

Original Article

Groundwater Recharge Potential Mapping Using Hydrological Modeling and Remote Sensing in the Lake Lanao Catchment, Philippines

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Abstract. Groundwater is an increasingly important component of water resources in large watershed systems, particularly in regions where surface water is subject to seasonal variability and increasing demand. In the Philippines, major catchments such as the Lake Lanao watershed play a critical role in supporting domestic use, agriculture, and regional water security, yet spatial information on groundwater recharge potential remains limited. This study mapped groundwater recharge potential zones within the Lake Lanao catchment using an integrated approach combining hydrological modeling and remote sensing techniques. The Soil and Water Assessment Tool (SWAT) was applied using data on meteorological conditions, slope gradient, soil type, LULC (land use and land cover), drainage density, and lineament density to simulate hydrological processes relevant to recharge estimation. The resulting groundwater recharge potential map was classified into five zones: Poor, Low, Moderate, Good, and Excellent. Results show that 19.34% (158km²) of the catchment area falls under the “Excellent” recharge category, 17.26% (141km²) under “Good,” 40.15% (328km²) under “Moderate,” 14.57% (119km²) under “Low,” and 8.69% (71km²) under “Poor.” Overall, the catchment is dominated by moderate recharge potential zones. Estimated groundwater recharge rates range from 301 mm to 360 mm annually across the catchment. The findings provide spatially explicit information that can support groundwater resource planning, watershed management, and sustainable water allocation strategies in the Lake Lanao catchment.

Keywords: Groundwater recharge mapping; Lake Lanao catchment; Remote sensing; Soil and water assessment tool.

Mindanao is home to one of the world's 15 ancient lakes and the second-largest lake in the Philippines: Lake Lanao. This catchment covers 180,460 hectares, including 35,700 hectares of lake, the surrounding region, and 12,420 hectares of the Agus River Watershed (Price et al., 2010). It is entirely inside the province of Lanao del Sur and is extremely important biologically, ecologically, economically, and socially (Garcia-Hansel & Metillo, 2016). Major freshwater catchments increasingly face pressure from population growth, agricultural expansion, and climate variability, making sustainable groundwater management essential to long-term water security. Because of overexploitation, groundwater supplies are expected to decline over time due to continuous pumping and the onset of dry seasons (Tamparan Municipality, 2020). Similarly, Dangar and Mishra

(2023) found that excessive extraction from nonrenewable groundwater storage primarily drives groundwater depletion and is projected to remain the dominant driver soon, even with anticipated increases in rainfall.

This challenge exists in the Lake Lanao catchment, where groundwater represents a potential supplementary water resource, yet spatial information on groundwater recharge potential remains limited. The lack of spatially explicit recharge information constrains evidence-based groundwater development, watershed protection, and integrated water resource planning. In the Lower Mekong Basin, Lacombe et al. (2017) similarly found that groundwater recharge remained largely unknown, hindering evaluation of groundwater resources despite rising dry-season water demand.

Remote sensing can examine groundwater recharge, determine the Earth's lineaments and geology (Davraz & Ozcelik, 2004), and identify the chosen path for groundwater (Vasileva, 2019), incorporated with Geographic Information System (GIS), a type of information technology that uses maps to combine data and other information (Shin et al., 2018). GIS can update maps easily and produce three-dimensional images. Additionally, GIS can integrate with remote sensing data to determine groundwater exploration (Vasileva et al., 2009) and delineate groundwater recharge potential zones (Yeh et al., 2008).

GIS has become increasingly popular for mapping groundwater recharge potential zones in recent studies. In recent years, researchers have investigated groundwater recharge potential zones using remote sensing and GIS, which provide clearer insights into multidisciplinary datasets (UNESCO, 1979; Deepa et al., 2016). Several thematic maps were combined to create a potential groundwater map, including annual rainfall/precipitation, lineament density, geology, slope gradient, land use, soils, and drainage density.

SWAT is a physically grounded, semi-distributed model that can forecast how climate change would affect the water balance and, eventually, groundwater recharge. The SWAT model, an interface for QGIS, has been shown to simplify the intricacies of groundwater modeling for groundwater resource development and sustainable management (Dekongmen et al., 2022). Using the Soil and Water Assessment Tool (SWAT) and remote sensing to estimate groundwater recharge for groundwater resource development and sustainable management helps reduce the complexity of groundwater modeling. Estimates of the significant components of the hydrologic cycle, such as runoff, recharge, transmission losses, and evaporation, are provided by the Soil and Water Assessment Tool (SWAT) model. It efficiently conceptualizes watershed processes in watersheds with high densities of urban and irrigation groundwater abstraction wells, humid climates, complex topography, and detailed LULC and soil classes (Yifru et al., 2020). The model's flexibility to conceptualize and compute complex watershed processes can be used to assess potential groundwater recharge zones across locations with varied climates and spatial distributions. The SWAT model was selected for the following reasons: (1) the model's open-source code allows for modifications as needed; (2) it simulates hydrologic processes continuously rather than just event by event, providing recharge estimates over long time scales; and (3) the model enables future simulations that can help with water management decisions.

Previous studies have identified several factors that influence groundwater recharge. Groundwater recharge varies with topography, geology, soil type, and land use/land cover (Todd, 2009; Jha & Peiffer, 2006; Chowdhury et al., 2009). In recharge potential mapping, multiple physical and environmental variables are commonly integrated, including elevation (topography), slope, land use/land cover, lithology, drainage density, lineament density, and hydraulic characteristics, as these are key controls on groundwater recharge (Malik et al., 2021). Groundwater recharge potential assessments commonly integrate thematic layers such as geology, geomorphology, slope, soil, drainage density, land use/land cover, rainfall, and lineament density, as these factors collectively control groundwater occurrence and recharge processes (Yıldırım, 2021; Son et al., 2023; Tsegaw et al., 2025).

In another study, Vasileva (2019) identified groundwater recharge through factor analysis. The researcher used layers relating to precipitation, lineaments, slope gradient, lithology, land cover, drainage features, and soil types of Bulgaria. Lithology, topography, geological structures, fracture extent, weathering depth, initial/secondary porosity, drainage patterns, slope gradient, landform, and climate were classified as factors that affect groundwater occurrence in the researchers' study regions (Santra & Mitra, 2017). Geology, including slope, lithology, soil types, elevation, lineament, and rainfall, affects groundwater presence (Edet et al., 1998).

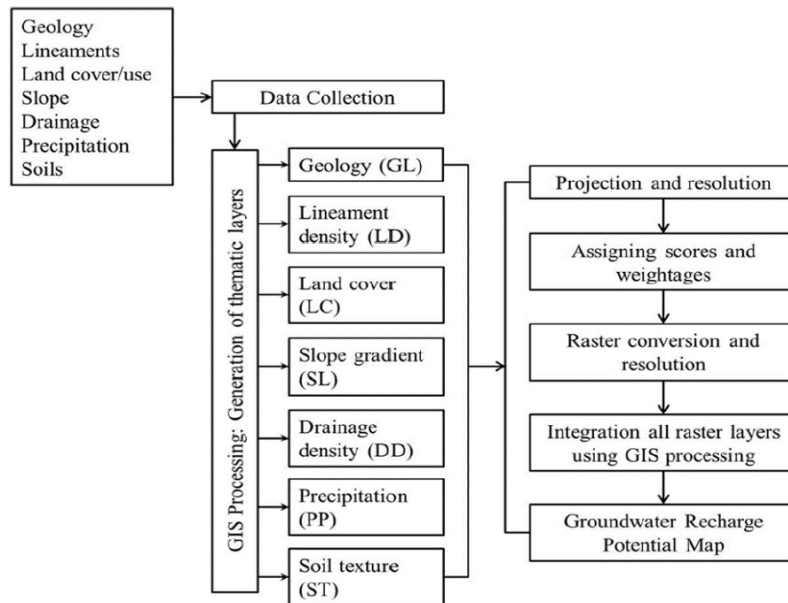


Figure 1. Flow Chart Used by Vasileva (2019) in Assessing Groundwater Potential Recharge Zone (Vasileva et al., 2019)

Vasileva et al. (2019) also classified the hierarchy of parameters by weight, considering the interactive influence of factors drawn from the same literature. According to Sun and Cornish (2005), the factors affecting groundwater recharge are ranked from highest to lowest as lineament density, geology, slope gradient, land cover, drainage density, precipitation, and soil texture. Likewise, Kumari (2022) assigned the highest weights to lineament density and geology, followed by slope, land use/land cover, drainage density, rainfall, and soil, highlighting that geological structures exert the strongest control on groundwater occurrence and recharge. In a related application, Vasileva et al. (2019) employed an integrated approach to identify potential groundwater recharge zones in Bulgaria by compiling data from multiple sources into thematic layers, which were then converted into 1 km × 1 km raster data. Figure 1 presents the flowchart of the methodology used in that study.

