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Assessment of Groundwater Vulnerability Using the DRASTIC Method: A Case Study of the Bued River Watershed

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Abstract: Groundwater plays a critical role in sustaining water supply for domestic, agricultural, and industrial uses, particularly in urbanising watersheds such as the Bued River Watershed in the Philippines. This study assessed the groundwater vulnerability of the watershed using the DRASTIC model integrated with Geographic Information System (GIS) mapping. The methodology involved evaluating seven hydrogeological parameters: depth to water table, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity. Data were obtained from relevant government agencies and processed using GIS to generate individual thematic layers and a composite vulnerability map. The findings indicate that approximately 90% of the watershed falls within a moderate vulnerability index, particularly in areas underlain by bedded sandstone, marine clastic formations, and karstic limestone lithologies, which are characterised by high permeability. In contrast, areas dominated by igneous and metamorphic rocks exhibited lower vulnerability due to their reduced porosity and permeability. The study concludes that the Bued River Watershed is moderately vulnerable to groundwater contamination, especially in its northern and central zones. It is recommended that local government units and water management agencies utilise the vulnerability map to inform land-use planning, groundwater protection strategies, and policy development. Future research should incorporate temporal assessments and additional hydrogeological data to improve the robustness and applicability of the findings.

Keywords: DRASTIC model; Groundwater vulnerability assessment; Bued Watershed; Geographic Information System; Water management

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1.0 Introduction

Groundwater is essential for drinking water supply, agriculture, irrigation, and industrial uses. Velis et al. (2017) state that groundwater accounts for approximately 98% of the Earth's available freshwater. It also plays a significant role in sustaining ecosystems, maintaining river baseflow, and supporting biodiversity (Famiglietti, 2014). Moreover, groundwater is vital for agriculture, supplying nearly 43% of global irrigation water (Siebert et al., 2010). This heavy reliance highlights its critical importance for achieving water security, particularly in regions with limited surface water availability.

One major concern is the increasing pollution of groundwater driven by rapid urbanisation. Urban expansion leads to dense construction patterns, where the proliferation of built-up areas and impermeable surfaces reduces natural infiltration and groundwater recharge (Foster & Chilton, 2003). At the same time, urban growth contributes to rising levels of pollutants originating from industrial waste, municipal sewerage systems, and agricultural runoff, all of which degrade groundwater quality (Lerner, 2002; Bauder, 2014). In rapidly developing urban areas, inadequate waste management further exacerbates the problem, allowing contaminants to seep into aquifers. In addition, continued population growth increases water demand, leading to excessive groundwater extraction. Such overexploitation intensifies the vulnerability of groundwater resources and raises concerns about long-term sustainability and impacts on both ecosystem and human health (Gleeson et al., 2012).

Contaminated groundwater poses serious public health risks, including waterborne diseases and chronic exposure to hazardous chemicals (World Health Organization, 2020). The presence of multiple contamination sources, combined with inadequate management strategies, underscores the need for effective groundwater governance. Sustainable groundwater management must integrate socio-economic considerations, resource conservation, and long-term water security planning.

Watersheds serve as critical components in groundwater systems, contributing to recharge processes, pollutant filtration, and the maintenance of freshwater ecosystems (Winter et al., 1998). However, watershed vulnerability remains a pressing issue, particularly in the Bued River Watershed in Benguet Province, Philippines. Despite its importance, this watershed remains relatively under-researched and warrants greater scientific attention.

The Bued River Watershed spans 33 barangays in the southern part of Baguio City, 7 barangays in Tuba, and 2 barangays in Itogon, covering approximately 14,318.60 hectares (143.19 km²). Tuba accounts for the largest share of the watershed, encompassing about 12,005.38 hectares (83.84%), followed by Baguio City with 2,237.75 hectares (15.63%), and Itogon with 75.45 hectares (0.53%) (Proposed Bued Watershed Management Plan, University of the Cordilleras).

The watershed, traversed by the Bued River, supports a population of 174,553 based on the 2020 Philippine Statistics Authority (PSA) census. Of this population, 70.57% resides in Baguio City, 16.98% in Tuba, and 12.44% in Itogon (Proposed Bued Watershed Management Plan, 2023; PSA, 2020). The area is characterised by sectoral economic activities such as small-scale mining, quarrying, and agriculture, all of which contribute to groundwater contamination risks. Notably, many small-scale mining operations lack proper siltation facilities, resulting in the discharge of untreated wastewater directly into rivers and surrounding environments.

Rapid population growth in urban barangays within the watershed places increasing pressure on local water resources. In addition, improper waste disposal practices further degrade water quality. As water demand continues to rise, concerns regarding the sustainability of groundwater resources are becoming increasingly urgent.

Currently, the groundwater system in the Bued Watershed faces three key interrelated challenges: (i) unregulated extraction, (ii) limited information on groundwater quality, and (iii) a projected water deficit. Developing a baseline groundwater vulnerability map is therefore essential to identify areas most at risk of contamination. Although groundwater benefits from natural filtration processes, making it generally less susceptible to contamination than surface water, remediation is significantly more difficult and time-consuming once contamination occurs (Alley et al., 2002).

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2.0 Study Area

The study area comprises a sequence of basaltic and andesitic flows, along with pyroclastic materials associated with the Pugo Formation. The Zigzag Formation consists of alternating layers of red and green sandstone and siltstone. This is followed by the Klondyke Formation, characterised by a thick sequence of clastic rocks dominated by polymictic conglomerates interbedded with sandstones and siltstones. Overlying the Klondyke Formation is the Mirador Limestone, identified as a karstic, coralline, cream-coloured limestone (Leith, 1938). In addition, the Black Mountain Porphyry Complex is composed of porphyritic quartz diorite stocks that intrude both the Pugo and Zigzag Formations.

3.0 Materials and Methodology

3.1 Geographic information system map generation using the drastic model

The overlay and index methods are widely recognised as essential and reliable techniques for developing groundwater vulnerability maps, primarily due to their minimal requirement for field data. These approaches incorporate multiple physical and hydrological factors that influence groundwater vulnerability within specific regions. By integrating these parameters, they help assess the movement of contaminants through the unsaturated zone toward the water table, thereby providing insight into potential risks to groundwater quality (Aller et al., 1987).

