

# Assessment of Groundwater Recharge Potential Using Integrated GIS, Remote Sensing, and Magnetotelluric Data in Banda Aceh-Indrapuri, Aceh Besar, Indonesia

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## Research Article

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# Assessment of Groundwater Recharge Potential Using Integrated GIS, Remote Sensing, and Magnetotelluric Data in Banda Aceh-Indrapuri, Aceh Besar, Indonesia

## Abstract

Groundwater recharge potential varies across tropical regions, emphasizing the importance of understanding spatial heterogeneity for effective management. This study evaluates groundwater recharge potential in the Banda Aceh-Indrapuri region of northern Sumatra using an integrated geographic information system (GIS), remote sensing (RS), and magnetotelluric (MT) approach. The recharge potential index was derived through a GIS-RS-based multicriteria spatial framework incorporating lithology, land use and land cover, lineament density, drainage density, and slope gradient, aggregated into a  $1 \times 1$  km groundwater index grid. The resulting recharge index ranges from 23.17 to 55.47 (mean = 39.55; standard deviation (SD) = 6.75) and is classified into five categories from Poor to Very Good. Good and Very Good zones collectively occupy 47.04% of the study area, mainly associated with lowland sedimentary environments and structurally controlled areas. Recognizing these links enhances regional groundwater management strategies. Independent shallow MT resistivity models (0–300 m depth) reveal that higher recharge index values align with lower subsurface resistivity. A negative Spearman rank correlation ( $\rho \approx -0.80$ ;  $n = 4$ ) demonstrates the effectiveness of combining geophysical and geospatial methods. This integrated approach offers a robust, physically grounded framework for regional groundwater recharge assessment in complex tropical hydrogeological settings, supporting informed decision-making.

**Keywords:** Groundwater recharge potential; GIS and remote sensing; Magnetotelluric method; Subsurface evaluation; Tropical hydrogeology

## 1. Introduction

Groundwater recharge is an essential yet challenging aspect of the hydrological cycle (Kuang et al., 2024), especially in humid tropical regions where high annual rainfall does not necessarily result in effective replenishment of subsurface water (Krishnaswamy et al., 2013; Jasechko and Taylor, 2015). Recharge processes are controlled by the interaction of geological structures, land-surface characteristics, and topographic gradients (Gnann et al., 2025). However, these factors vary spatially and often operate at scales that are not directly observable. Consequently, regional assessments of groundwater recharge potential typically rely on indirect indicators, introducing uncertainty into both scientific interpretation and groundwater management strategies.

In rapidly developing coastal regions, such uncertainty carries significant implications. Northern Sumatra, particularly the Banda Aceh-Indrapuri region, has seen significant urban growth (Achmad et al., 2015), intensified agricultural activity (Baihaqi et al., 2021), and land-use changes over recent decades (Syamsidik et al., 2017; Chapkanski et al., 2023). Groundwater has become an increasingly vital resource for domestic and municipal use, especially during dry periods and in areas where surface water is limited. Despite receiving abundant rainfall (Alvares et al., 2013), the potential for groundwater recharge and the resulting groundwater conditions vary widely, due to complex interactions among coastal alluvial systems, structurally influenced uplands, and diverse subsurface formations (Hokanson et al., 2019). Therefore, identifying areas favorable for recharge and understanding the subsurface controls that govern them represent both a scientific and management priority.

Remote sensing and GIS-based methods have become key tools for mapping groundwater recharge potential on a regional scale (e.g., Oikonomidis et al., 2015; Agarwal and Garg, 2016; Selvam et al., 2016). By integrating surface and near-surface parameters such as lithology, land use and land cover, drainage characteristics, lineament density, and slope, GIS-RS frameworks create spatially continuous representations of areas favorable for recharge. This methodological approach was established by Yeh et al. (2009). The study demonstrated that multi-criteria spatial integration can effectively represent the combined influence of key factors controlling groundwater recharge, even in the absence of direct hydrogeological data. Accordingly, the framework has been widely adopted and further developed in subsequent studies, positioning it as a commonly used approach for regional groundwater assessment (e.g., Yeh et al., 2016; Singh et al., 2019; Kaewdum and Chotpantararat, 2021).

Despite their widespread application, most GIS-RS-based groundwater recharge assessments rely predominantly on surface-derived indicators. Subsurface conditions such as permeability, saturation, structural connectivity, and lithological heterogeneity ultimately govern recharge and groundwater flow (Lerner, 2020), yet they are rarely independently verified at the regional scale. In geologically complex environments, surface indicators may not accurately represent subsurface hydrogeological behavior (Binley et al., 2015). This limitation is particularly critical in tectonically active basins, where fault systems (Tsutsumi et al., 2020), buried sedimentary structures (Chapkanski et al., 2023), and variable weathering profiles can decouple surface characteristics from groundwater-bearing formations at depth (Dewandel et al., 2017). Thus, the reliability of GIS-RS-derived recharge potential maps depends on independent subsurface validation, which remains infrequently incorporated in humid tropical settings.

The Banda Aceh-Indrapuri region offers a unique opportunity to address existing knowledge gaps in groundwater assessment. The area transitions from coastal alluvial plains to inland structurally controlled terrains composed of Quaternary sediments, sedimentary sequences, and volcanic units (Bennett et al., 1981). Active fault systems extend from the northern tip of Sumatra toward offshore regions (Nanda et al., 2020), exerting structural control on subsurface permeability and groundwater pathways (Rusdy et al., 2020). These geological complexities both challenge conventional surface-based recharge assessments and create an opportunity to examine whether spatial patterns derived from GIS-RS analysis are consistent with independently observed subsurface conditions.

Magnetotelluric (MT) methods provide a robust means of characterizing subsurface resistivity structures (Ismail et al., 2011). MT measurements are sensitive to variations in electrical resistivity (Borah et al., 2015), which are linked to factors such as lithology, fluid content, and pore connectivity (Asaue et al., 2012; Becken and Ritter, 2012). This sensitivity allows for the distinction between conductive groundwater-bearing zones and more resistive geological formations (Yadav et al., 2020). In contrast to surface-based indicators, MT observations directly sample the subsurface over depth ranges relevant to groundwater occurrence, while remaining independent of the GIS-RS workflow. However, explicit integration of MT-based subsurface verification into GIS-RS-derived regional recharge potential assessments remains limited, especially in humid tropical regions.

This study addresses this methodological gap by explicitly integrating GIS-RS-based groundwater recharge potential mapping with independent subsurface verification using magnetotelluric observations in the Banda Aceh-Indrapuri region. Recharge potential is first derived through multicriteria spatial integration of key surface and near-surface controlling factors. Shallow MT resistivity models are subsequently employed to evaluate the consistency between zones identified as favorable for recharge and conductive subsurface conditions associated with structurally controlled groundwater pathways. Through this integrated approach, the study provides both a regional recharge potential assessment and a physically grounded framework for strengthening GIS-RS-based groundwater investigations in complex hydrogeological environments.

## 2. Study Area

This study was conducted in the Banda Aceh-Indrapuri region, located in Aceh Besar Regency, Aceh Province, at the northern tip of Sumatra Island, Indonesia (**Figure 1**). Covering an area of approximately 977 square kilometers (km<sup>2</sup>), the region stretches from the coastal urban zone of Banda Aceh in the north to the more undulating interior terrains of Indrapuri in the south (Barber and Crow, 2005). This transitional landscape offers a diverse range of geomorphological, geological, and hydrological characteristics, making it an ideal setting for assessing groundwater recharge potential through integrated surface and subsurface analysis.

Climatically, the study area falls within the tropical rainforest (Af) zone according to the Köppen-Geiger climate classification (Beck et al., 2018). The region experiences high annual rainfall of approximately 2,500 mm, with seasonal variability influenced by regional monsoonal circulation. Although precipitation is abundant, effective groundwater recharge remains strongly controlled by lithology, topography, and land-surface characteristics. The interaction between rainfall and topographic variation significantly influences surface runoff and infiltration dynamics (Ghomash et al., 2019), while the effectiveness of recharge is further mediated by slope gradient, vegetation cover, and soil permeability (Owuor et al., 2016).

**Figure. 1.** Area of study in (a) Banda Aceh City and Indrapuri, Aceh Besar Regency, (b) Aceh Province, (c) Indonesia.

However, the region presents a gradual elevation increase from the flat, urbanized floodplains near Banda Aceh to the dissected hills and structural ridges of Indrapuri. This terrain variation not only governs hydrological flow paths but also affects land use distribution. Urban and built-up areas dominate the lowland zones, while agricultural fields, forests, and open green spaces are more prevalent in the southern upland regions. Geologically, the study area is characterized by a mixture of Quaternary alluvial deposits, Tertiary sedimentary units, and volcanic rocks, including breccias and pyroclastic flows (Bennett et al., 1981). These formations differ in porosity and permeability, resulting in varying capacities to absorb and transmit groundwater (Younger, 2009). The presence of structural features such as faults, fractures, and joints, expressed as lineaments in remote sensing data, further influences subsurface water movement, acting as potential pathways for infiltration or as hydraulic barriers (Elshalkany et al., 2025).

Moreover, the region is traversed by several drainage systems, with the Krueng Aceh River being the most prominent. These river networks contribute to the surface-groundwater interaction and also reflect the structural and lithological control over surface water distribution. Together, the area's climatic regime, topographic gradients, geological diversity, and drainage characteristics provide a comprehensive natural laboratory for evaluating groundwater recharge potential using a combination of geospatial and geophysical approaches.

### **3. Methods and Materials**

This study integrates remote sensing data, Geographic Information System (GIS), and geophysical methods to assess the groundwater recharge potential zones in the Banda Aceh-Indrapuri region, Aceh Besar Regency. The analysis is based on surface parameters that influence water infiltration, while independent subsurface evaluation is conducted using resistivity information derived from magnetotelluric (MT) measurements, which is capable of identifying saturated zones and potential groundwater flow paths. The overall methodological framework of this study is illustrated in **Figure 2**.

**Figure. 2.** Methodology flowchart for groundwater potential zone mapping.

#### **3.1. GIS and Remote Sensing-Based Groundwater Recharge Potential Factors**

The recharge potential model is constructed based on local site characteristics and evaluated through five key thematic parameters, i.e., lithology, land use and land cover (LULC), lineament density, drainage density, and slope gradient. All parameters were analyzed spatially using cloud-computing platforms for data processing and subsequently visualized using conventional GIS software.

##### **3.1.1. Lithology**

Lithology is one of the most critical factors influencing groundwater recharge, primarily due to its control over rock permeability, porosity, and the degree of weathering (Lachassagne et al., 2021). In this study, lithological data were acquired from the regional geological map of the Banda Aceh-Indrapuri area and subsequently digitized and classified into four major lithological units based on their depositional environment and genetic origin (Bennett et al., 1981). These units include extrusive-intermediate volcanic rocks, tectonite/metamorphic formations, clastic sedimentary units consisting of sandstone, conglomerate, and fine-grained deposits, and carbonate sedimentary units such as limestone and reef limestone.