Studies by Yeh et al. (2008) and Vasileva (2019) both used the same hydraulic model or equation input into GIS to accurately overlay the factors affecting the groundwater recharge zone. However, before computation, they identified interactions between factors to assign weights based on their impact. Because the number of factors differs, the overall datasets differ; however, the interrelationship between each effect remains the same. Figure 2 shows the interactive influence of the factors that were used in Vasileva's study. The recharge potential's representative weight is calculated by summing the weights of each element. A weight of 1.0 is given to a major effect between two factors, while a weight of 0.5 is given to a minor effect between factors.

This paper aimed to create a potential groundwater recharge map of the shoreline municipalities around Lake Lanao, Lanao del Sur. Its objective was to simulate the groundwater recharge potential zone map using SWAT and Remote Sensing. Moreover, government officials who apply and use the formulated groundwater recharge zone map can develop management policies and action plans to sustain the ecological balance of Lake Lanao. The authors studied the Lake Lanao catchment, located in the province of Lanao del Sur, Philippines, as shown in Figure 2.

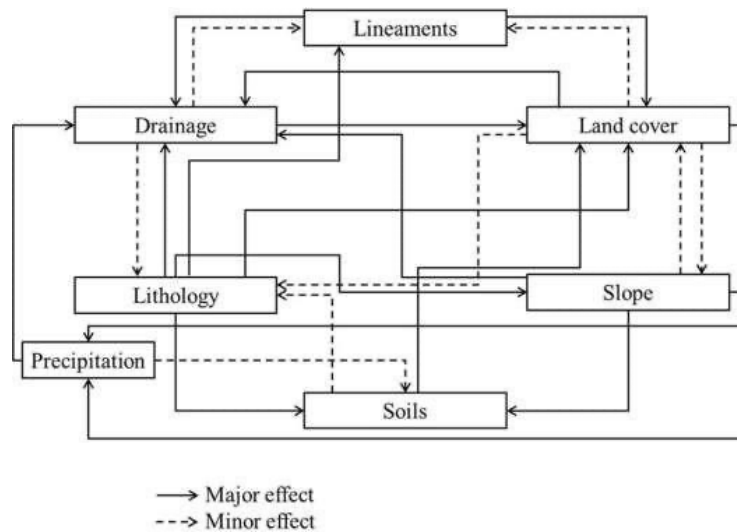


Figure 2. Interactive Influence of Factors that Affect Groundwater Recharge from Vasileva (2019)

Methodology

Research Design

This study employed a quantitative descriptive research design using hydrological modeling and Geographic Information System(GIS)-based spatial analysis to determine and map groundwater recharge potential within the Lake Lanao catchment. The design was selected because it enables the systematic analysis of spatial and environmental datasets to characterize groundwater recharge conditions across the watershed without manipulating any variables. Further, as shown in Figure 3, the research design supports objective assessment of groundwater recharge potential through numerical hydrological simulation and spatial analysis, providing a comprehensive representation of recharge variability across the study area.

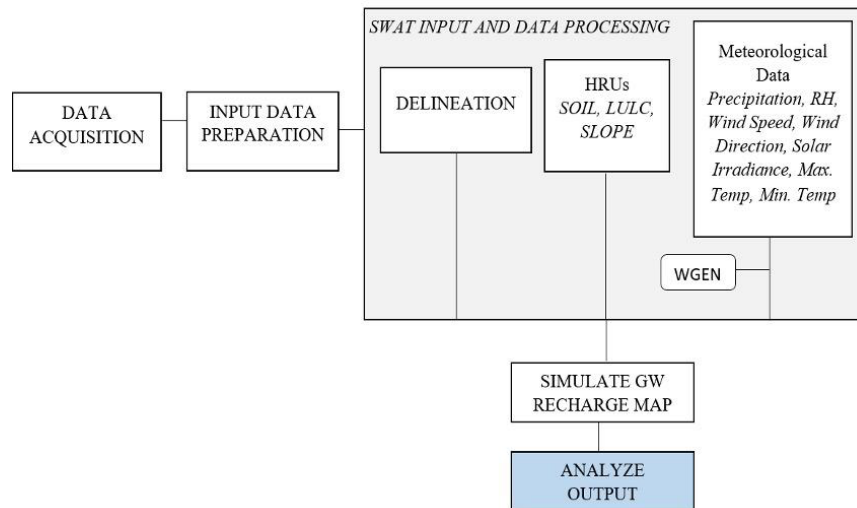


Figure 3. Methods for Mapping Potential Groundwater Recharge using SWAT

The Soil and Water Assessment (SWAT) model was used to simulate groundwater recharge at monthly, seasonal, and annual scales across the Lake Lanao Catchment, including its hydrological response units (HRUs), using meteorological, soil, slope, land use and land cover (LULC), drainage density, and lineament density datasets prepared from remote sensing products and secondary geospatial data within a GIS environment. The resulting recharge estimates were classified into five categories – Poor, Low, Moderate, Good, and Excellent – to characterize their spatial distribution. To further delineate recharge potential, the thematic layers representing soil, geology,

lineament density, drainage density, and slope were converted to raster format, assigned corresponding weights and scores based on their relative influence on groundwater recharge, and integrated through a GIS-based weighted overlay procedure. A weight of 1.0 was assigned where a factor was considered to have a major influence relative to another factor, while 0.5 represented a minor influence. The weighted thematic layers were subsequently overlaid to produce the final groundwater recharge potential map. Thus, SWAT provided simulated recharge estimates; remote sensing and GIS supported the preparation and spatial integration of the thematic datasets; and the weighting and overlay process derived the spatial recharge-potential classes.

Study Area

Lake Lanao, the second-largest lake in the Philippines and the largest in Mindanao, is regarded as one of the world's 15 most ancient lakes. Five of its basins have significant rivers and tributaries totaling 431 km. The Agus River is the lake's only outlet for water from its tributaries. The catchment formed partly because tectonic-volcanic damming created a basin between two mountain ranges, and a volcano erupted. Lake Lanao has a maximum depth of 122 meters (400 feet), and its average depth is 60.3 meters (198 ft). The basin is shallower in the north and gradually deepens toward the south. Lake Lanao has a maximum elevation of 1,798m and a minimum elevation of 614m, averaging 787 m.

The lake is bordered by sizable forests to the south and southeast, and much of its coastline is covered by enormous reed beds. The lake basin is the shallowest in the north, even though it gradually deepens as it moves south. The groundwater recharge potential zone is strongly influenced by watershed delineation (Chowdbury et al., 2009). This study focused on the watersheds covering its shoreline municipalities, namely: Maraw, Buadiposo-Buntong, Mulondo, Taraka, Tamparan, Poona Bayabao, Masiu, Lumbayanague, Ganassi, Bacolog Kalawi, Tugaya, and Balindong (see Figure 4).