3.2 Data collection and identification of parameters

DRASTIC is a widely recognised overlay and index-based technique for parametric groundwater vulnerability mapping. It was developed in the United States under a project by the Environmental Protection Agency (EPA) to support decision-making among managers, planners, and administrators. Owing to its relatively low implementation cost and ease of data acquisition, the DRASTIC model is suitable for application in a wide range of settings (Aller et al., 1987). The method is user-friendly and evaluates intrinsic vulnerability based on the physical and hydrogeological characteristics of aquifers. Consequently, it has been extensively applied by researchers worldwide to assess groundwater vulnerability.

The DRASTIC model evaluates vulnerability using seven key parameters, each assigned specific ratings and weights to derive a composite DRASTIC index value (Rosen, 1994). These parameters include: (D) depth to groundwater, (R) net recharge, (A) aquifer media, (S) soil media, (T) topography, (I) impact of the vadose zone, and (C) hydraulic conductivity. Despite its widespread application, the DRASTIC technique has several limitations. A primary concern is its inherent subjectivity, particularly in the selection and weighting of parameters, which may affect the robustness of the results (Panagopoulos et al., 2006). In response, numerous studies have proposed modifications to improve its accuracy. For instance, some researchers have excluded hydraulic conductivity from the model, while others have incorporated additional factors such as land use to enhance vulnerability assessment.

3.3 Weights

Each parameter is assigned a weight and a rating value, typically ranging from 1 to 5, based on its relative importance in contributing to groundwater contamination. The weights are fixed and are not subject to modification. Parameters of greatest significance are assigned a weight of 5, whereas those of lesser importance are assigned a weight of 1 (Table 1).

Table 1. Weight of each Parameters

Parameter	Weight
Depth to Water Table	5
Net Recharge	4
Aquifer Media	3
Soil Media	2
Topography	1
Impact to the Vadose Zone	5
Hydraulic Conductivity	3

3.4 Data collections

The data used in this study were obtained from previous work conducted by government agencies, academic institutions, and non-governmental organisations. Records of wells and springs within the watershed were collected from the Baguio Water District (BWD), Mines and Geosciences Bureau (MGB), City Planning and Development Office (CPDO) of Baguio City, Watershed and Water Resources Research and Development Extension Center (WWRRDEC), and the River Basin Control Office. Mean annual rainfall and mean annual temperature data were sourced from the Proposed Bued River Watershed Management Plan. These data were used to estimate net recharge using the Thornthwaite water balance method.

Geological maps obtained from the MGB were utilised to derive aquifer media characteristics, supplemented by records from the water district and academic sources. Soil data for the study area were acquired from the Department of Agriculture, Bureau of Soils and Water Management (DA-BSWM). Additional thematic layers were generated using Digital Elevation Model (DEM) data from the National Mapping and Resource Information Authority (NAMRIA), processed through Geographic Information System (GIS)–based spatial analysis. Figures 1 and 2 illustrate the workflow for the generation of groundwater vulnerability parameter maps.

Table 2. Data type and sources of data.

OUTPUT LAYER	DATA TYPE	SOURCE
Depth to Water Table	Water Level data	Baguio Water District, WWRDDEC, MGB
Net Recharge	Precipitation	DOST-PAGASA
Aquifer Media	Geologic Map	MGB
Soil Media	Soil Map	Geoportal, Bureau of Soils
Topography	Digital Elevation Model (DEM)	Geoportal, NAMRIA
Impact on Vadose Zone	Geologic Interpretation	MGB
Hydraulic Conductivity	Hydraulic Data, Geologic Interpretation	MGB, books

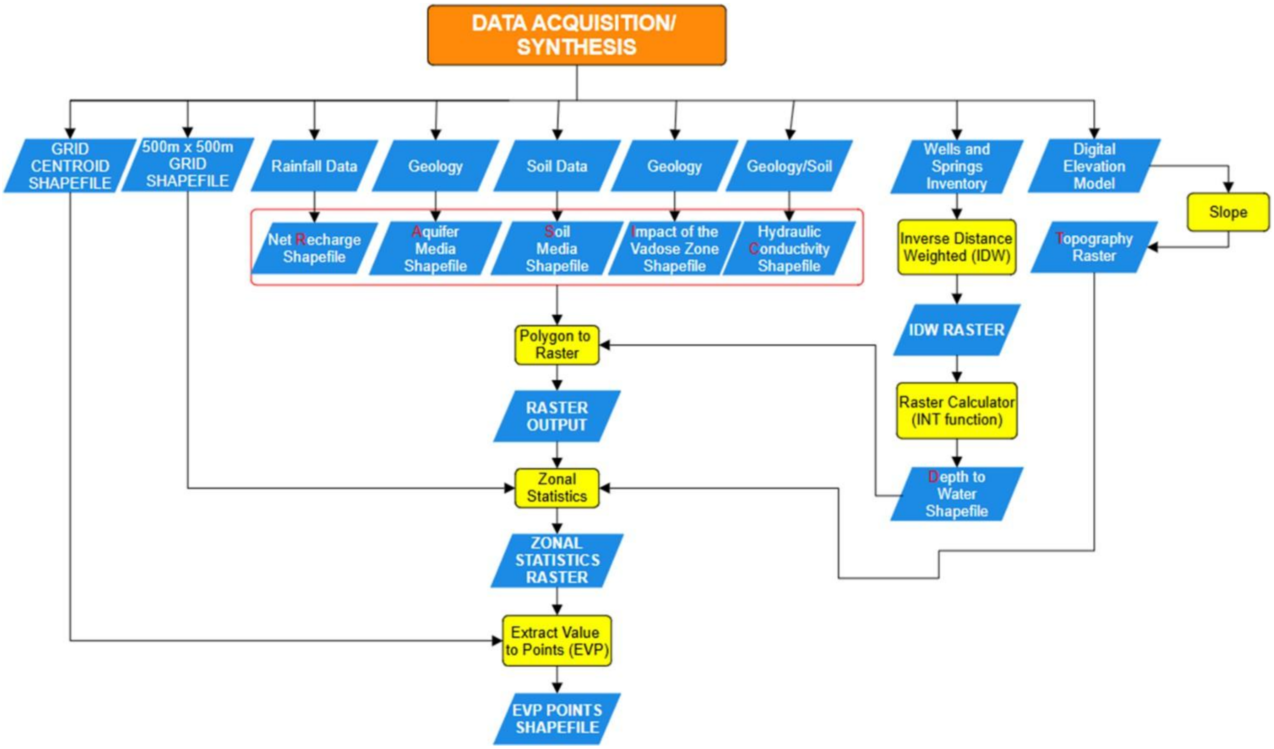


Figure 1. Workflow for groundwater vulnerability parameters.