Each lithological unit was evaluated according to its potential to facilitate groundwater infiltration. Clastic sediments and carbonate formations were interpreted as having a relatively higher recharge potential due to their inherent porosity and the possibility of secondary permeability features, such as fractures or dissolution pathways (Mazzullo, 2004). In contrast, metamorphic and extrusive volcanic rocks were regarded as comparatively less favorable for infiltration because of their compact structure and limited pore connectivity (Manning and Ingebritsen, 1999).

Shaban et al. (2006) emphasized that the type of rock exposed at the surface significantly affects groundwater recharge processes, as different lithologies exhibit distinct infiltration behaviors. Furthermore, Letz et al. (2021) highlighted that lithology controls groundwater percolation through its influence on subsurface flow paths. Although some investigations rely solely on drainage and lineament patterns as indirect indicators of porosity and permeability, this study explicitly includes lithology to reduce uncertainties in interpreting those secondary features.

### 3.1.2. Land Use/Land Cover (LULC)

Land use and land cover (LULC) are key surface parameter that significantly affects groundwater recharge by influencing infiltration rates, evapotranspiration, and runoff behavior. It encompasses not only vegetation and surface sealing, but also the distribution of soil types and built-up areas (Vieillard et al., 2024). In this study, LULC data were obtained from the globally standardized Sentinel-2 10-meter Land Use/Land Cover dataset developed by Impact Observatory and Esri (Karra et al., 2021). This dataset was produced using deep learning algorithms trained on billions of human-labeled pixels and applied to Sentinel-2 Level-2A imagery within Microsoft's Planetary Computer. The year 2024 was selected as the temporal reference, offering high spatial and thematic consistency.

From the original nine global LULC classes, the data were reclassified into four major categories relevant to groundwater recharge assessment, i.e., built-up areas, forest, agricultural land, and surface water. Each category was evaluated based on its capacity to promote or restrict infiltration. Forest and agricultural areas were assigned higher recharge potential due to the role of vegetation in enhancing percolation and reducing direct evaporation. As noted by Shaban et al. (2006), vegetation supports groundwater recharge in several ways: (1) root decomposition helps loosen soil and rock, enhancing percolation; (2) canopy cover reduces direct evaporation from the soil surface; and (3) plant roots regulate moisture retention. Furthermore, Leduc et al. (2001) demonstrated that changes in vegetation and land utilization can significantly affect groundwater levels, reinforcing the importance of LULC in recharge dynamics. Built-up areas, in contrast, were classified as having low to very low recharge potential due to the dominance of impervious surfaces, while surface water bodies were considered neutral in terms of infiltration but important in maintaining regional hydrological balance (Uppendra et al., 2024).

### 3.1.3. Lineament

Lineaments serve as crucial indicators of subsurface geological discontinuities, including faults, joints, and fractures. These features play a vital role in shaping secondary porosity and facilitating groundwater movement (Bense et al., 2013). Since the 1930s, the analysis of lineaments has proven instrumental in unlocking the secrets of geological structures, particularly through aerial and satellite imagery. O'Leary et al. (1976) characterize lineaments as linear or slightly curved features that highlight significant structural alignments, such as faults, cleavages, and fractures, which can be effectively identified via remote sensing technology. However, it is essential to acknowledge that the interpretation of lineaments is not always straightforward. Factors such as image type, scale, and resolution can influence the analysis, leading to the potential inclusion of non-geological features, like roads, canals, or field boundaries. To combat misclassification and enhance accuracy, this study integrates geological maps and field verification, ensuring that remotely detected features are validated and refined. By doing so, we can achieve a more precise understanding of the geological landscape and its implications for resource management and environmental sustainability.

In the context of hydrogeology, lineaments serve as proxies for identifying groundwater conduits, as their presence typically implies enhanced permeability. Abotalib et al. (2019) were among the first to propose using lineament analysis to locate groundwater-rich zones. Subsequent research has confirmed the utility of this method in complex geological environments (Yamusa et al., 2018). In this study, lineaments were extracted from the National DEM (DEMNAS) were developed by Indonesia's Geospatial Information Agency digital elevation with a resolution of 0.27 arc-second (Badan Informasi Geospasial, 2018) model using hillshading and edge-detection techniques to enhance linear features. The validated lineaments were then used to compute lineament-length density ( $L_d$ ), which represents the total length of lineaments per unit area. As defined by Greenbaum (1985), lineament density is calculated as:

$$L_d = \frac{\sum_{i=1}^{i=n} L_i}{A} \quad (1)$$

where  $\sum L_i$  is the total length of lineaments (km) within the analysis unit and  $A$  is the unit area (km<sup>2</sup>). Areas with higher  $L_d$  values are interpreted to have greater secondary porosity, implying higher groundwater recharge potential.

#### 3.1.4. Drainage

The structural configuration of a drainage network is crucial for evaluating groundwater recharge potential, as it illustrates how surface runoff interacts with subsurface infiltration processes. The density and arrangement of drainage systems are affected by underlying geology, topography, and soil permeability, all of which collectively determine the percolation capacity of a given area (Fan et al., 2019). Regions with low drainage density tend to promote infiltration due to longer water residence times. In contrast, areas with a highly dissected landscape may increase surface runoff and decrease the potential for groundwater recharge (Dorici et al., 2016).

In this study, drainage networks were derived from the DEMNAS digital elevation model using standard hydrological modeling procedures, including sink filling, flow direction and accumulation analysis, and stream delineation based on calibrated thresholds. From the extracted stream network, drainage density ( $D_d$ ) was calculated to represent the total stream length per unit area, as defined by Greenbaum (1985) in eq. (2):

$$D_d = \frac{\sum_{i=1}^{i=n} S_i}{A} \quad (2)$$

where  $\sum S_i$  is the total stream length of drainage segments (km) within the analysis unit and  $A$  is the unit area (km<sup>2</sup>). The resulting drainage density raster serves as an indicator of recharge potential. Low to moderate values generally corresponding to favorable conditions for infiltration (Fagbohun, 2018).

Although the relationship between drainage density and recharge is often inversely proportional, several studies have demonstrated that zones with well-developed but less dense drainage networks, especially in permeable lithologies, can exhibit enhanced recharge (Fagbohun, 2018; Lerner, 2020). Accordingly, the  $D_d$  values were reclassified into five categories ranging from very low to very high recharge potential, using natural breaks in the data distribution.

#### 3.1.5. Slope

Slope gradient is a key topographic factor that affects the rate of surface runoff and the potential for groundwater recharge. In tropical and subtropical regions, where rainfall is the main source of groundwater replenishment, the slope significantly influences whether precipitation infiltrates into the ground or is lost as runoff. Steeper slopes tend to decrease infiltration opportunities because rainwater quickly flows over the surface, leaving insufficient time for it to percolate into the soil and recharge the saturated zone. In contrast, gentler slopes slow down runoff, allowing for longer residence time and increased rates of infiltration.

In this study, the slope layer was derived from the DEMNAS digital elevation model using Eq. (3) (Horn, 1981):

$$\text{slope} = \arctan\left[\sqrt{(dz/dx)^2 + (dz/dy)^2}\right], \quad (3)$$

where  $dz/dx$  and  $dz/dy$  represent elevation gradients in the  $x$  and  $y$  directions of the DEM. The resulting calculation, expressed in degrees, was categorized into four slope classes: 0-15°, 15°-35°, 35°-55°, and 55°-90°. These classes were then reclassified according to their expected recharge potential, with lower slopes receiving higher ratings.

### 3.2. Spatial Analysis of Groundwater Recharge Potential Factors

The spatial analysis of groundwater recharge potential factors was carried out using a weighted spatial overlay framework implemented in a Geographic Information System (GIS). The analytical concept was adapted from

Yeh et al. (2009), in which groundwater recharge potential is assessed through the spatial integration of multiple controlling factors with unequal contributions. In this study, the relative importance of groundwater recharge factors was represented implicitly through factor-specific maximum scores, rather than by applying explicit multiplicative weights. This strategy enables proportional factor contribution while avoiding redundancy in weighting during spatial integration. The maximum score assigned to each factor reflects its relative influence on groundwater recharge, and the sum of the maximum scores across all factors was standardized to 100.

The assignment of factor-specific maximum scores follows the proportional weighting logic described by Yeh et al. (2009), where the relative influence of recharge-controlling factors is determined based on their conceptual interrelationships and normalized to a total score of 100. In the present study, this framework was adapted to reflect the hydrogeological characteristics of the Banda Aceh-Indrapuri region while preserving the relative ranking among factors reported in previous groundwater recharge potential studies. The hierarchical ordering of lithology, land use/land cover, lineament density, drainage density, and slope is consistent with established hydrogeological principles, in which geological properties exert primary control over infiltration capacity and subsurface storage. At the same time, geomorphological factors modulate runoff-infiltration dynamics. Thus, the maximum scores represent a modified implementation of an established GIS-based recharge assessment model rather than an arbitrary numerical selection.

All groundwater recharge potential factors were discretized into classes representing increasing recharge favorability. This unified scoring logic was applied to both categorical and continuous variables to ensure methodological consistency. Class scores ranged from low to high recharge potential and were capped by the maximum score of the corresponding factor. The complete classification and scoring scheme are presented in **Table 1**.

**Table 1.** Classification criteria and factor-specific scores used for the GIS-RS-based groundwater recharge potential assessment (adapted from Yeh et al. 2009)

Lithology was assigned the highest maximum score due to its dominant control on infiltration processes through primary and secondary porosity. Land use/land cover and lineament-length density were assigned intermediate maximum scores, reflecting their influence on surface permeability and subsurface preferential flow pathways. Drainage density and slope gradient were assigned relatively lower maximum scores, as their impacts on groundwater recharge are more indirect and strongly mediated by interactions with other factors. Prior to spatial integration, all thematic layers were resampled and standardized to a uniform spatial resolution of 30 m to ensure spatial compatibility and to minimize scale-induced bias during raster overlay operations. Each raster cell was assigned a score based on its corresponding class within each factor layer.

The groundwater recharge potential index was computed by summing the scores of all five factors for each raster cell. This additive integration approach allows the combined effects of lithological, geomorphological, structural, and land surface characteristics to be represented spatially in a transparent and reproducible manner. The resulting composite index provides a relative spatial measure of groundwater recharge potential and serves as the basis for delineating groundwater recharge potential zones. The derived spatial patterns further provide a consistent reference for subsequent analyses incorporating independent subsurface information.

To facilitate regional-scale analysis, the 30 m recharge potential raster was subsequently aggregated to a 1×1 km grid using spatial averaging. Following aggregation, a quality-control filtering step was applied to generate the analysis-ready dataset used for statistical evaluation. Grid cells flagged as invalid (ValidFlag ≠ 1), including boundary and non-representative areas, were excluded to ensure spatial consistency within the defined study domain. The filtered 1×1 km dataset was used for descriptive statistical analysis and regional classification presented in the Results section.