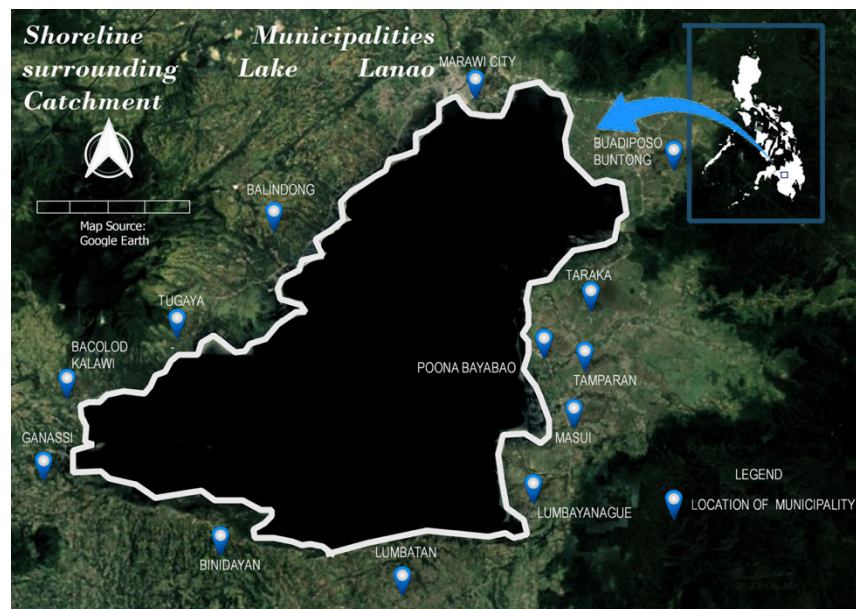


Figure 4. Shoreline Municipalities Around Lake Lanao Catchment

Data Gathering Procedure

Data inputs based on the parameters were collected for model simulation. The meteorological data were collected from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA); the topographical data from the Digital Elevation Model from the University of the Philippines Training Center for Applied Geodesy and Photogrammetry (UP TCAGP); soil type from the Food and Agriculture Organization (FAO); the Philippine Soil Map to be retrieved from the Bureau of Soils and Water Management (BSWM); Land Use Map from Landsat imagery; and Lineament Density from SWAT Integration.

To prepare the SWAT inputs, the raw datasets were first converted into formats compatible with the SWAT

database and subjected to data quality checks, including identifying missing fields and correcting irrelevant or inconsistent entries. Where satellite and in-situ observations were not directly comparable, bias correction (bias adjustment) was applied to the NASA satellite datasets to align them with the climatological trends represented by observations from PAGASA stations. The SWAT model was calibrated by modifying applicable model parameters and rerunning the simulation until it converged. These procedures ensured the datasets used for simulation were properly prepared and that the model outputs aligned with available reference observations.

Soil type was incorporated as a thematic factor because soil properties influence groundwater recharge by controlling water movement during infiltration. Soil texture affects infiltration and percolation, with coarse-grained soils generally permitting greater water movement through pore spaces, whereas fine-grained soils tend to retain more water and restrict infiltration and downward percolation (Kumari, 2022; Alaoui, 2023). The soil map was prepared in the GIS environment using the FAO soil shapefile, which was opened and filtered to the Philippines (COUNTRY=PH), then clipped to the study-area boundary through a geoprocessing intersection. The resulting soil layer was classified by dominant soil type (DOMSOI) and symbolized to produce the soil thematic map. The resulting soil dataset was subsequently incorporated into the spatial analysis and recharge-potential assessment. For the SWAT simulation, infiltration into the soil was represented using the Green-Ampt equation, as shown in Equation 1.

$$i = K \frac{(L_f + H_0 - H_f)}{L_f} \quad \text{Eq (1)}$$

where:

i is the infiltration rate;

K is the soil hydraulic conductivity;

L_f is the distance from the soil surface to the wetting front;

H_0 is the pressure head at the soil surface; and

H_f is the pressure head at the wetting front.

Land use/land cover (LULC) is an important parameter in identifying areas with potential groundwater recharge zones (Baker & Miller, 2013). Changes in LULC can significantly modify groundwater recharge by altering infiltration, surface runoff, interception, and evaporation processes, making LULC an essential thematic layer in groundwater recharge potential mapping (Ghoto et al., 2025; Waindeshkar et al., 2025; Yildirim, 2021). Land cover classes such as forest vegetation and water bodies can influence hydrological processes and, consequently, groundwater recharge. Similarly, slope is an important factor affecting runoff and infiltration. Steeper slopes generally promote greater surface runoff and reduce infiltration, while gentle slopes tend to generate less runoff and allow greater infiltration. Changes in vegetation can also affect the water fluxes associated with interception and evapotranspiration, as well as soil hydrophysical properties such as water-holding capacity, bulk density, and hydraulic conductivity (Izady et al., 2015). LULC was also used as an important input in the SWAT model to represent the spatial distribution of land-use conditions within the study area. The SWAT classification generated eight LULC classes: water, trees, flooded vegetation, crops, built areas, rock, bare ground, and rangeland. We obtained the corresponding class names from the SWAT look-up tables and prepared the LULC data according to the classification system used by the Environmental Systems Research Institute, Inc. (ESRI).

We prepared the LULC map using Landsat 8 imagery and GIS/remote-sensing processing. The downloaded TIFF images were opened and processed by compositing Bands 4, 3, and 2 to produce a natural-color image. The Copy Raster function was then used to remove image margins, followed by Mosaic to New Raster to combine the processed images. The resulting natural-color raster was clipped to the study-area boundary using Extract by Mask, with the study-area shapefile as the mask. Bands 5 and 4 were similarly processed and composited to generate the normalized difference vegetation index (NDVI) image. The processed imagery was subsequently opened in ENVI, where the band images were stacked, and regions of interest (ROIs) were collected for the selected LULC classes. The classification algorithm was then run to generate the LULC map. The resulting thematic map was prepared for integration into the SWAT model and the subsequent groundwater recharge potential analysis.

Land slope is a key factor affecting runoff, as it is inversely related to infiltration rate. Steeper slopes increase surface runoff, reducing infiltration, while areas with gentle slopes generally experience less runoff and, consequently, higher infiltration rates (de Vries, 2000). The slope gradient map was generated from the elevation raster derived from the DEM and reclassified into five slope classes using the Land Use/Soils/Slope Definition command and the Multiple Slopes option. The Current Slope Class was set to 1, and the Class Upper Limit was assigned incrementally for each class, beginning with 10%, using the SWAT Classification Table as a reference; the layers were then reclassified and overlaid with the Create HRU Feature Class option enabled. After preparing the individual thematic maps, the hydrologic response units (HRUs) were defined using the HRU Analysis and HRU Definition functions in SWAT, where small HRUs were aggregated into larger units, and the final HRU distribution was generated to represent the spatial breakdown of parameters within the watershed. SWAT's slope analysis function was used to evaluate slope variation across the study catchment, with terrain information derived from the DEM. The resulting slope gradient map is presented in Figure 10, while the corresponding classification and identification of each slope class are shown in Table 4.

Meteorological conditions are also significant factors influencing projections of groundwater recharge (Sophocleous & Buchanan, 2003). The authors note that changes in precipitation patterns and rising temperatures—which in turn increase evapotranspiration—are the primary climate-change drivers affecting groundwater recharge. Similarly, a systematic review by Al Atawneh et al. (2021) concludes that most regions worldwide are expected to experience decreases in groundwater recharge under future climate scenarios, although the extent of change varies depending on climate models and emission pathways. Meteorological datasets typically include variables such as precipitation, relative humidity, wind speed, wind direction, solar irradiance, and maximum and minimum temperatures. Table 1 presents the coordinates and elevations of each weather station.

Table 1. *Coordinates of the Weather Stations*

Weather Station	Coordinates	Elevation
NASA	7.8902° N, 124.2539° E	741.88 m
Cotabato	7.1625° N, 124.2130° E	50,14 m
Malaybalay	8.1514° N, 125.1388° E	627.0 m
El Salvador	8.4091° N, 124.6121° E	182.0 m
MSU-Marawi	7.9988° N, 124.2586° E	794.0 m

Figure 5 shows the basis and location of the in situ and satellite data. NASA provided satellite weather observations from 2001-2022. In-situ data were retrieved from the PAGASA central office; these stations are Malaybalay, El Salvador, and Cotabato, with datasets ranging from 2002 to 2021. The last in-situ data were retrieved from the MSU PAGASA Office.