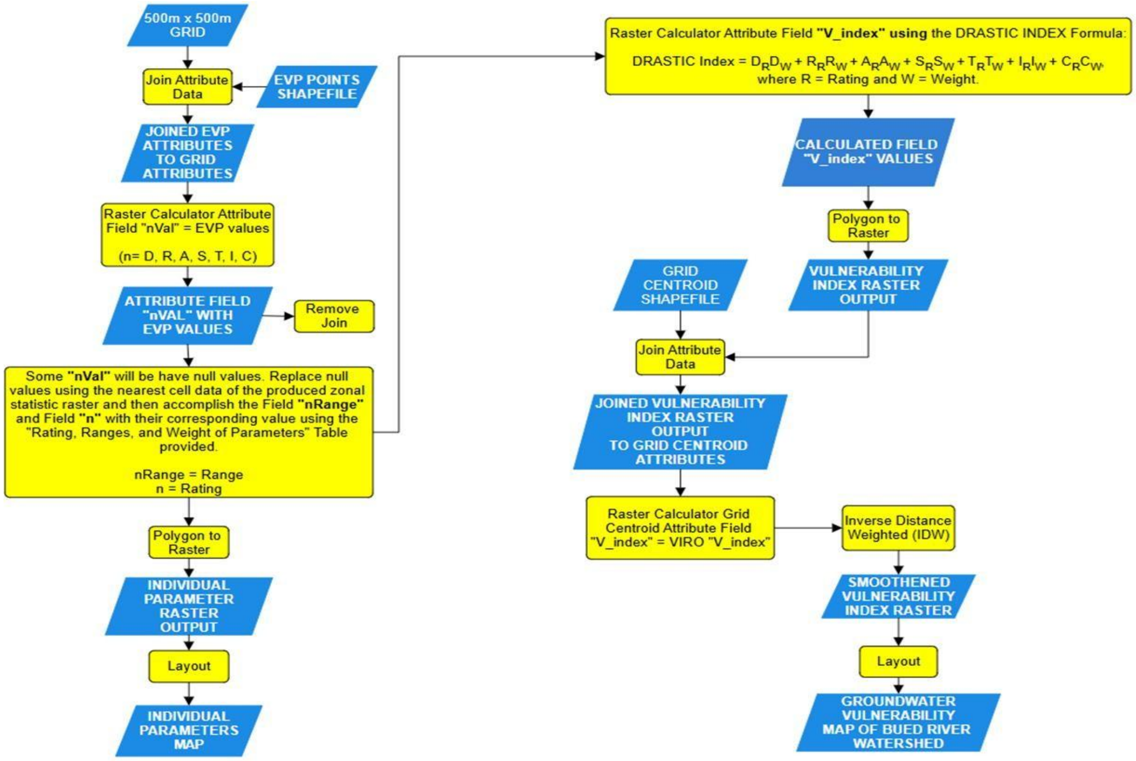
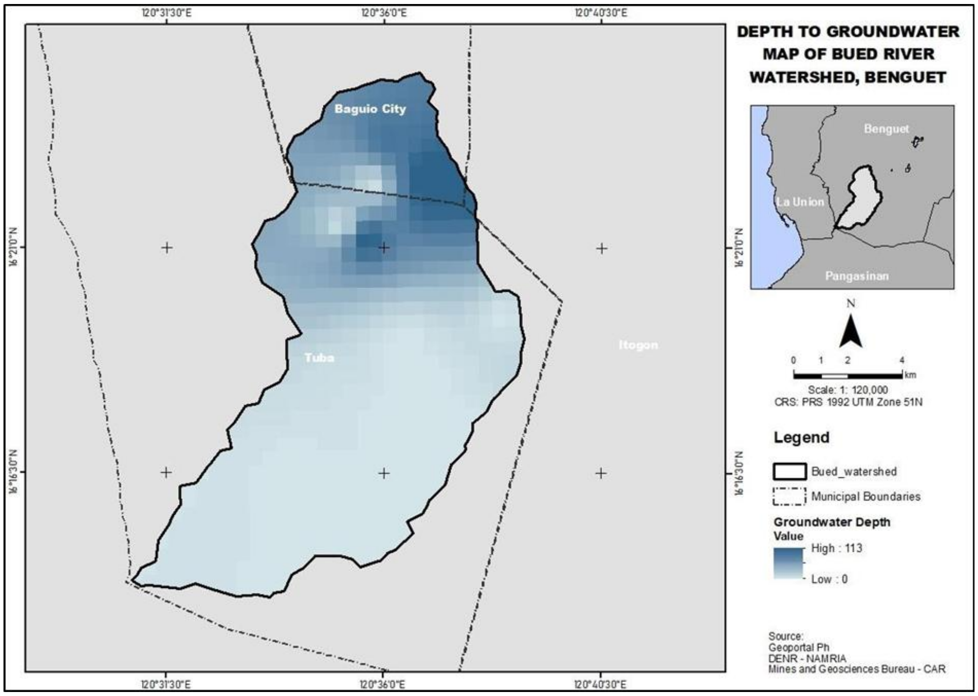


Figure 2. Workflow for groundwater vulnerability map generation.

4 Results and Discussion

4.1 Depth to Water Table

Depth to the water table is a critical parameter in the DRASTIC method (Figure 3), as it represents the vertical distance a contaminant must travel through the unsaturated zone before reaching the aquifer, thereby influencing the potential for groundwater contamination. Aller et al. (1987) state that greater depths to groundwater correspond to longer travel times for contaminants to reach the saturated zone. In the study area, the depth to groundwater reaches up to 1,496 metres. As shown in Figure 3, a large portion of the municipality of Tuba, as well as parts of the Santo Tomas School Area in Baguio City, exhibit relatively shallow water tables compared to the rest of the Bued River Watershed, as inferred from well and spring inventory data. Macalam et al. (2020) further note that shallower groundwater depths increase the susceptibility of aquifers to contamination. The depth-to-groundwater map was generated using data from five deep wells and fourteen springs, sourced from the Baguio Water District and the Bued River Watershed Characterization and Vulnerability Assessment Report by WWRDDEC-DENR.