### 3.3. Magnetotelluric Method

MT data were acquired at four stations (IDP-1, IDP-2, IDP-3, and IDP-4) strategically located within the Banda Aceh-Indrapuri region, Aceh Besar Regency (**Figure 1**). The inter-station spacing ranged from 5 to 15 km, providing sufficient lateral coverage to resolve regional-scale subsurface resistivity variations. Station locations were preferentially selected near the main river channel and its tributaries, as river systems exert primary control

on groundwater flow and recharge processes (Zhu et al., 2021).

Data acquisition was conducted using a KMS-820 main unit equipped with three LEMI-120 broadband induction coil magnetometers and four LEMI-701 non-polarizable electrodes. The magnetic sensors were installed orthogonally in accordance with geographic orientation, with the horizontal components  $H_x$  and  $H_y$  aligned along the north-south and east-west directions, respectively, and the vertical component  $H_z$  installed vertically. The electric field was measured using orthogonal dipoles ( $E_x$  and  $E_y$ ) oriented north-south and east-west, with a dipole length of 50 m. To reduce electrode-ground contact resistance, the electrodes were treated with NaCl CuSO<sub>4</sub> solution prior to installation. Continuous time-series data were recorded for approximately 14 hours at each station using a sampling rate of 1 kHz to ensure adequate signal stability and broadband frequency coverage. After robust processing and noise suppression, the effective frequency range retained for inversion was approximately 0.86-66.4 Hz. This band provided reliable impedance estimates and adequate sensitivity to shallow subsurface structures within the upper few hundred meters.

Raw MT data consisted of time-series recordings of natural electric and magnetic field variations. Time-domain signals were transformed into the frequency domain using Fast Fourier Transform (FFT) to estimate impedance transfer functions. Robust processing techniques were applied to suppress outliers and minimize cultural and transient noise contamination. The processed data were stored in standard EDI format containing complex impedance tensors for each frequency. Apparent resistivity and phase responses were subsequently derived from the impedance tensors.

One-dimensional resistivity models were obtained through inversion using the IPI2WIN MT software (Bobachev, 2002), which employs a Newton-type optimization scheme with Tikhonov regularization to stabilize the solution. Frequency-dependent apparent resistivity and phase data were used as inversion inputs. Inversion was conducted using the transverse electric (TE) mode, which exhibits higher sensitivity to conductive subsurface structures than the transverse magnetic (TM) mode (Berdichevsky et al., 1998; Pedersen and Engels, 2005), making it suitable for delineating conductive aquifer layers.

The inversion aimed to achieve an optimal fit between observed and modeled MT responses. However, MT inversion is inherently non-unique, as multiple subsurface models may reproduce similar data responses (Peng et al., 2024). To reduce ambiguity, geological cross-section information was incorporated as a priori constraints. This integration improved the geological plausibility and reliability of the resulting resistivity models.

## 4. Results

This section presents the spatial characteristics of the controlling factors, the integrated groundwater recharge potential model derived from GIS and RS analysis, and its validation using independent magnetotelluric (MT) data.

### 4.1. Spatial Patterns of Groundwater Controlling Factors

The spatial variability of groundwater potential in the Banda Aceh-Indrapuri region reflects the combined influence of geological structure, land surface conditions, and topographic characteristics. Lithology represents a fundamental control on groundwater occurrence, as lowland areas dominated by clastic and carbonate sedimentary formations provide favorable conditions for groundwater storage and hydraulic conductivity (Figure 3a). These lithological units are typically associated with higher porosity and permeability, whereas volcanic and metamorphic rocks prevailing toward higher elevations generally correspond to reduced groundwater potential due to limited primary porosity.

Land use and land cover (LULC) further modulate these geological controls by influencing infiltration and surface runoff processes. Agricultural land and surface water bodies are predominantly distributed across the low-lying plains, facilitating infiltration and potential groundwater recharge (Figure 3b). In contrast, built-up areas locally reduce infiltration capacity but occupy relatively limited spatial extents, resulting in a minor influence on the regional groundwater potential pattern.

Furthermore, structural features, as reflected in lineament density, delineate zones of enhanced fracture-controlled permeability that may serve as preferential pathways for groundwater movement (Figure 3c). Areas

with higher lineament density commonly coincide with improved groundwater favorability, highlighting the role of tectonic structures in subsurface fluid circulation. On the other hand, drainage density and slope exert a constraining influence on groundwater recharge. Regions characterized by high drainage density and steep slope gradients exhibit enhanced surface runoff and reduced infiltration potential, whereas areas with low slope gradients and low drainage density favor infiltration and subsurface flow accumulation (**Figure 3d and Figure3e**).

**Figure 3.** Spatial distribution of groundwater controlling factors: (a) lithology, (b) land use/land cover (LULC), (c) lineament density, (d) drainage density, and (e) slope.

Nevertheless, the spatial relationships exhibit limited statistical interdependence. Spearman rank correlation analysis indicates low to moderate correlations ( $|\rho| < 0.6$ ) among the factors, with no evidence of strong multicollinearity. Moderate correlations between slope and lineament density reflect structural influences on terrain development, while the association between lithology and topography is consistent with the regional geological framework. The absence of strong interdependence indicates that each factor provides complementary information for the groundwater potential assessment, supporting their integration within a weighted overlay framework (**Figure 4**).

Furthermore, structural features, as reflected in lineament density, delineate zones of enhanced fracture-controlled permeability that may serve as preferential pathways for groundwater movement (**Figure 3c**). Areas with higher lineament density commonly coincide with improved groundwater favorability, highlighting the role of tectonic structures in subsurface fluid circulation. On the other hand, drainage density and slope exert a constraining influence on groundwater recharge. Regions characterized by high drainage density and steep slope gradients exhibit enhanced surface runoff and reduced infiltration potential, whereas areas with low slope gradients and low drainage density favor infiltration and subsurface flow accumulation (**Figure 3d and Figure3e**).

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**Figure 4.** Spearman rank correlation matrix of groundwater controlling factors based on grid-based score values.

#### 4.2. Integrated Groundwater Recharge Potential Model

The integration of groundwater controlling factors using a weighted overlay approach yielded a spatially coherent groundwater recharge potential model for the Banda Aceh-Indrapuri region. The groundwater recharge potential zonation map delineates five classes (very good, good, moderate, low, and poor), distributed systematically across the study area in accordance with spatial variations in lithology, land use/land cover (LULC), lineament density, drainage density, and slope gradients (**Figure 5**). This integrated pattern reflects the cumulative influence of geological, structural, and surface characteristics on groundwater occurrence.

**Figure 5.** Groundwater recharge potential zonation map derived from weighted overlay of lithology, LULC, lineament density, drainage density, and slope factors, classified into five classes (Poor-Very Good). MT stations and river streams are shown for reference.

Moreover, quantitative analysis based on the filtered  $1 \times 1$  km analysis-ready grid (ValidFlag = 1) highlights the spatial dominance of favorable groundwater conditions within the study domain. After quality-control filtering, 1012 grid cells were retained, corresponding to an effective analysis area of approximately 972 km<sup>2</sup>. Approximately 47% of this area ( $\approx 457$  km<sup>2</sup>) falls within the Good to Very Good recharge potential categories, while Poor potential zones account for about 10% (Table 2). Moderate recharge potential covers roughly 21% of

the area, indicating transitional hydrogeological conditions between high and low potential zones. The groundwater recharge potential index values range from 23.17 to 55.47, with a mean of 39.55 and a standard deviation (SD) of 6.75, indicating moderate spatial variability across the region.

**Table 2.** Areal distribution of recharge potential classes based on the filtered  $1 \times 1$  km grid (ValidFlag = 1)

To examine the influence of river proximity, recharge-potential classes were summarized within three river-buffer distances (**Table 3**). Areas within 0-500 m of the river network are dominated by moderate to very good classes, whereas areas beyond 1,000 m show substantially higher proportions of low to poor classes.

**Table 3.** Percentage distribution of recharge potential classes across river-buffer distance.

Additionally, the spatial distribution of groundwater potential varies among sub-districts at the administrative level (**Table 4**). The subdistricts of Indrapuri and Ingin Jaya show a relatively high proportion of Potential Area (%), which is defined as the combined area of good and very good classes, indicating more favorable groundwater conditions. Conversely, the Banda Raya and Kuta Alam areas are dominated by moderate to poor groundwater recharge potential, highlighting zones where groundwater availability may be more limited and require careful management strategies. These spatial contrasts suggest the relevance of the groundwater potential model for regional planning and groundwater resource management.

**Table 4.** Distribution of recharge potential classes by sub-district, expressed as class percentages and potential area.

### 4.3. Magnetotelluric (MT) Resistivity Model

Magnetotelluric (MT) data collected from stations IDP-1, IDP-2, IDP-3, and IDP-4 cover a frequency range of approximately 0.86 to 66.4 Hz. Within this band, the apparent resistivity and phase curves exhibit smooth and continuous trends, with no pronounced irregular oscillations. The overall response pattern suggests predominantly vertical variations in electrical structure over the investigated depth range.

**Figure 6.** MT observed versus calculated apparent resistivity curves and inversion misfit (%) for sites (a) IDP-1, (b) IDP-2, (c) IDP-3 and (d) IDP-4.

A qualitative assessment of the phase responses indicates variations consistent with vertical contrasts in electrical properties. Higher phase values are commonly associated with more conductive materials, often related to water-saturated or fine-grained sediments at shallow depths, whereas lower phase values typically correspond to relatively resistive formations (Vozoff, 1991). The dominance of vertical resistivity variations in the MT responses supports the application of one-dimensional (1D) inversion for resolving the principal subsurface structures relevant to groundwater occurrence.

The reliability of the inversion results is evident from the close agreement between observed and calculated apparent resistivity curves (**Figure 6**). The inversion misfit values range from 6.18% to 9.71% across the four stations, indicating satisfactory agreement between observed and modeled responses. These misfit levels suggest that the 1D resistivity models reasonably reproduce the measured MT data within an acceptable error margin. The resulting resistivity depth models reveal a broadly layered structure beneath each station, while variations in resistivity magnitude and layer thickness reflect local geological heterogeneity (**Figure 7**).

**Figure 7.** 1D-MT resistivity inversion model for the depths at sites IDP-1, IDP-2, IDP-3 and IDP-4. Resistivity values in the shallow layer (0-300 m) were used to validate the groundwater recharge potential index.

Shallow subsurface layers extending from the surface to approximately 300 m are characterized by relatively low resistivity, commonly associated with unconsolidated sediments, weathered formations, and increased fluid saturation. These conductive zones are more pronounced at stations IDP-2 and IDP-3, indicating comparatively more conductive subsurface conditions in these areas. At greater depths, resistivity generally increases, suggesting more compact and less permeable geological units that may represent basement or weakly fractured formations.

The observed vertical and lateral resistivity variations provide a physically grounded basis for comparison with the GIS-RS-derived groundwater recharge potential model.