Figure 5. *Station for Meteorological Observations*

Research Instrument

The SWAT Weather Generator (SWAT WGEN) was employed to process the meteorological time series and represent precipitation at daily, monthly, and annual temporal resolutions for the study area. After preparing the model inputs, the SWAT model was set up and run to simulate hydrological processes and generate groundwater recharge estimates used to identify potential groundwater recharge zones. The simulated recharge values were classified into five categories to assess the degree and spatial distribution of groundwater recharge across the study area. The simulation was performed using the Setup and Run SWAT Model Simulation command, where the printout settings were configured according to the required model outputs before completing the SWAT setup and running the simulation. Figure 6 shows the methodology that was followed by the authors of this paper, as follows: (1) data acquisition, (2) data processing, (3) input data preparation per the requirements of SWAT, (4) simulate groundwater recharge, and, finally, (5) yield the groundwater recharge map.

This final procedure in SWAT modeling requires running the model to simulate the data and help identify the potential groundwater recharge zone. To assess the degree and amount in specific areas, five (5) class intervals were assigned as: Poor, Low, Moderate, Good, and Excellent, according to the modeling results.

Steps to simulate the groundwater recharge are as follows:

Step 1. Open the Setup and Run SWAT Model Simulation command

Step 2. Fill in the printout settings to generate the desired output

Step 3. SWAT setup is finished

Rainfall recharges groundwater in mountains, hills, plains, and rivers. Recharged groundwater then slowly seeps into deep aquifers. We analyze the water cycle to determine groundwater recharge. Below is the water balance equation that was used for this analysis.

$$R = (P - E) + RO - Q - S \quad \text{Eq (2)}$$

where:

R is the groundwater recharge;

P is the precipitation rate in mm/yr;

E is the evapotranspiration rate in mm/yr;

RO is the surface runoff in mm. yr;

Q is the Actual Evapotranspiration in mm/yr; and

S is the soil moisture storage.

In Equation 2, groundwater recharge is the amount of water that enters the groundwater system from the soil and the unsaturated zone. Hence, groundwater recharge is computed by subtracting the sum of the evapotranspiration rate, actual evapotranspiration rate, and soil moisture storage from the sum of the precipitation rate and surface runoff. Rain that falls on the Earth's surface seeps into the soil. Water that infiltrates the soil replenishes lost moisture, after which it becomes partly direct runoff and partly groundwater recharge. Based on this assumption, the above equation was used to compute groundwater recharge.

In hydrology and soil science, the Green-Ampt equation is a well-known empirical formula for calculating infiltration rates into soils. John Philip Green and Gordon A. Ampt created it in 1911, and it is based on the idea that gravity and capillary forces control infiltration into soil. Equation (3) expresses the cumulative infiltration depth (I) as a function of time (t) during a rainfall event, considering the initial soil moisture content, soil hydraulic conductivity, wetting front hydraulic conductivity, and hydraulic head at the wetting front.

$$I = Kt + \frac{[(\theta_s - \theta_i) - Kt + \frac{K_f + Ht}{S}]^2}{4Kt} \quad \text{Eq (3)}$$

where:

I is the cumulative infiltration depth (L)

K is the soil hydraulic conductivity (L/T)

t is the time that rain starts (T)

θ_s is the soil porosity (dimensionless)

θ_i is the initial soil moisture content (dimensionless)

K_f is the hydraulic conductivity of the wetting front (L/T)

Ht is the hydraulic head at the wetting front (L)

S is the sorptivity of the soil (L/T^{0.5})

Data Analysis Procedure

The collected spatial, meteorological, and environmental datasets were processed and analyzed using the Soil and Water Assessment Tool (SWAT) integrated with Geographic Information System (GIS) and remote sensing techniques to estimate groundwater recharge and identify groundwater recharge potential zones within the Lake Lanao catchment. Before implementing the model, we preprocessed all datasets to ensure compatibility with the SWAT database. This included data formatting, quality checking, correcting missing or inconsistent values, and bias-correcting satellite-derived meteorological data using observations from PAGASA stations. The calibrated model outputs were subsequently processed in a GIS environment to generate a groundwater recharge potential map, classify recharge potential into five categories, and determine the spatial extent of each recharge zone.

The shoreline municipalities' areas around Lanao del Sur were qualitatively assessed in five classes, from Excellent to Poor, based on their potential groundwater recharge zone. Google Earth was used as a reference to identify the specific areas with potential groundwater recharge zones. The delineation map, shown in Figure 6, describes the channel's total length per unit area. Moreover, this map also interprets the drainage spacing, from which the catchment distribution can be inferred.

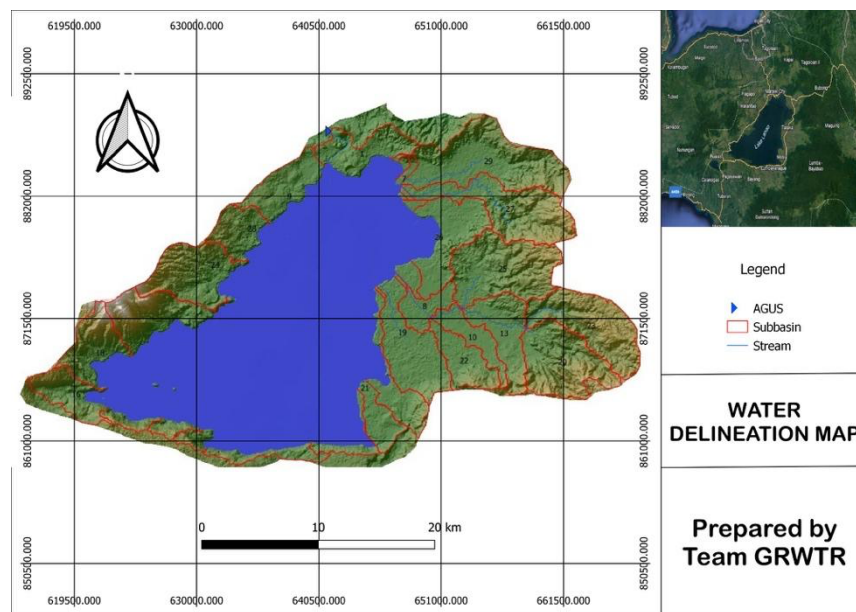


Figure 6. Delineation Map of Study Catchment

Based on the map, the low-lying stream is in the Agus River at an elevation of 638 meters, based on the slope gradient map (Figure 10). This indicates that the water in the catchment travels towards and exits into the Agus River, as shown in Figure 7.



Figure 7. Watershed Streamflow Exit Point (Agus River)

Results and Discussion

Soil Type Map

Figure 8 shows the simulated soil type map of the catchment. The results show three soil types: Sandy Clay Loam, Sandy Loam, and Clay. Table 2 shows the infiltration rates for the different soil types, in accordance with FAO (Food and Agriculture Organization). Soil infiltration rate refers to the volume flux of water flowing into the profile per unit area of the soil surface. From the data provided in the table below, sand has the highest infiltration rate, followed by sandy loam, loam, sandy clay loam, and then clay. This connects to the concept of geology that fine-grained soils are difficult for water to penetrate, while coarse-grained soils are easier for water to penetrate.

Table 2. Infiltration Rate of Basic Soil Type Classifications (Brouwer et al., 1988)

Soil Type Classification	Infiltration Rate
Clay	1 – 5 mm/h
Sandy Clay Loam	5 – 10 mm/h
Loam	10 – 20 mm/h
Sandy Loam	20 – 30 mm/h
Sand	Less than 30 mm/h

From the derived soil type map, sandy clay loam is the dominant soil type, covering nine (9) of twelve (12) municipalities: Marawi, Balindong, Buadipuso-Buntong, Mulondo, Taraka, Tamparan, Poona Bayabao, Masiu, and Lumbayanague. Sandy clay loam is classified as a moderately fine-textured soil, characterized by a relatively balanced proportion of sand and clay that results in moderate infiltration and water-holding capacity (Rawls et al., 1982; Bagallero et al., 2022). This soil type is associated with relatively slow infiltration rates, ranging from about 5–10 mm/h. In contrast, the three remaining municipalities (Tugaya, Bacolod-Kalawi, and Ganassi) are classified as sandy loam soils, which have higher infiltration rates of approximately 20–30 mm/h. Awan (2014) describes sandy loam as a coarse-grained texture, indicating comparatively higher infiltration capacity and, consequently, greater potential for groundwater recharge in these areas.