Source:
Geoportal Ph
DENR - NAMRIA
Mines and Geosciences Bureau - CAR

Figure 3. Depth to groundwater map of the Bued River watershed.

4.2 Net Charge

Figure 4 presents the net recharge map of the Bued River Watershed. Precipitation serves as the primary source of groundwater, infiltrating the land surface and percolating downward to the water table (Aller et al., 1987). Net recharge refers to the volume of water per unit area that penetrates the ground surface and reaches the aquifer (Tuonan et al., 2024, unpublished). It is commonly estimated as the product of annual precipitation, the specific yield of soil types, and a coefficient (typically around 20%). However, in this study, net recharge was conservatively assumed to be 10% of the total annual precipitation.

Based on data from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) Baguio Synoptic Station, the Bued River Watershed receives an average annual rainfall of 3,824 mm. Accordingly, the estimated annual net recharge for the watershed is approximately 383 mm. This indicates a high recharge rate, which in turn suggests a high vulnerability to groundwater contamination across the study area.

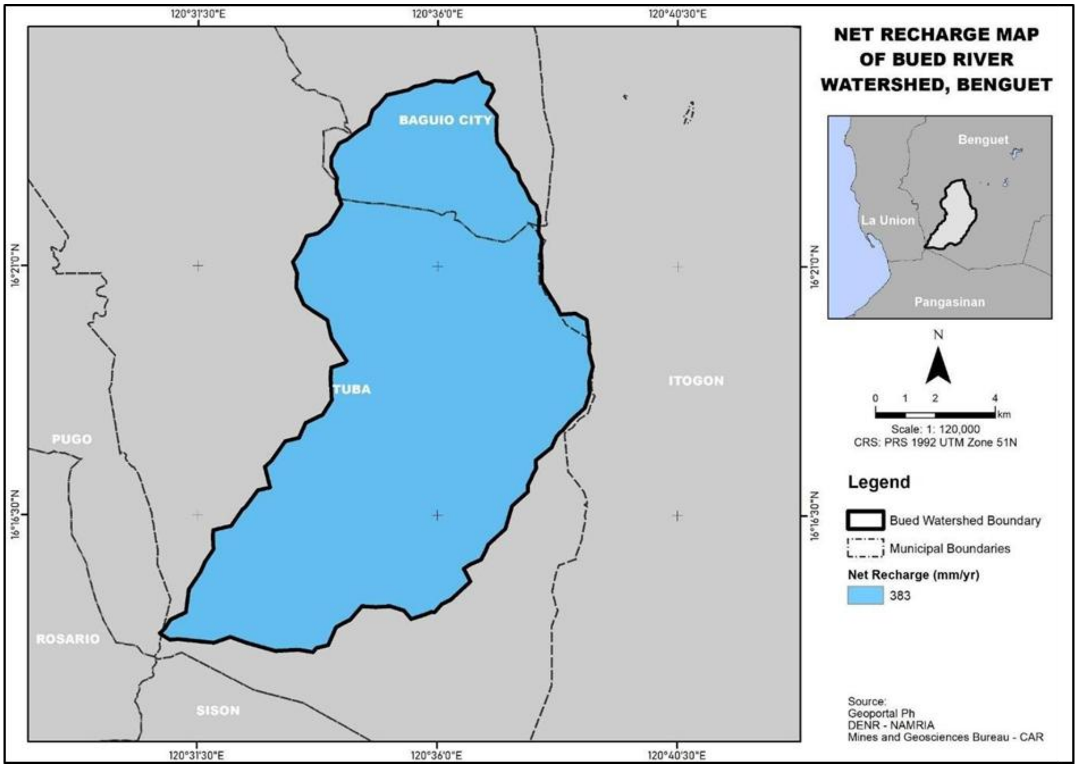


Figure 4. Net recharge map of the Bued River watershed.

4.3 Aquifer Media

The aquifer media refer to the consolidated or unconsolidated geological materials that function as aquifers. Figure 5 presents the aquifer media map of the Bued River Watershed. The flow system within an aquifer is influenced by the characteristics of the aquifer material, and the pathways followed by contaminants are governed by this flow system (Aller et al., 1987). Aquifers with larger grain sizes, as well as those with numerous fractures or openings, tend to exhibit higher permeability and lower attenuation capacity, thereby increasing their susceptibility to contamination (Aller et al., 1987).

The aquifer media classification was derived from the Geologic Map of Benguet Province (MGB, 2018). The watershed is underlain by several geological formations, including the Pugo Formation (metamorphic/igneous), represented by yellow pixels; the Zigzag Formation (thin-bedded sandstone, limestone, and shale sequences); the Klondyke Formation (marine clastic and pyroclastic), represented by light orange pixels; and the Mirador Limestone (karstic limestone), represented by orange pixels. In addition, the Central Cordillera Diorite Complex (weathered metamorphic/igneous) is depicted in blue.

Low-permeability rocks, such as metamorphic and igneous formations, as well as their weathered equivalents, are generally less susceptible to contamination due to their limited primary porosity. However, these rocks may still become vulnerable when highly fractured or weathered (Tuonan et al., 2024, unpublished). In contrast, marine clastic and pyroclastic deposits, along with bedded sandstone, limestone, and shale sequences, are more prone to contamination due to the presence of primary porosity and relatively high permeability, which facilitate the movement of contaminants through the subsurface. Furthermore, karstic limestone, particularly in the north-western portion of the watershed, is highly susceptible to contamination due to its large, interconnected cavities and fractures, which allow rapid contaminant transport.