#### 4.4. Magnetotelluric (MT) Evaluation of the Recharge Potential Model

Independent magnetotelluric (MT) data were used to evaluate the reliability of the groundwater potential model derived from the GIS-RS analysis. For point-based validation, recharge potential index values were extracted from the original (unfiltered) 1×1 km weighted overlay grid to preserve local variability at station locations and compared with shallow MT resistivity values representative of the upper 0–300 m of the subsurface (Table 5).

**Table 5.** Comparison between GIS-RS-derived recharge potential classes and shallow MT resistivity (0–300 m) at MT stations.

The comparison indicates an inverse relationship between recharge-potential category and shallow MT resistivity (Figure 8). Sites characterized by lower resistivity values correspond to higher recharge-potential classes, whereas sites with higher resistivity values are associated with lower recharge potential. This relationship is hydrogeophysically plausible, as lower electrical resistivity commonly reflects increased fluid saturation and enhanced pore connectivity.

**Figure 8.** Relationship between groundwater recharge potential index and shallow MT resistivity (0–300 m) at four MT sites.

For statistical evaluation, recharge-potential interpretations were converted to ordinal ranks (Low < Low–Moderate > Moderate–Good < Very Good). Spearman rank correlation between ordinal recharge potential and shallow MT resistivity yields  $\rho \approx -0.80$  ( $n = 4$ ), suggesting a strong inverse monotonic association. Although the number of MT stations is limited, the observed trend supports consistency between the GIS-RS-derived recharge model and independent subsurface resistivity observations.

## 5. Discussion

### 5.1. Interpretation of Groundwater Potential Patterns Derived from GIS-RS Analysis

The groundwater potential patterns derived from the GIS-RS analysis can be understood as the outcome of interacting surface and near-surface controls rather than the dominance of any single factor. In the Banda Aceh-Indrapuri region, groundwater occurrence reflects a balance among geological capacity for storage, topographic regulation of recharge, and land-surface processes that influence infiltration and runoff. Such integrative behavior is widely recognized in remote-sensing-based groundwater assessments, particularly in humid and tectonically active regions (Yeh et al., 2009; Adams et al., 2022).

Lithology provides the fundamental framework governing groundwater storage and flow potential. Sedimentary environments typically offer more favorable hydraulic conditions than crystalline or volcanic terrains, allowing other surface-related factors to exert a meaningful influence on recharge processes (Bera et al., 2022). Within this framework, topography and drainage characteristics regulate the residence time of surface water and its potential to infiltrate. Areas characterized by lower slope gradients and less developed drainage networks tend to favor recharge, whereas steeper terrain promotes rapid runoff and limits subsurface replenishment (Fan et al., 2019). Similar relationships between topography, drainage development, and groundwater potential have been reported across a range of GIS-RS studies (Fagbohun, 2018; Upendra et al., 2024).

Furthermore, land use and land cover modify these natural controls by altering near-surface hydrological processes. Agricultural landscapes and surface water bodies generally enhance surface-subsurface connectivity and support recharge (Banks et al., 2011; Han et al., 2017), whereas urbanized areas may locally restrict infiltration due to increased surface sealing (Charzyński et al., 2017; Locatelli et al., 2017). However, at the regional scale considered in this study, land cover acts primarily as a modifying factor rather than a dominant

control, reinforcing the importance of geological and geomorphological settings in shaping groundwater potential. This hierarchical influence of factors is consistent with conceptual groundwater recharge models proposed for humid tropical environments (Brauman et al., 2012; Owuor et al., 2016).

Collectively, the GIS-RS-derived groundwater potential patterns align with established hydrogeological understanding of the combined influence of lithology, topography, drainage, and land surface conditions on groundwater systems. Rather than reproducing isolated spatial patterns, the integrated model captures the broader process-based controls governing groundwater occurrence. This conceptual consistency strengthens the interpretability of the groundwater potential map and provides a robust foundation for subsurface validation using independent geophysical information.

## **5.2. Subsurface Validation of GIS-RS-Based Groundwater Potential Mapping**

Independent subsurface constraints obtained from MT measurements provide an essential means of evaluating the reliability of groundwater potential maps derived from surface-based indicators. In this study, shallow MT resistivity models (0-300 m depth) were employed to examine whether zones identified as having higher groundwater potential through the GIS-RS framework are also characterized by more conductive subsurface conditions, which are commonly associated with groundwater-bearing formations.

A consistent and physically meaningful relationship is observed between recharge-potential categories and shallow MT resistivity. Areas classified within higher recharge-potential classes tend to correspond to lower resistivity, whereas zones categorized as low to poor potential generally show higher resistivity responses. This inverse pattern reflects the established sensitivity of electrical resistivity to groundwater saturation and pore connectivity (Muchingami et al., 2012; Kayode et al., 2016). Field-based applications further demonstrate the capacity of electrical methods to resolve subsurface hydrogeological contrasts (Kamaraj et al., 2023).

Spearman rank correlation analysis ( $\rho \approx -0.80$ ;  $n = 4$ ) indicates a strong inverse monotonic association between ordinal recharge-potential categories and shallow MT resistivity. The Association between the two independent datasets supports the robustness of this relationship (van den Heuvel and Zhan, 2022). This relationship does not result from direct parameter coupling, as MT-derived resistivity information was not incorporated into the construction of the recharge-potential model. Instead, the observed agreement suggests that the GIS-RS framework effectively captures surface expressions that reflect underlying hydrogeological conditions.

At the site scale, recharge-potential categories extracted at MT station locations are consistent with shallow resistivity characteristics inferred from MT inversion results. Stations associated with very good recharge-potential classes exhibit relatively low shallow resistivity, whereas stations within low to moderate potential zones show comparatively higher resistivity. This correspondence reinforces the conceptual linkage between surface-controlled factors such as lithology, drainage development, and topographic setting and subsurface electrical properties indicative of groundwater occurrence (e.g., Ebong et al., 2021; Genedi and Youssef, 2026).

Despite the limited number of MT sites, the consistency in both the direction and magnitude of the observed relationship provides meaningful support for the validity of the GIS-RS-derived groundwater potential model. Hence, the combined use of spatially continuous RS-based analysis and point-based geophysical observations represents a complementary and effective strategy for groundwater assessment (Basharat et al., 2025), particularly in regions where direct hydrogeological data are limited (Wali et al., 2024).

## **5.3. Implications and Limitations of the Integrated GIS-RS and MT Approach**

The integration of GIS-RS-based groundwater potential mapping with independent MT observations has clear implications for regional groundwater assessment. By linking spatially continuous surface information with subsurface geophysical constraints, the approach enables a more coherent interpretation of groundwater occurrence than would be achieved using surface indicators alone (Khan et al., 2024). This is particularly relevant in regions where direct hydrogeological data are sparse, and where groundwater assessments must rely on indirect but complementary sources of information.

The consistency between the GIS-RS-derived groundwater recharge potential index and shallow MT resistivity demonstrates the methodological strength of combining surface-based and subsurface-based

perspectives. While the GIS-RS framework captures the spatial expression of lithological, geomorphological, and hydrological controls (Ajayakumar, 2024), MT measurements provide an independent view of subsurface electrical conditions (Simpson and Bahr, 2005; Ismail and Pedersen, 2011) that are closely related to groundwater saturation and permeability. Their agreement suggests that the integrated approach effectively bridges the gap between surface proxies and subsurface hydrogeological conditions, thereby increasing confidence in spatial groundwater evaluations (Kant and Wrat, 2025).

At the same time, the scope of the present assessment is shaped by several inherent constraints. The limited number of MT stations restricts the resolution at which subsurface heterogeneity can be examined, and the groundwater recharge potential index represents relative favorability rather than absolute groundwater availability. In addition, the weighted overlay scheme involves expert-based judgment in assigning factor weights, which, although grounded in hydrogeological reasoning and supported by previous studies (Yeh et al., 2009), introduces an element of subjectivity. These limitations, however, are characteristic of regional-scale groundwater potential studies and do not undermine the internal consistency of the results.

Nevertheless, the integrated GIS-RS and MT approach provides a robust and practical framework for groundwater potential assessment at the regional scale. The ability to reconcile surface-derived indicators with independent subsurface evidence represents a meaningful step toward more reliable groundwater mapping in complex hydrogeological settings, such as the Banda Aceh-Indrapuri region, where conventional data coverage remains limited.

From a regional management perspective, the delineated recharge potential zones provide a spatially explicit framework that can inform groundwater protection strategies and land-use planning in Aceh Besar Regency. Areas classified as Good and Very Good recharge potential may be considered priority zones for infiltration preservation, green-space allocation, and the regulation of urban expansion to maintain recharge capacity. In contrast, zones identified as Low to Poor potential may require more cautious groundwater abstraction management and enhanced monitoring to mitigate overexploitation risks. By translating spatial recharge patterns into management-relevant units, the integrated GIS-RS and MT framework developed in this study offers a science-based decision-support tool for local authorities in designing sustainable groundwater protection and spatial planning policies.

## 6. Conclusion

This study has successfully established an integrated approach for evaluating groundwater recharge potential in the Banda Aceh-Indrapuri region by combining a GIS-RS-based multicriteria spatial framework with independent subsurface validation through Magnetotelluric (MT) data. The spatial analysis identified five distinct recharge potential zones, where high-potential areas are predominantly located in lowland sedimentary environments characterized by favorable lithology and structural controls. Conversely, upland regions with steeper slopes and higher drainage density exhibited lower recharge favorability.

A key contribution of this research is the robust validation of surface-derived indicators using shallow MT resistivity models. The consistent spatial agreement between high recharge indices and low resistivity values ( $< 100 \Omega\text{m}$ ) supports the interpretation that surface parameters can effectively reflect subsurface hydrogeological conditions when validated by independent geophysical observations. This finding underscores that in wet tropical regions, high annual rainfall does not automatically translate to effective replenishment, as it is heavily governed by local geomorphological and geological factors.

Beyond the local context, the integrated framework developed in this study offers significant global implications. The methodology provides a physically grounded and cost-effective solution for groundwater assessment in complex hydrogeological environments, particularly in data-limited settings where extensive borehole data are unavailable. By demonstrating that remote sensing data can be effectively validated through non-invasive geophysical observations, this study provides a replicable model for other humid tropical regions worldwide. Consequently, this framework serves as a strategic tool for stakeholders in enhancing sustainable water resource management and strengthening climate change resilience in similar geological terrains.

## 7. Ethics approval and consent to participate

Not applicable.