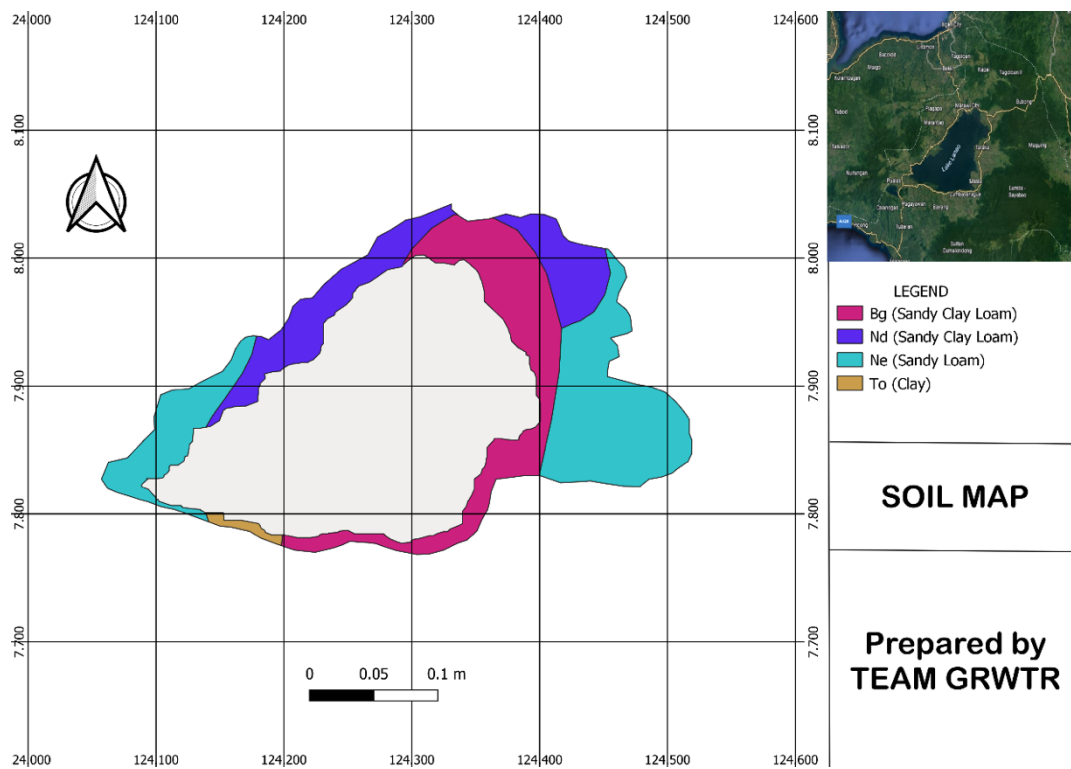


Figure 8. Soil Type Map of Study Catchment

LULC Map

Another important input in the SWAT model is the LULC (Land Use/Land Cover) Map, as shown in Figure 9. According to UNESCO (1979), locations classified as semi-arid and with a precipitation ratio of 0.2 to 0.4 have potential evapotranspiration (ET) units. Changes in vegetation's ability to intercept and evaporate water, and modifications to soil hydrophysical characteristics such as water-holding capacity, bulk density, or hydraulic conductivity, affect the amount and quality of water fluxes (Izady et al., 2015). Figure 10 shows the derived LULC map for the study area, using the FAO LULC Map as input. SWAT generates eight (8) classes: water, trees, flooded vegetation, crops, built areas, rock, bare ground, and range land. The corresponding name for each LULC class is obtained from SWAT-calibrated lookup tables. The data are from Environmental Systems Research Institute, Inc. (ESRI). Table 3 shows the land cover distribution in the study area. Trees cover nearly 30.8% of the watershed, while bare ground occupies the least area, at approximately 0.0%. Crops also cover a fair share of the watershed, at 17.28%.

Table 3. LULC Area Distribution

LULC Classification	Area (km ²)	Watershed %
Trees	264.429	30.8
Range Land	40.4	4.71
Bareground	0.0126	0
Water	356.74	41.51
Built Areas	46.65	5.43
Crops	148.34	17.28
Rock	0.0531	0.01
Flooded Vegetation	2.25	0.26

Most of the areas in seven (7) out of twelve (12) municipalities: (1) Buadipuso Buntong, (2) Mulondo, (3) Taraka, (4) Tamparan, (5) Poona Bayabao, (6) Masium, and (7) Lumbayanague fall to the crop category. Agricultural lands generally exhibit infiltration rates ranging from approximately 0.5 to 6 cm/hr, depending on soil texture, structure, and compaction (Rawls et al., 1983; Hillel, 1998). More recent studies indicate that infiltration rates in agricultural soils vary widely but commonly fall within moderate ranges depending on soil structure, bulk density, and

compaction, with reduced infiltration observed in compacted or fine-textured soils (Bagarello et al., 2022; Jobbágy et al., 2023; Alaoui, 2023), suggesting a relatively high potential for groundwater recharge in such areas.

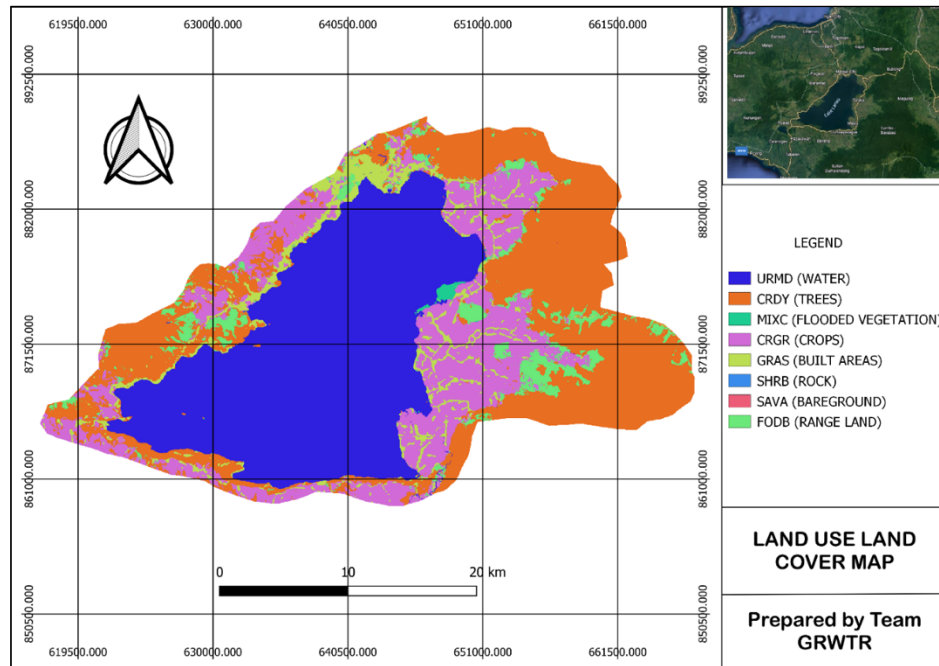


Figure 9. LULC Map of Study Catchment

Among the municipalities considered, only Marawi is dominated by built-up land use/land cover (LULC), where natural terrain has largely been replaced by paved surfaces. In such conditions, infiltration is significantly reduced, with only about 20% of surface runoff infiltrating into the soil (Zelenakova, 2014). This indicates poor groundwater recharge potential in the area when assessed based on land cover alone. In general, urban and sparsely vegetated land-cover types are associated with low infiltration and high surface runoff, reducing groundwater recharge, while forested and well-vegetated areas promote higher infiltration and enhanced recharge (Abate et al., 2022).

The land use/land cover (LULC) of Ganassi is classified as forest/tree. According to Scanlon et al. (2005), evapotranspiration rates in natural forests and savanna can be higher than in other open vegetation types. Similarly, Gee et al. (1992) found that areas dominated by deep-rooted vegetation, such as forests, generally have lower groundwater recharge rates compared with areas covered by shallow-rooted vegetation, such as annual crops. In addition, Li et al. (2025) reported that deep-rooted afforestation species can reduce groundwater recharge by at least 67.2% compared with adjacent shallow-rooted crops (e.g., maize, wheat, and millet), with rooting depth identified as the main factor controlling recharge differences. Overall, increased evapotranspiration influences the proportion of precipitation that becomes surface runoff or infiltrates to recharge groundwater. Over long periods, such changes in recharge patterns can affect groundwater levels, groundwater-surface water interactions, and soil moisture dynamics.

