods can be applied to other growing cities and varied landscapes that experience similar groundwater challenges.

Sustainable groundwater management in Tagum City relies on regulated extraction, monitoring, and protection of recharge areas, supported by well improvements and solar-powered systems. Continued research on salinity intrusion, recharge dynamics, and adaptive governance is essential to balance the present demands with future sustainability.

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