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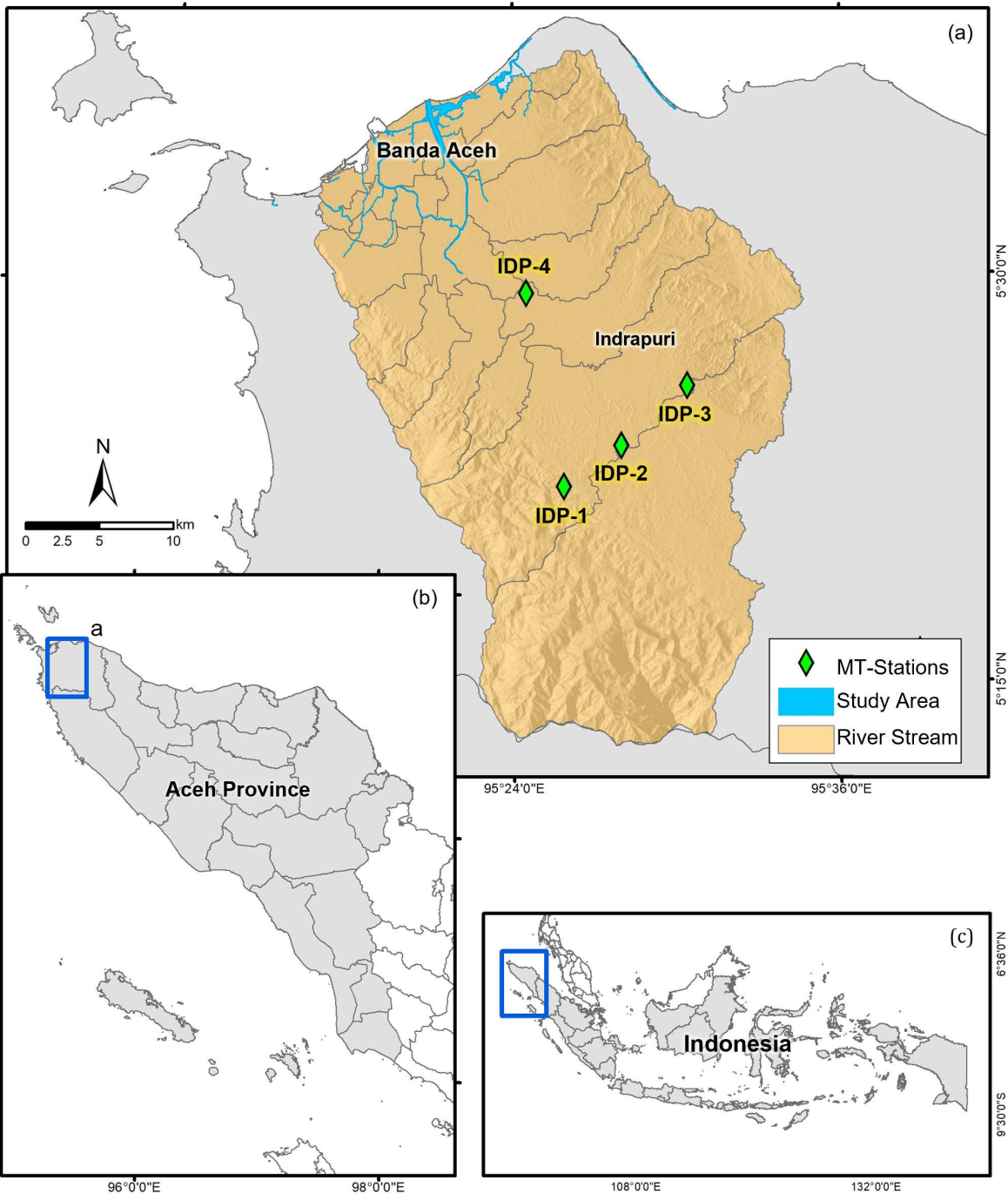
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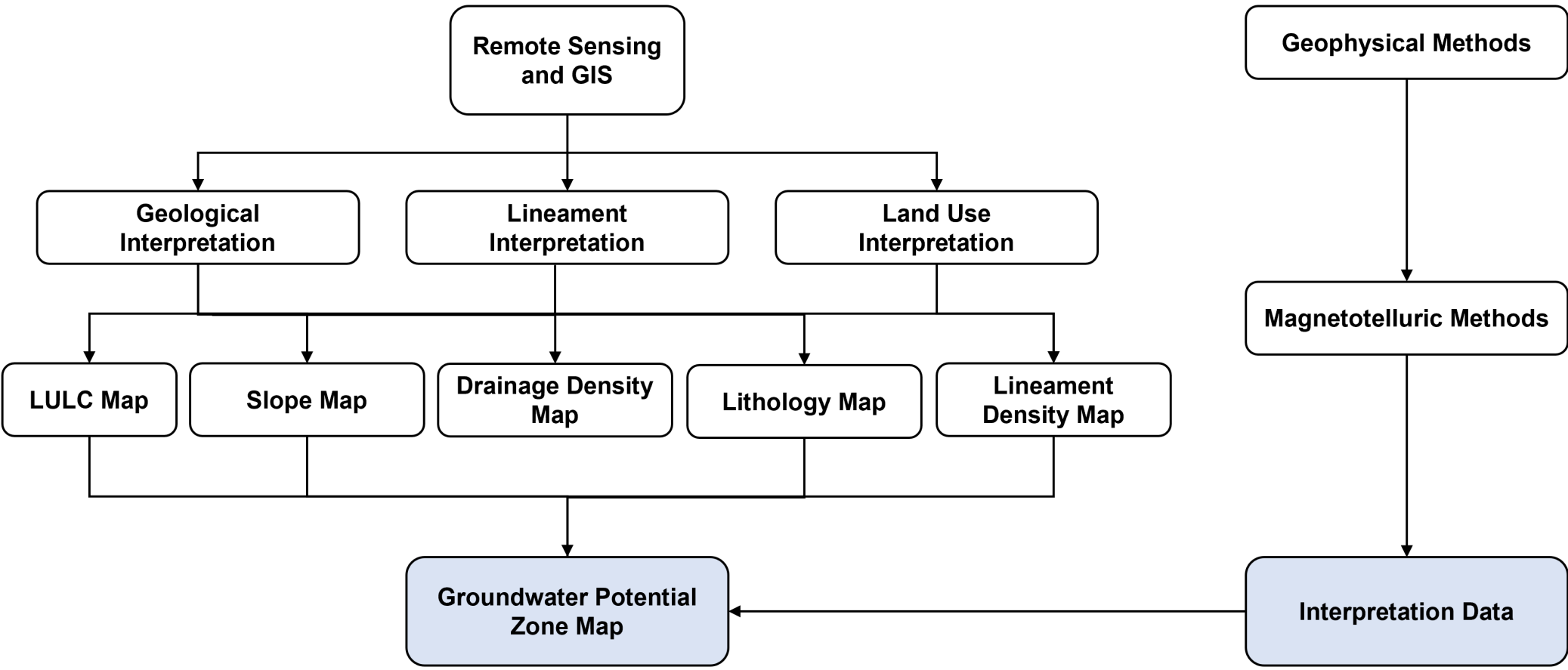
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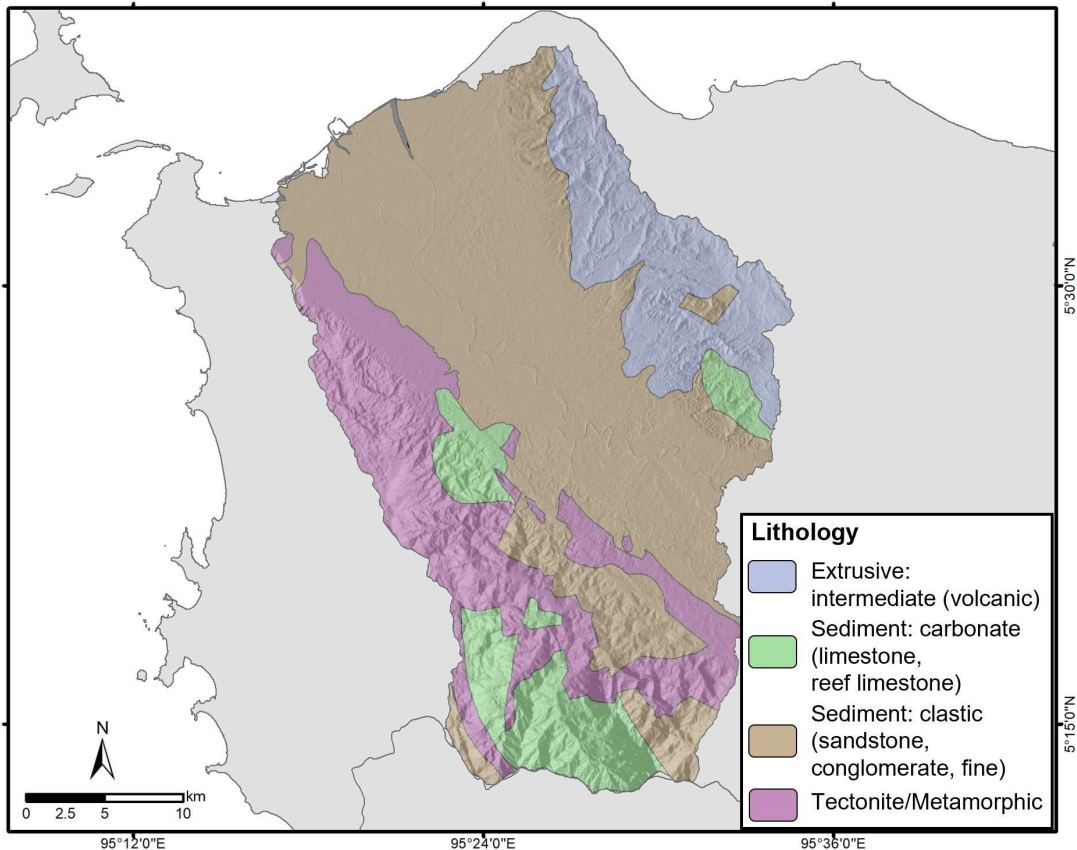