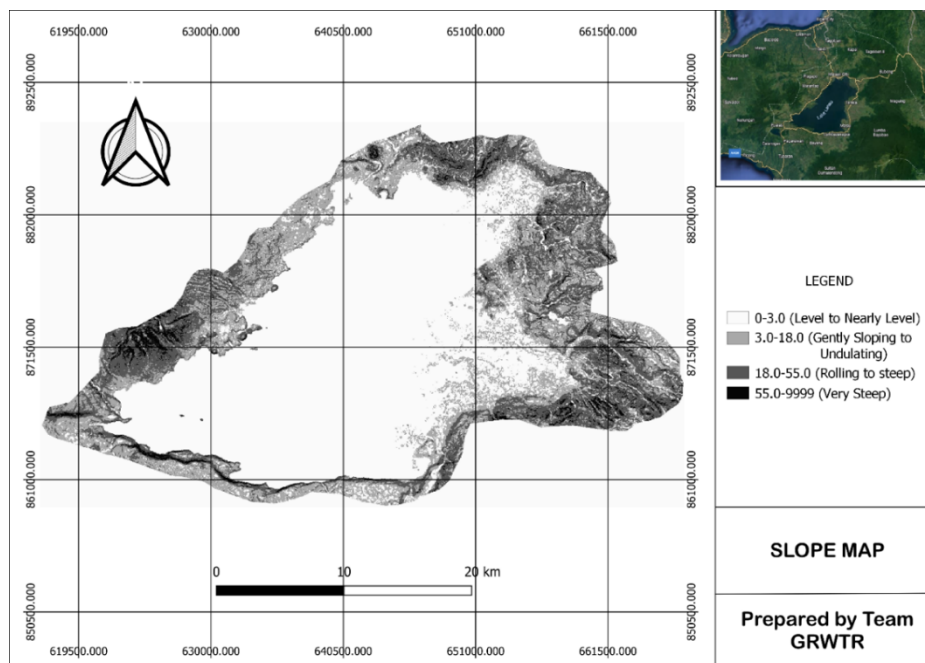
Slope Gradient Map

The result of the slope gradient map shows a pattern that the municipalities situated closest to the lake have low level to nearly level elevation (0-3.0) or gently sloping to undulating slopes (3.0-18.0). This implies that the water runoff rates are slow. As a result, water has more time to infiltrate the ground, increasing the infiltration rate. Hence, these municipalities have a great potential of groundwater recharge: (1) Buadipuso Buntong, (2) Mulondo, (3) Taraka, (4) Tamparan, (5) Poona Bayabao, and (6) Masiu. The results show a maximum elevation of 1795 m and a minimum of 638 m; the lowest elevation is in the Agus River, which supports the delineation map's implication that the river serves as the basin outlet.

Table 4. Slope Classes and Categories (Panondi & Izumi, 2021)

Slope Class	Categorization
0-3.0	Level to Nearly Level
3.0-18.0	Gently Sloping to Undulating
18.0-50.0	Rolling to Steep
50.0-99.99	Very Steep Hills and Mountainous

From the map, most of Marawi falls within the 3.0–18.0 range, suggesting gently sloping to undulating terrain. While this suggests potential groundwater recharge, it may not be as high as in the six preceding municipalities mentioned. Some areas in Marawi are still very steep, as indicated by the map. Thus, its groundwater recharge zone is inconsistent. The municipality of Lumbayanague has parallel findings to Marawi. The remaining four (4) municipalities, namely: Balindong, Tugaya, Bacolod Kalawi, and Ganassi, have rolling to steep (18.0–50.0) or Very Steep (50.0–99.99) slopes. This results in greater runoff in their areas, which is linked to a lower infiltration rate and, therefore, poor groundwater recharge potential.

**Figure 10. Slope Gradient Map of Study Catchment**

Meteorological Data Graphs

Finally, data on temperature, relative humidity, wind speed, wind direction, solar irradiance, and precipitation are gathered via in situ and satellite observations. The ability of large-scale irrigation plans to recharge groundwater depends on rainfall and the amount of supplied irrigation water. For the following few decades, this sum is unlikely to change because of system design. Changes in rainfall and minimum and maximum temperatures, however, can significantly affect groundwater recharge in large irrigation schemes.

SWAT Weather Generator (WGEN) was used to simulate meteorological data using daily time series as parameter inputs, which were translated into monthly periods and applied to simulate groundwater recharge zones. SWAT creates synthetic weather input series for long-term simulation using an inbuilt statistical weather generator. The observation data period is 20 years, from January 2002 to December 2021. Figure 11, Figure 12, Figure 13, and Figure 14 show the monthly distributions of rainfall, surface runoff, lateral flow, and actual evapotranspiration that contribute to monthly groundwater recharge, respectively.

Groundwater recharge occurs when water from precipitation infiltrates through the soil and unsaturated zone

and enters the groundwater system. The water balance was used to assess the groundwater recharge in the study area, with recharge represented by the relationship among precipitation, evapotranspiration, surface runoff, actual evapotranspiration, and soil moisture storage.

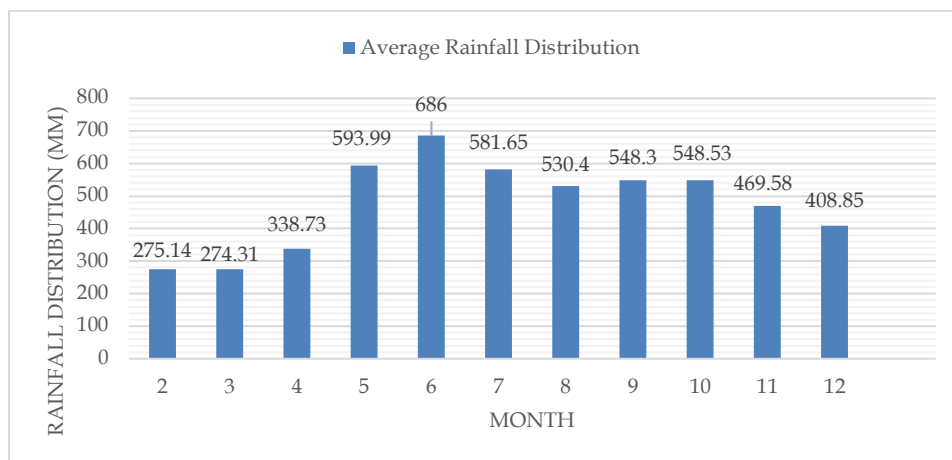


Figure 11. Average Monthly Rainfall Distribution

In Figure 11, June got the highest rainfall distribution, with 686 mm, while Month 3 had the lowest rainfall distribution, with 274.31 mm.

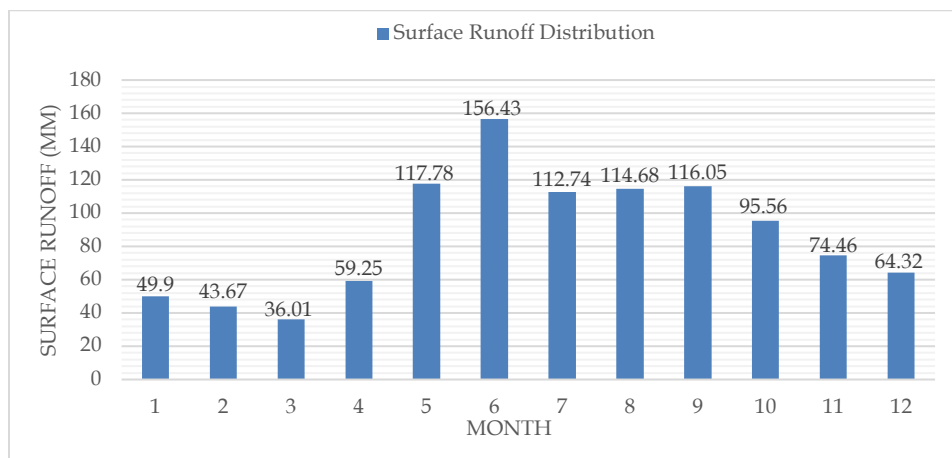


Figure 12. Average Monthly Surface Runoff Distribution

Figure 12 shows the monthly surface runoff distribution. The highest surface runoff occurs in Month 6 (156.43 mm), while the lowest occurs in Month 3 (36.01 mm). Rainfall strongly influenced surface runoff. Heavy precipitation leads to high surface runoff, and light rain will result in low surface runoff.