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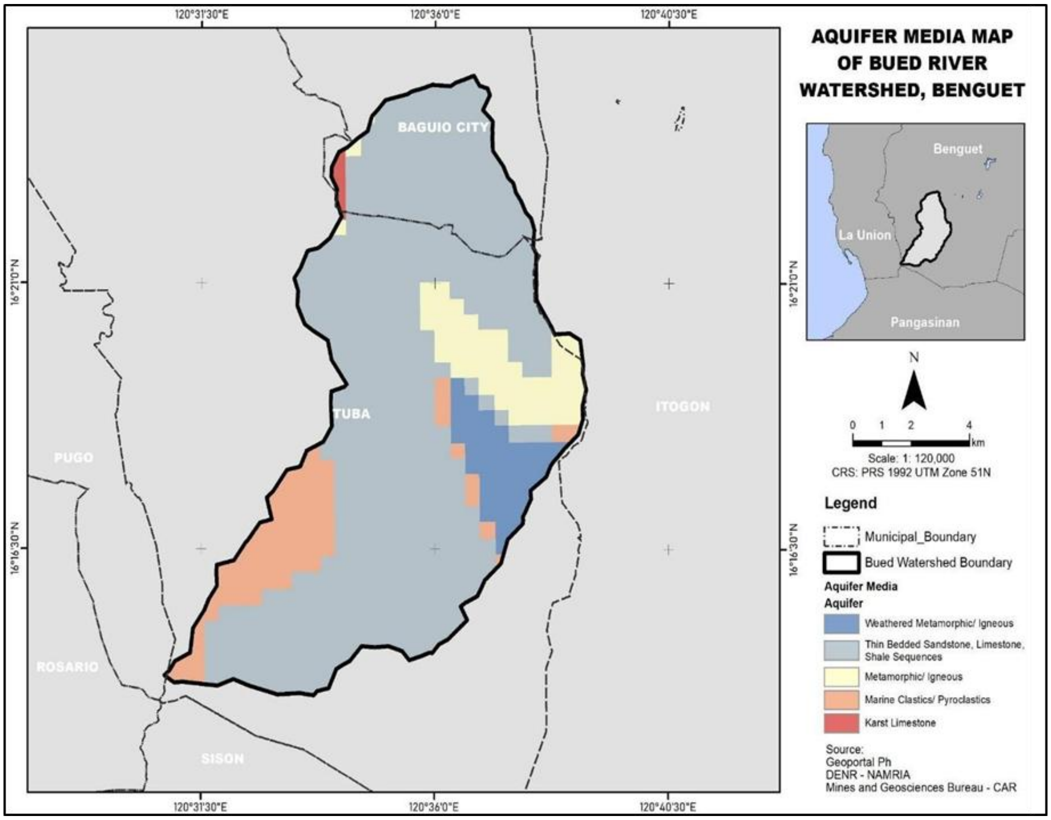

Figure 5. Aquifer media of the Bued River watershed.

4.4 Soil Media

Soil plays a significant role in controlling the amount of recharge that can infiltrate into the ground (Lee, 2003). Figure 6 presents the soil media map of the Bued River Watershed. The pollution potential of soil is strongly influenced by factors such as clay content, shrink–swell capacity, and particle size (Amadi, 2003). Generally, soils with lower shrink–swell potential and finer grain sizes exhibit lower pollution potential due to reduced permeability (Macalam et al., 2020; Tuonan et al., 2024).

Soil data were obtained from the Geoportal PH database and used to determine soil media values. The Bued River Watershed comprises clay loam (red), non-shrinking and non-aggregated clay (yellow), and sandy loam (blue). The north-central portion of the watershed is considered less prone to contamination due to its high clay content, which restricts permeability and acts as a barrier to contaminant movement. Similarly, the north-western portion, characterised by non-shrinking and non-aggregated clay, exhibits low vertical permeability, thereby reducing pollution potential. In contrast, sandy loam, which dominates the western to southern parts of the watershed, is more susceptible to contamination due to its higher porosity and permeability, allowing contaminants to move more easily through the subsurface.

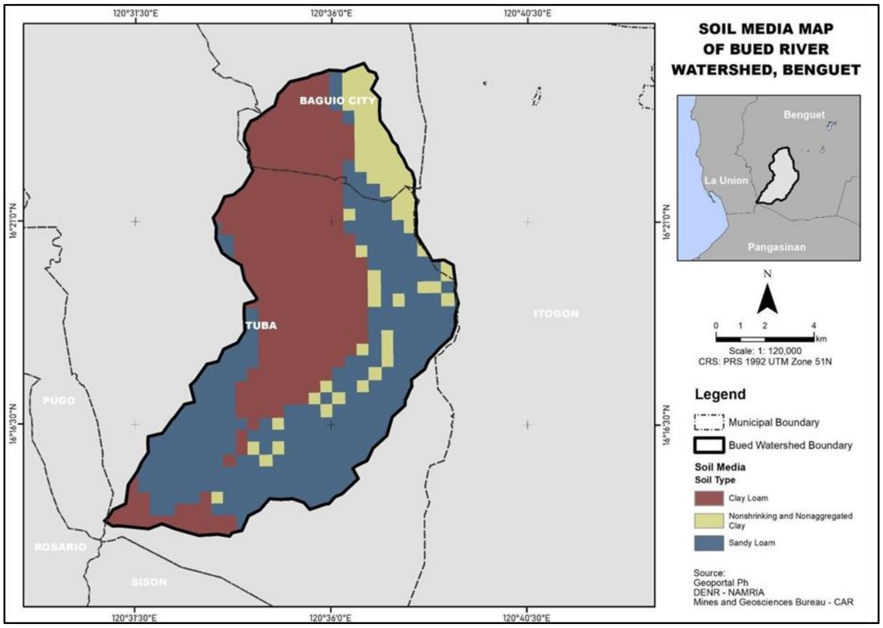

Figure 6. Soil media of the Bued River watershed.

4.5 *Topography*

Topography refers to the slope and variation of the ground surface. Figure 7 presents the slope map of the Bued River Watershed. This parameter is essential in determining whether contaminants are likely to run off or remain on the surface long enough to infiltrate into the soil. Topography also influences groundwater flow, as the slope gradient and direction often reflect subsurface flow patterns. Steeper slopes are generally associated with higher groundwater velocities and increased surface runoff.

The slope map of the watershed was derived from a Digital Elevation Model (DEM) generated using Interferometric Synthetic Aperture Radar (IFSAR) data. The majority of the watershed exhibits slopes exceeding 18%, while some eastern and north-eastern portions of Baguio City fall within the 6–18% slope range. Overall, the Bued River Watershed is characterised predominantly by steep terrain, with limited areas of moderately sloping or undulating land.