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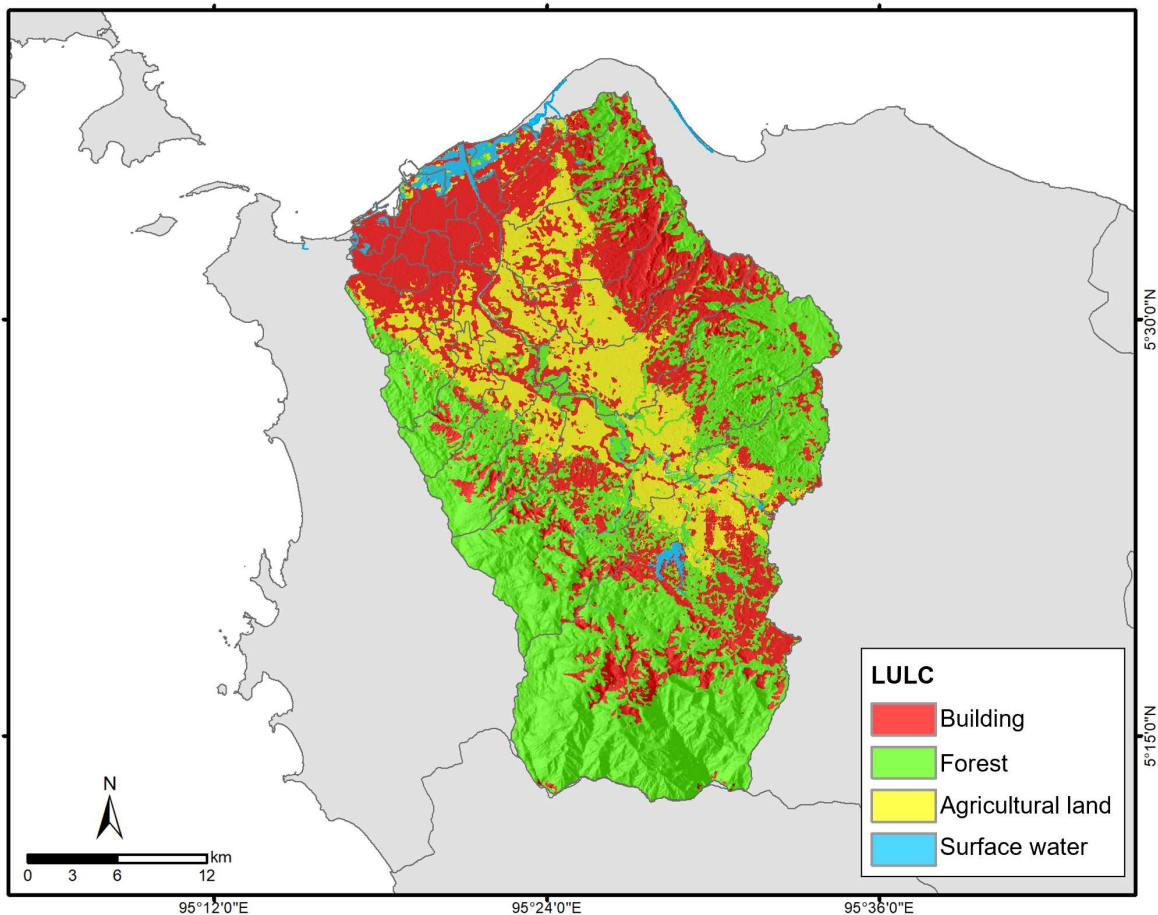
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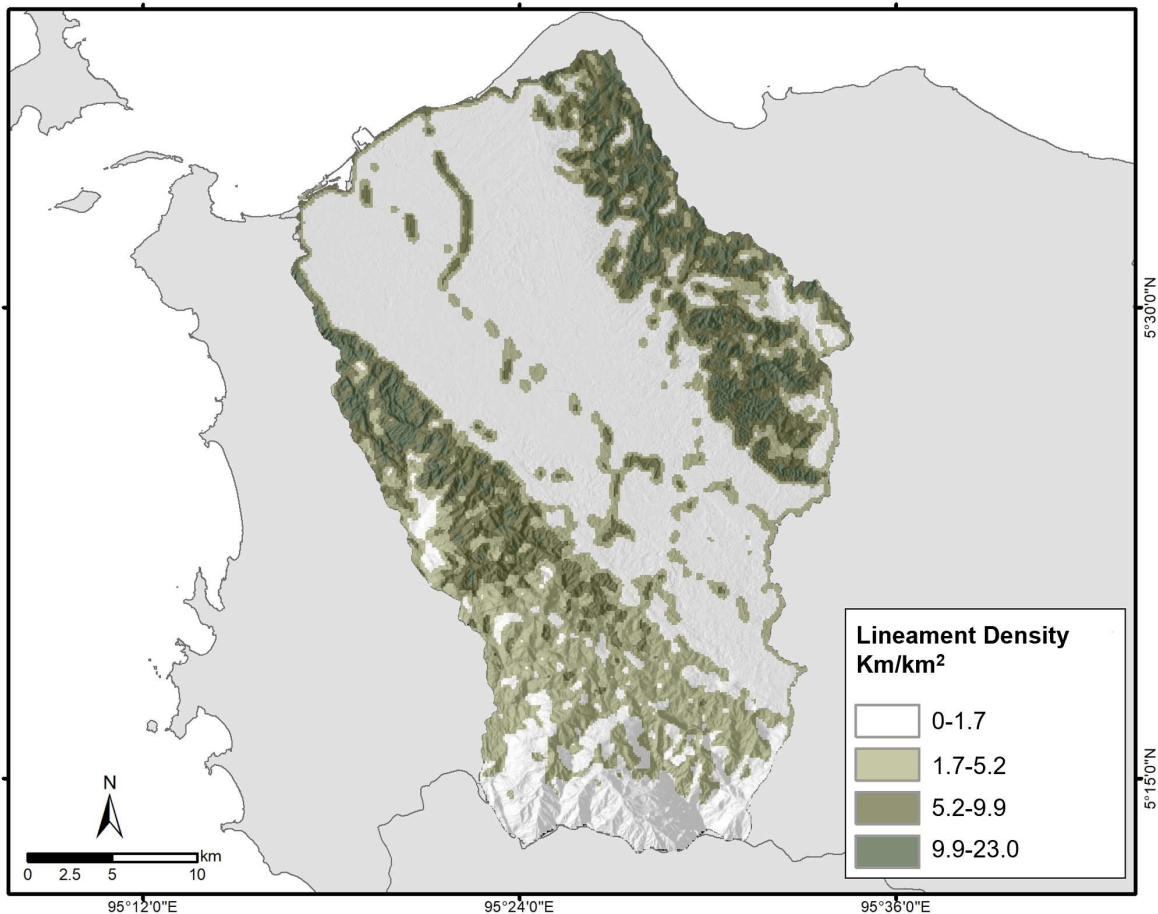
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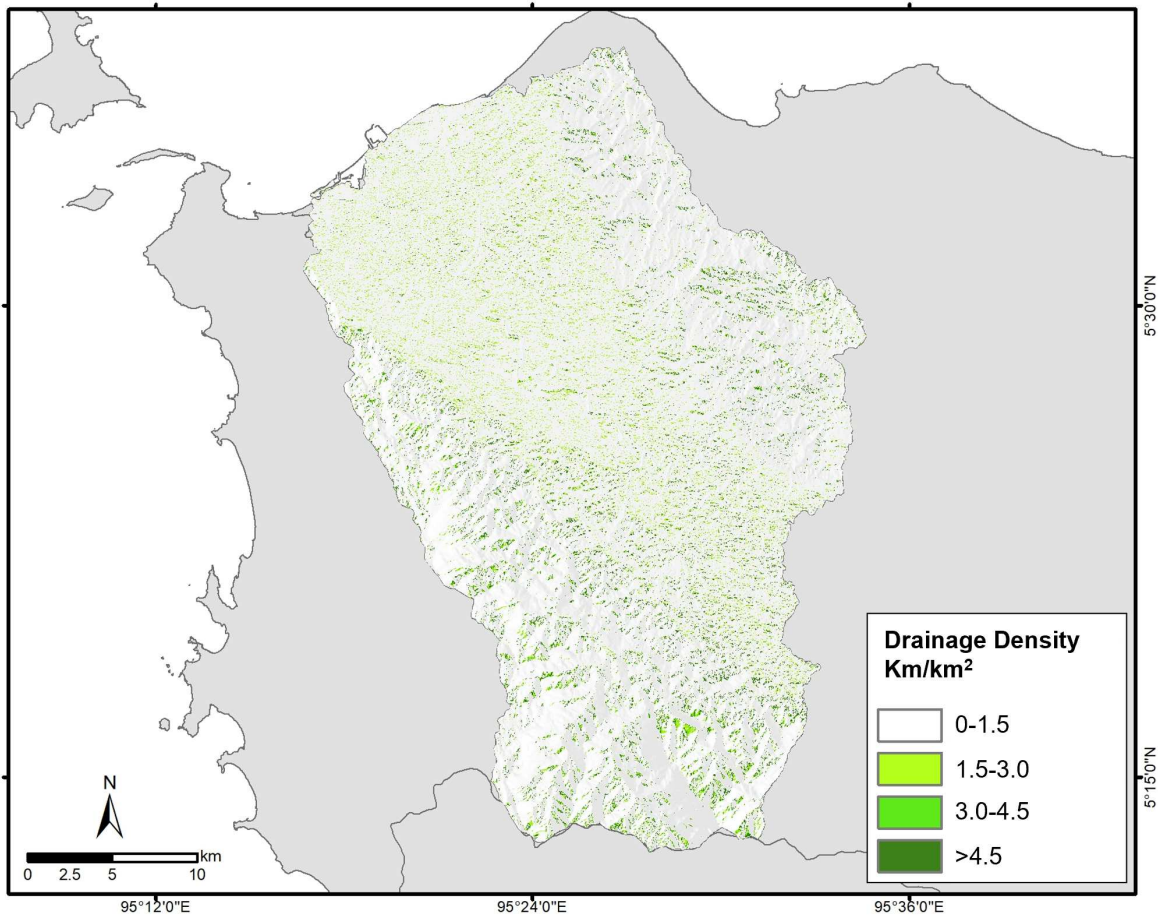