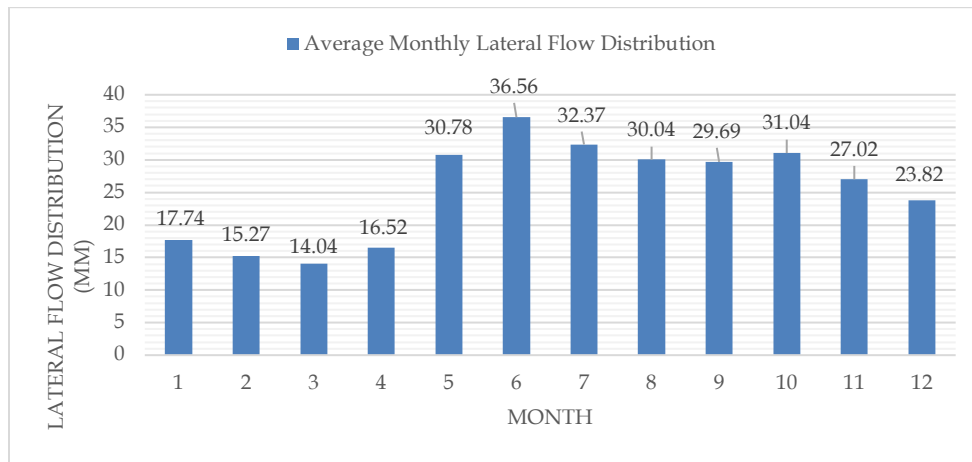


Figure 13. Average Monthly Lateral Flow Distribution

Lateral flow increases when surface runoff is high and decreases when the surface runoff is low. Month 6 has the highest lateral flow, while Month 3 has the lowest lateral flow distribution, as shown in Figure 13.

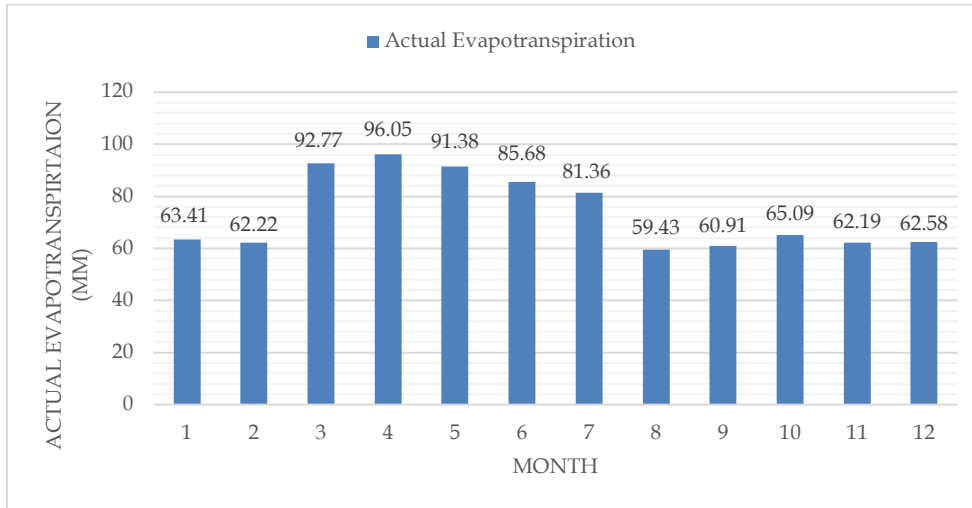


Figure 14. Average Monthly Actual Evapotranspiration

Figure 14 shows that actual evapotranspiration was highest in Month 4 (96.05 mm), while it was lowest in Month 8 (59.43 mm).

Groundwater Potential Map

Following the overlay analysis, the resulting groundwater recharge potential map was classified into five categories based on the simulated groundwater recharge rates: Poor (≤ 205 mm), Low (205 – 300mm), Moderate (301 – 360mm), Good (361 – 456mm), and Excellent (> 457 mm), as presented in Figure 15. These classifications show spatial variation in groundwater recharge potential across the study catchment and provide a basis for identifying areas with relatively higher or lower potential for groundwater replenishment.

Table 5 presents the maximum, minimum, and yearly monthly average groundwater recharge rates simulated for each of the 29 sub-basins during the study period. The results show substantial variation in recharge rates among the sub-basins, reflecting differences in the catchment's hydrological and physical characteristics. Sub-basin 13 recorded the highest yearly average groundwater recharge (430.7 mm), while sub-basin 12 had the lowest average recharge rate (113.4mm). The maximum simulated recharge values ranged from 254.6mm in sub-basin 14 to 533.1mm in sub-basin 25, whereas the minimum values varied from 35.1mm in sub-basin 14 to 197.3mm in sub-basin 25. This variability demonstrates that groundwater recharge is not spatially uniform within the Lake Lanao

catchment and that different portions of the watershed respond differently to prevailing hydrological and environmental conditions.

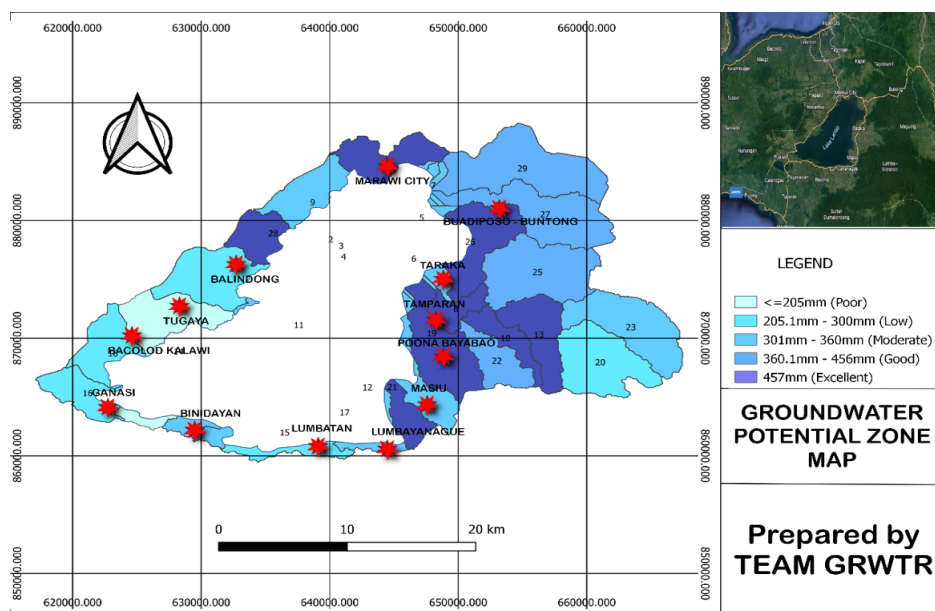


Figure 15. Final Groundwater Potential Recharge Zone Map of Study Catchment

Table 5. Yearly Monthly GW Recharge Rate for Each Sub-basin

Sub-basin	Maximum GW Recharge (mm)	Minimum GW Recharge (mm)	Yearly Monthly Average GW Recharge (mm)
1	478.9	165.2	209.5
2	363.9	99.5	299.5
3	456.5	143.2	333.1
4	363.5	99.4	299.2
5	347.8	99.69	299.4
6	364.2	99.66	257.3
7	380.1	101.2	244.3
8	506.5	144.99	418.2
9	360.6	98.38	296.7
10	502.6	143.68	414.9
11	345.8	99.0	298.1
12	362.5	99.1	113.4
13	457.3	138.9	430.7
14	254.6	35.1	165.2
15	324.8	69.6	257.3
16	286.6	85.7	228.7
17	362.5	99.1	216.9
18	263.8	76.7	209.5
19	482.4	144.4	416.2
20	263.1	70.2	226.7
21	482.3	144.4	416.7
22	456.5	128.5	376.4
23	376.1	102.7	311.4
24	263.0	87.0	231.5
25	533.1	197.3	390.9
26	480.5	143.7	352.9
27	439.1	123.3	363.9
28	469.5	139.8	405.1
29	429.1	124.8	367.5

Table 6 summarizes the spatial distribution of the five groundwater recharge potential classes within the study catchment. The predominance of the Moderate class indicates that a substantial portion of the Lake Lanao catchment has intermediate groundwater recharge potential, while the combined Good and Excellent classes indicate that a considerable area also exhibits relatively favorable recharge conditions.