In terms of contamination potential, the northern portion of the watershed is more susceptible, as gentler slopes in these areas allow precipitation and contaminants to remain on the surface for longer periods, thereby increasing the likelihood of infiltration rather than rapid runoff.

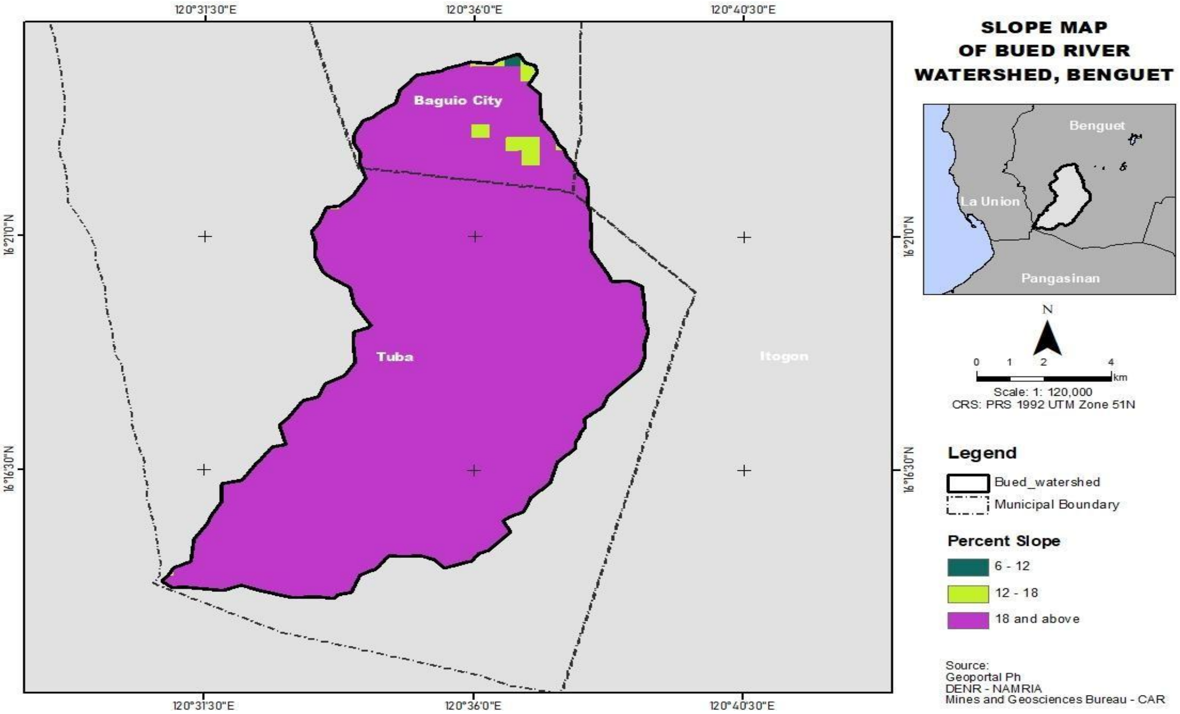

Figure 7. Slope of the Bued River watershed.

4.6 *Impact to the Vadose Zone*

The vadose zone, or unsaturated zone, plays a crucial role in determining the attenuation and transport of contaminants before they reach the water table. The type of media present within this zone significantly influences its absorption capacity, as well as the flow path and travel distance of contaminants. These factors, in turn, affect the time available for attenuation processes and the extent of interaction between contaminants and subsurface materials. The presence of fractures can further alter flow pathways and enhance contaminant migration through the vadose zone (Fetter, 2001). Figure 8 presents the impact of the vadose zone within the Bued River Watershed.

The data used to generate the vadose zone layer were derived from the Geologic Map of Benguet Province (Mines and Geosciences Bureau–CAR, 2018). Based on the map, high-permeability formations, such as bedded limestone, siltstone, shale, and marine clastic or pyroclastic deposits (represented by red-orange and orange colours), are more susceptible to contamination. In contrast, low-permeability formations, including metamorphic and igneous rocks (pink) and their weathered equivalents (blue), are generally less prone to contamination. However, these rock types may also become vulnerable where significant fracturing and weathering are present, which can increase permeability and facilitate contaminant transport.