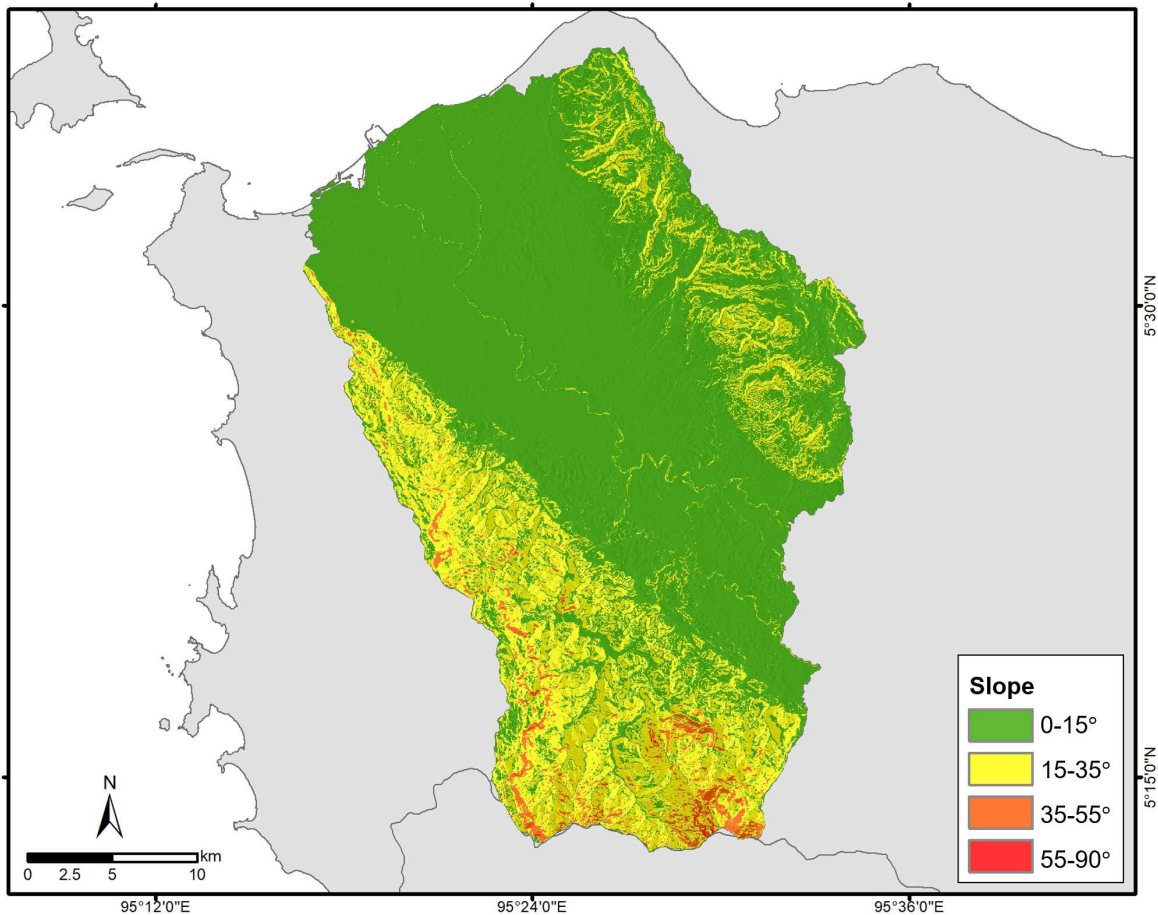


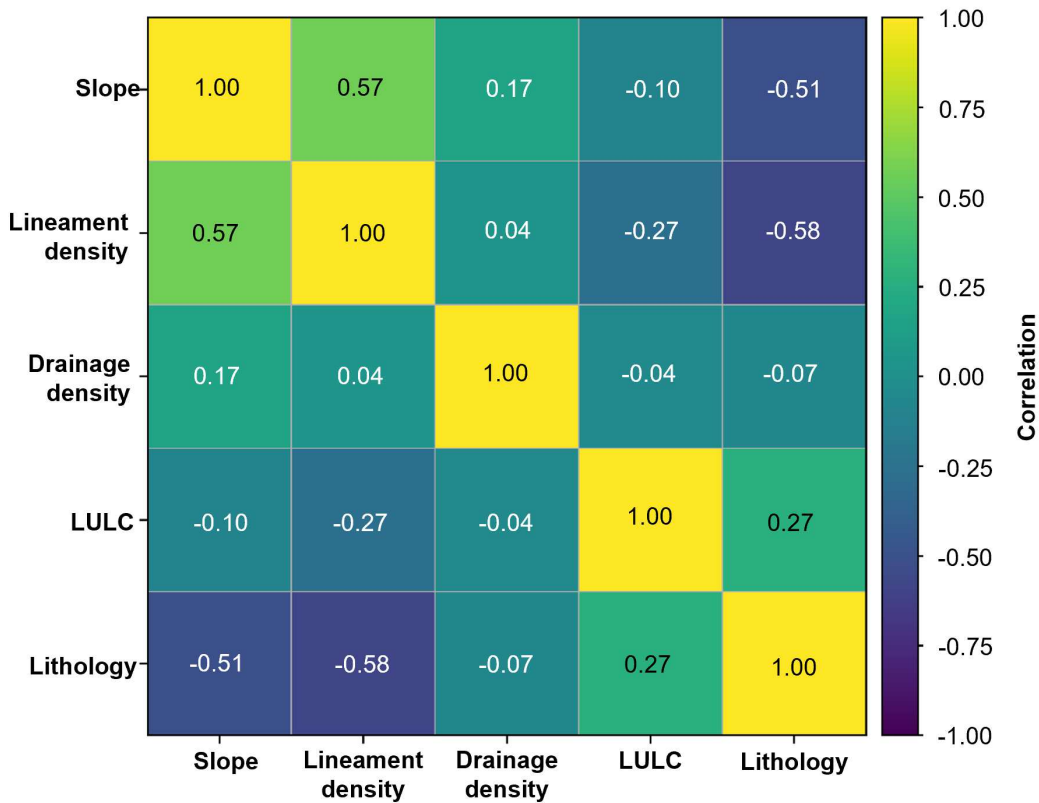


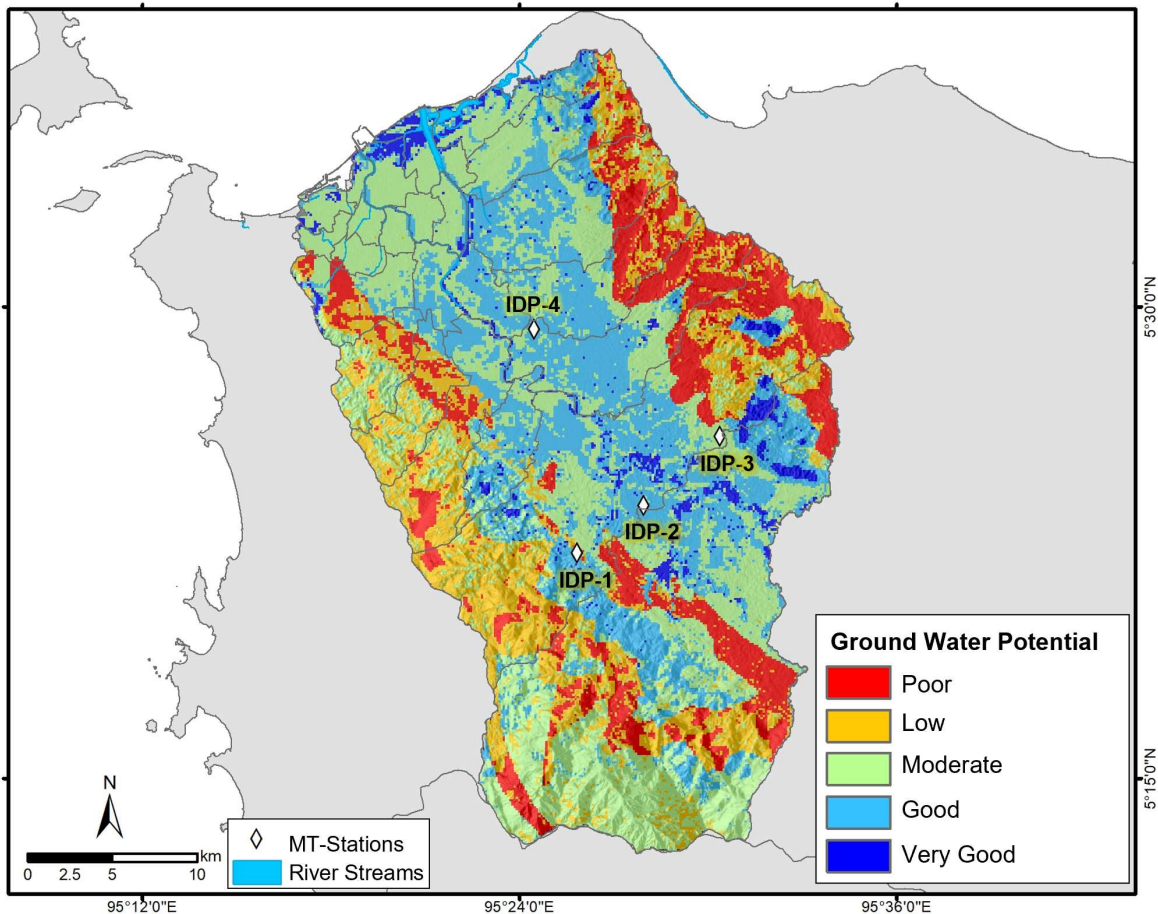




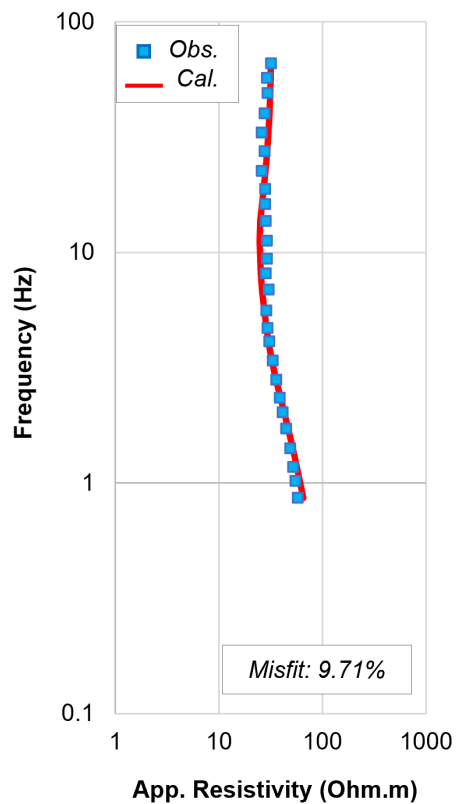






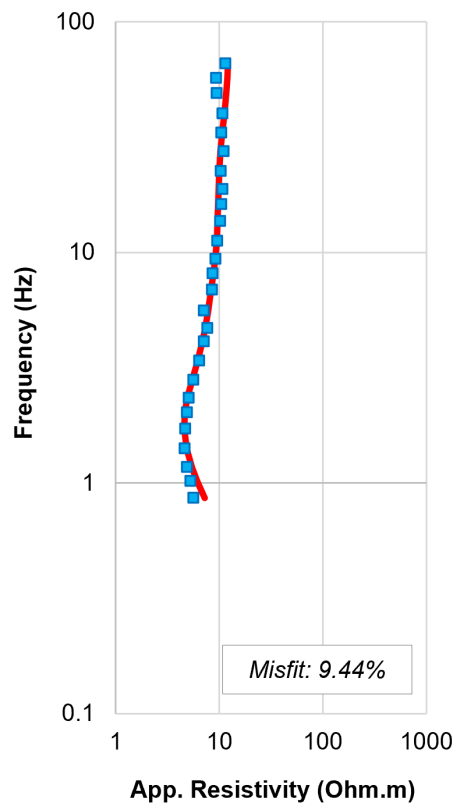


IDP-1



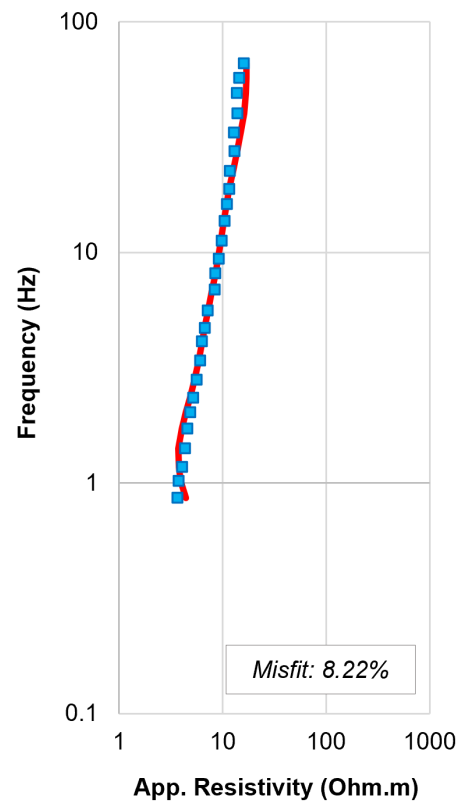
(a)