Table 6. *Area Distribution of Groundwater Recharge*

Groundwater Zone Classification	Area (km²)	Watershed %
Poor	71	8.69
Low	119	14.57
Moderate	328	40.15
Good	141	17.26
Excellent	158	19.34

The groundwater recharge potential map indicates that Marawi City, Buadiposo-Buntong, Mulondo, Taraka, Tamparan, Poona Bayabao, and Masiu fall within the Excellent recharge category. Among these municipalities, Taraka recorded the highest simulated groundwater recharge rate at 506.8 mm yr⁻¹, while Tamparan exhibited an average simulated recharge of 430.7 mm yr⁻¹ during 2021. Overall, the Lake Lanao catchment is dominated by the Moderate recharge category, with estimated recharge values ranging from 301 to 360 mm yr⁻¹. The spatial pattern shows that higher recharge potential is concentrated in specific portions of the catchment rather than distributed uniformly throughout the watershed.

Areas classified under the intermediate recharge categories occupy a substantial portion of the catchment, indicating that much of the watershed possesses conditions generally favorable for groundwater replenishment. Despite this predominance, recharge potential varies distinctly across the study area. Excellent recharge zones are concentrated primarily in the eastern portion of the catchment, particularly within the municipalities of Buadiposo-Buntong, Tamparan, and Poona Bayabao. Additional areas of high recharge potential are observed in Marawi City, Mulondo, Taraka, Masiu, and portions of the surrounding municipalities.

The spatial distribution of the Excellent recharge zones corresponds with several environmental characteristics considered in the groundwater recharge assessment. These areas are generally associated with level to nearly level terrain (0-3%) and gently sloping to undulating terrain (3-18%), as illustrated in the slope gradient map (Figure 10). They also coincide with areas of relatively high drainage density identified from the watershed delineation results (Figure 7), predominantly agricultural croplands based on the land use/land cover classification (Figure 9), and sandy clay loam soil. The concurrence of these characteristics with the higher recharge classes suggests that the selected environmental factors contributed to the spatial pattern generated by the recharge assessment. Areas with lower slope gradients may provide greater opportunity for rainfall to remain on the land surface and infiltrate into the soil, while soil characteristics influence the capacity of water to move through the soil profile. Agricultural areas may also exhibit different infiltration and evapotranspiration characteristics than highly urbanized surfaces.

However, interpret the relationship between drainage density and groundwater recharge within the study's analytical framework. Relatively high drainage density does not necessarily indicate greater groundwater recharge because dense drainage networks can also rapidly concentrate and convey surface water. In the present analysis, high drainage density within some Excellent recharge areas should therefore be understood alongside other recharge-conditioning factors and SWAT-simulated recharge outputs, rather than as an independent cause of high recharge. The resulting classification reflects the integrated influence of the parameters incorporated into the overlay and weighting procedures. Thus, the association between drainage density and Excellent recharge zones reflects a spatial pattern in the model results and should not be interpreted as a direct hydrological causal relationship without additional field-based validation.

Conversely, areas classified as having Poor recharge potential are distributed throughout the catchment, particularly within the municipalities of Ganassi, Bacolod-Kalawi, and Balindong in the southwestern portion of the watershed, Lumbatan in the southern portion, and isolated areas in the easternmost section of the study area. These locations generally correspond to rolling to very steep terrain, relatively low drainage density, sandy loam soils, and extensive tree cover. Although forested areas can contribute to infiltration by maintaining soil structure and reducing the direct impact of rainfall on the soil surface, steep terrain can increase the likelihood of surface

runoff and reduce the proportion of precipitation available for infiltration. Together with the other parameters incorporated into the recharge assessment, these characteristics may explain the lower recharge values simulated in these portions of the catchment.

Marawi City, located in the northern portion of the catchment and geographically closer to the Agus River than the other shoreline municipalities, was also classified within the Excellent recharge category. Although the area contains a substantial extent of built-up land cover, the area is also characterized by sandy clay loam soils, gently sloping terrain, and relatively high drainage density. The occurrence of Excellent recharge potential in this predominantly built-up area should therefore be interpreted based on the combined results of the environmental-factor analysis and the SWAT simulation rather than by assuming that favorable soil, slope, and drainage conditions directly offset the effect of urban land cover. Nevertheless, interpret the results considering the limitations of the spatial datasets and model assumptions used in the analysis.

Conclusion

This study demonstrates that integrating hydrological modeling, remote sensing, and spatial analysis provides a practical approach for characterizing the spatial variability of groundwater recharge in the Lake Lanao catchment. The study's principal scientific contribution is identifying a spatially heterogeneous recharge system in which groundwater replenishment is governed by the combined interaction of topography, soil characteristics, land use/land cover, drainage characteristics, and meteorological conditions rather than a single environmental factor. By integrating SWAT-simulated groundwater recharge with spatially distributed environmental parameters through overlay analysis and the Analytical Hierarchy Process (AHP), the study provides a watershed-scale representation of how these interacting factors influence the distribution of groundwater recharge potential. This integration extends the understanding of groundwater recharge dynamics within the Lake Lanao catchment, particularly in areas where comprehensive groundwater monitoring and hydrogeological observations remain limited.

The results further show that areas with relatively higher simulated recharge are concentrated in parts of the catchment where combined environmental and hydrological conditions favor groundwater replenishment, while lower recharge potential occurs where prevailing conditions are less conducive to infiltration and subsurface water movement. The resulting recharge potential pattern therefore provides a spatial inventory of recharge classes and illustrates the catchment's heterogeneous response to interacting watershed characteristics. The study contributes a spatially explicit framework for interpreting groundwater recharge at the watershed scale and provides baseline information that can support future hydrogeological investigations, groundwater assessment, and watershed-scale resource planning.

The generated groundwater recharge potential map provides a scientific basis for identifying areas that warrant greater consideration in groundwater conservation and watershed management. Areas with relatively high recharge potential warrant conservation and watershed management. Areas with relatively high recharge potential may be prioritized for protection against land-use changes that could reduce infiltration and alter natural recharge processes, while areas with lower recharge potential may require appropriate soil and water conservation and land-use management measures. The spatial dataset can also serve as baseline information for future assessments of groundwater availability and changes in recharge conditions resulting from urbanization, land-use conversion, climate variability, and other watershed pressures.

Beyond the Lake Lanao catchment, this study demonstrates the applicability of combining SWAT-based hydrological simulation with remote sensing and spatial multi-criteria analysis for groundwater recharge assessment in data-scarce watersheds. The methodological framework provides an approach that can be adapted to other catchments where spatially distributed groundwater recharge resource assessment is needed and helps guide the prioritization of areas for subsequent field investigation and monitoring. Future studies should validate the simulated groundwater recharge estimate using field-based hydrogeological observations, groundwater-level measurements, and long-term monitoring data. Further improvement may also be achieved by incorporating higher-resolution environmental datasets, additional recharge-related variables, and complementary hydrological or hydrogeological modeling approaches. Such efforts would strengthen the validation, accuracy, and reliability of recharge estimates and improve the understanding of groundwater-surface water interactions within the Lake Lanao catchment.

Contributions of Authors

Author 1: conceptualization, proposal writing, data gathering
Author 2: supervision, research guidance, manuscript review
Author 3: manuscript restructuring, synthesis, journal preparation
Author 4: conceptualization, data analysis, data gathering
Author 5: conceptualization, data analysis, data gathering

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Conflict of Interests

The authors declare no conflict of interest.

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