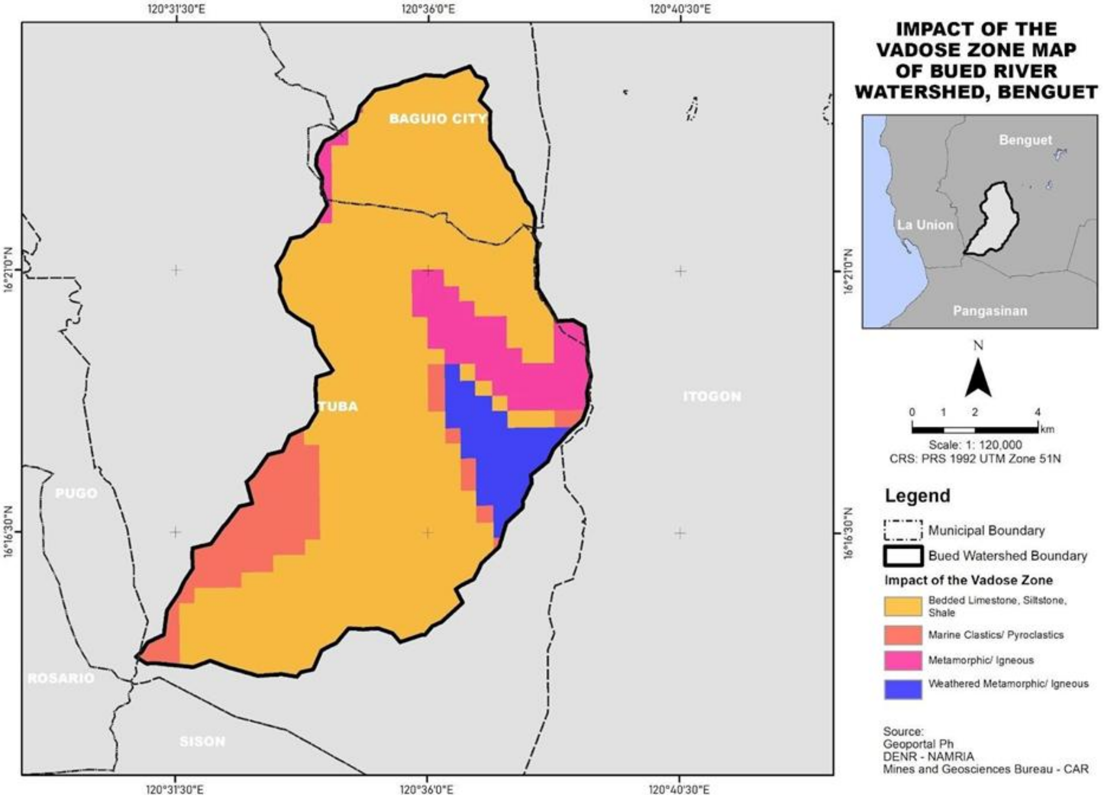

Figure 8. Impact to vadose zones of the Bued River watershed.

4.7 *Hydraulic Conductivity*

Hydraulic conductivity is a key parameter in groundwater flow, representing the ease with which water moves through a saturated porous medium (Fetter, 2001). Hydraulic conductivity values are typically obtained from aquifer pumping tests and published hydrogeological studies. In this study, the values were adopted from Average Hydraulic Conductivity of Consolidated and Unconsolidated Rocks by Domenico and Schwartz (1990). Figure 9 presents the hydraulic conductivity map of the Bued River Watershed.

Based on the map, areas represented in green indicate low hydraulic conductivity, whereas zones shown in pink, which dominate much of the watershed, exhibit high hydraulic conductivity.

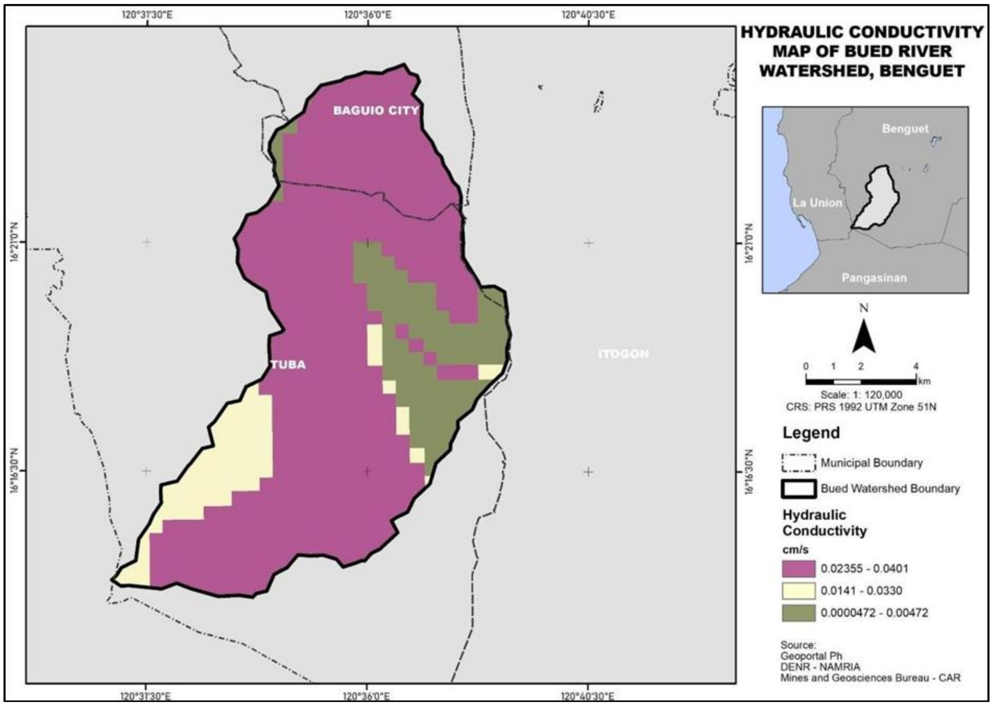

Figure 9. Hydraulic conductivity of the Bued River watershed.

4.8 *Land-use Type*

Figure 10 presents the land use map of the Bued River Watershed. A large portion of the watershed exhibits very high vulnerability, primarily due to the prevalence of agricultural activities. Areas classified as water bodies are also highly vulnerable. Urban areas show moderate vulnerability, largely attributable to the presence of impervious surfaces associated with built-up environments. In addition to mining activities, much of Tuba, Benguet, is predominantly dependent on upland farming.

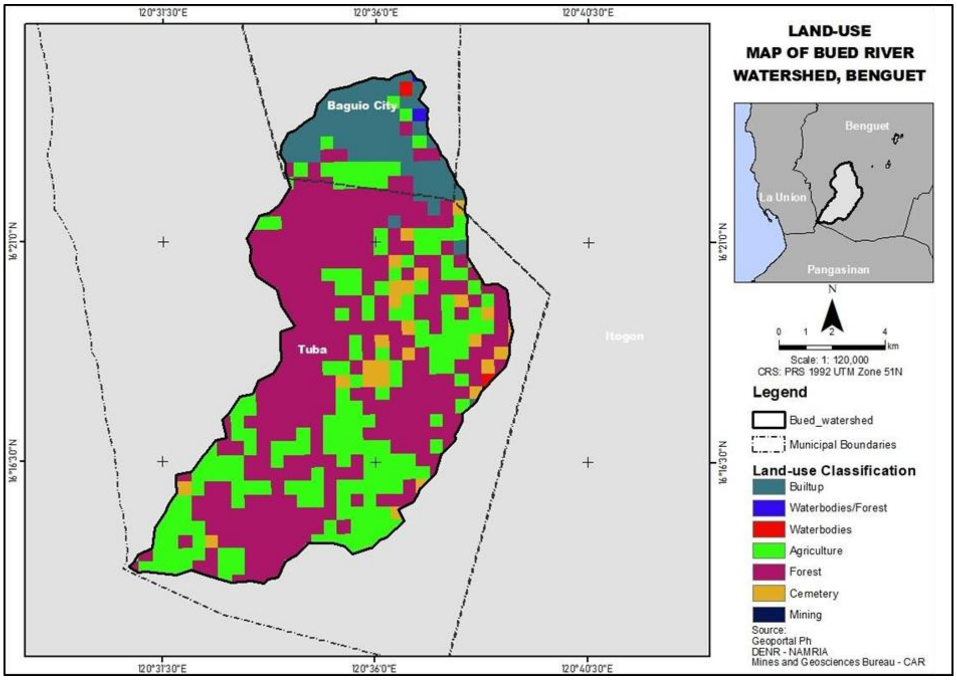

Figure 10. Landuse types of the Bued River watershed.

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4.9 Ground vulnerability

The groundwater vulnerability map of the Bued River Watershed (Figure 11) indicates spatial variations in vulnerability levels across the study area. Areas classified under the Very High Vulnerability Index are primarily located in the municipality of Tuba, particularly in Barangays Camp 4, Camp 3, Camp 1, Twin Peaks, and Tabaan Sur. These high-risk zones are largely associated with intensive agricultural activities.

Areas with a High Vulnerability Index are found in parts of the Santo Tomas School Area in Baguio City, as well as in Barangays Poblacion, Camp 4, Camp 1, Camp 3, Twin Peaks, and Tabaan Sur in Tuba Municipality, and portions of Ampucao in Itogon Municipality. Meanwhile, areas classified under the Moderate Vulnerability Index include several barangays in Baguio City, such as Apugan-Loakan, Atok Trail, Bakakeng Central, Bakakeng North, Balsigan, BGH Compound, Camp 7, Camp 8, Country Club Village, Dagsian, Lower Dagsian, Upper Dontogan, DPS Area, Ferdinand (Happy Homes Campo Sioco), Fort del Pilar, Gabriela Silang, Greenwater Village, Hillside, Imelda R. Marcos (La Salle), Kias, Liwanag-Loakan, Loakan Proper, Military Cut-off, Phil-Am, Poliwes, San Vicente, Santa Escolastica, Santo Rosario, Santo Tomas Proper, Santo Tomas School Area, Scout Barrio, SLU-SVP Housing Village, and South Drive. In Tuba Municipality, moderate vulnerability is observed in Barangays Camp 4, Twin Peaks, Camp 3, Poblacion, and Camp 1.

The moderate vulnerability zones are predominantly underlain by bedded sandstone, limestone, shale, and marine clastic or pyroclastic formations. These lithologies are characterised by relatively high permeability, which facilitates contaminant movement through the aquifer system. In contrast, areas classified under the Low Vulnerability Index, such as parts of Camp 4 in Tuba and portions of Dontogan and Santo Tomas Proper in Baguio City, are underlain by igneous and metamorphic rocks with low permeability, thereby reducing their susceptibility to contamination.

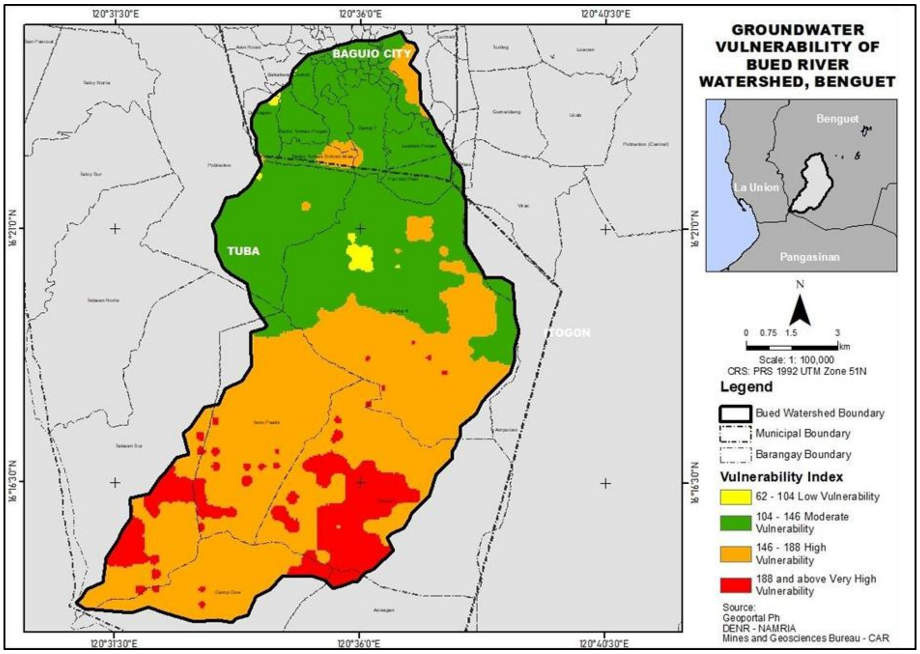

Figure 11. Groundwater vulnerability of the Bued River watershed.

5.0 Conclusions & Recommendations

The groundwater vulnerability of the Bued River Watershed was assessed using the DRASTIC model integrated with Geographic Information System (GIS) analysis. The watershed was classified into four groundwater vulnerability categories: low, moderate, high, and very high. Areas with a Very High Vulnerability Index are primarily located in the municipality of Tuba, particularly in Barangays Camp 4, Camp 1, Camp 3, Twin Peaks, and Tabaan Sur. A total of thirty-three (33) barangays in Baguio City and two (2) barangays in Tuba Municipality fall under the Moderate Vulnerability Index. Areas with a Low Vulnerability Index include portions of Camp 4 and Poblacion in Tuba, as well as parts of Dontogan and Santo Tomas Proper in Baguio City.

High-permeability formations identified in the study include bedded sandstone, limestone, shale, and marine clastic or pyroclastic deposits, while low-permeability formations consist of weathered igneous and metamorphic rocks, as well as unweathered igneous and metamorphic formations. Most areas classified under the Very High Vulnerability Index are associated with agricultural land use, where the application of fertilisers and pesticides increases the risk of groundwater contamination.

Further refinement of the vulnerability assessment requires more detailed data collection, particularly on well inventories, static water levels, and hydraulic conductivity. It is recommended that local government units and water management agencies utilise the generated groundwater vulnerability map to support planning and decision-making processes. In addition, field validation and ground-truthing are essential to verify the accuracy of the results and ensure their consistency with actual site conditions.

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