IDP-2



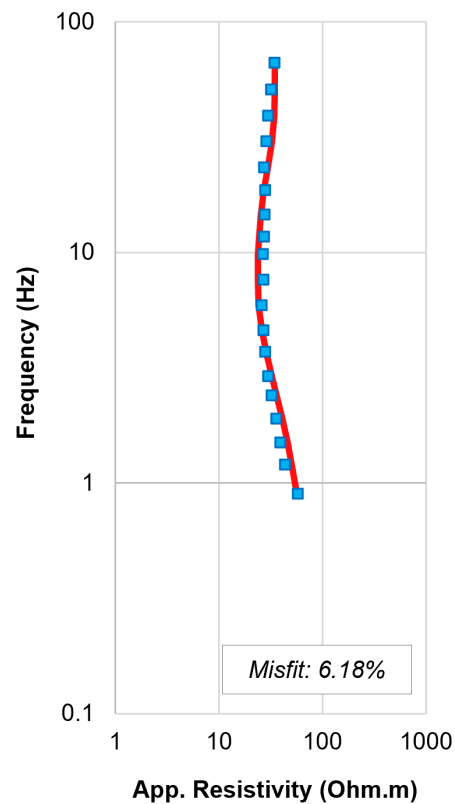
(b)

IDP-3

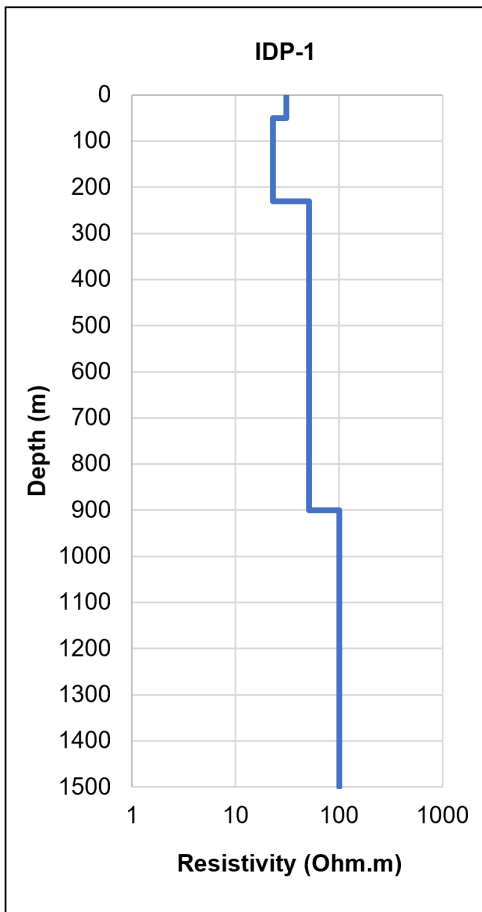


(c)

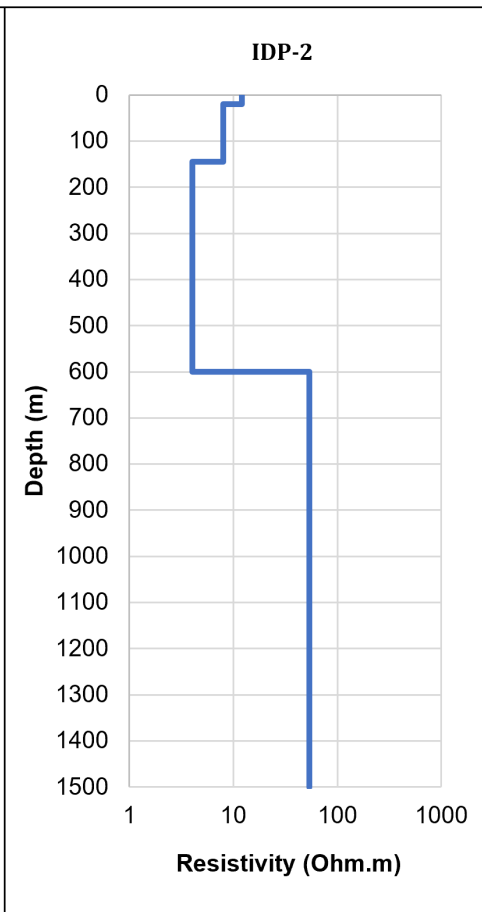
IDP-4



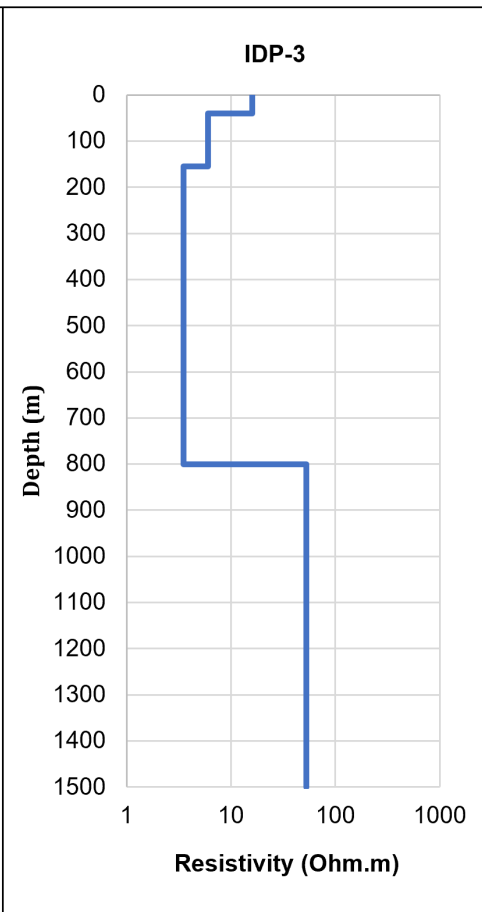
(d)



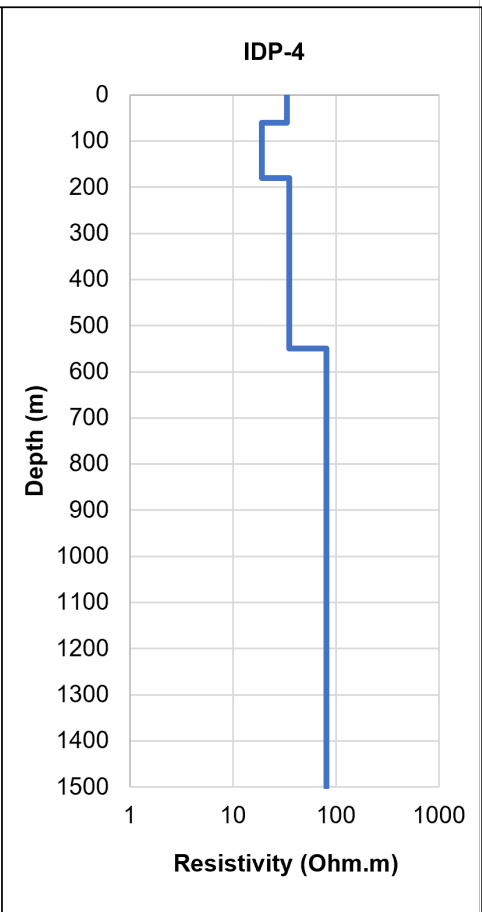
(a)



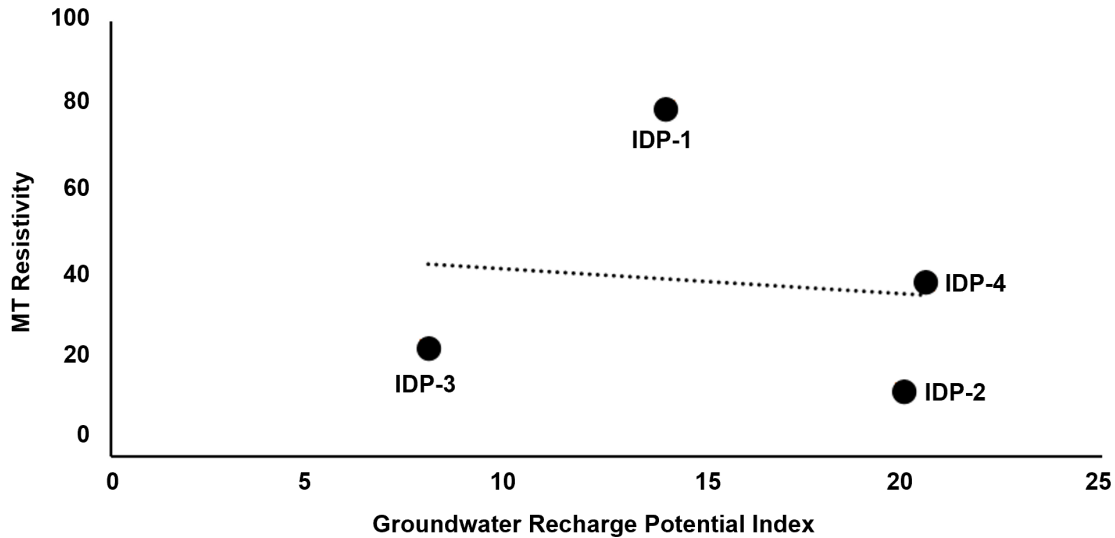
(b)



(c)



(d)



## TABLES

**Table 1.** Classification criteria and factor-specific scores used for the GIS-RS-based groundwater recharge potential assessment (adapted from Yeh et al. 2009)

| Factor                                            | Domain of effect                                  | Proposed weight of effect |
|---------------------------------------------------|---------------------------------------------------|---------------------------|
| Lithology                                         | Extrusive: intermediate (volcanic)                | 13                        |
|                                                   | Tectonite / Metamorphic                           | 18                        |
|                                                   | Sediment: carbonate (limestone, reef limestone)   | 27                        |
|                                                   | Sediment: clastic (sandstone, conglomerate, fine) | 29                        |
| Land Use/Land Cover                               | Building                                          | 6                         |
|                                                   | Forest                                            | 12                        |
|                                                   | Agricultural land                                 | 18                        |
|                                                   | Surface water                                     | 24                        |
| Lineament-length density<br>(km/km <sup>2</sup> ) | 0.0-1.7                                           | 6                         |
|                                                   | 1.7-5.2                                           | 10                        |
|                                                   | 5.2-9.9                                           | 15                        |
|                                                   | 9.9-23.0                                          | 19                        |
| Drainage density<br>(segments per 1 km<br>square) | 0.0-1.5                                           | 4                         |
|                                                   | 1.5-3.0                                           | 7                         |
|                                                   | 3.0-4.5                                           | 11                        |
|                                                   | > 4.5                                             | 14                        |
| Slope gradient (deg)                              | 55-90°                                            | 4                         |
|                                                   | 35-55°                                            | 7                         |
|                                                   | 15-35°                                            | 11                        |
|                                                   | 0-15°                                             | 14                        |

**Table 2.** Areal distribution of recharge potential classes based on the filtered 1 × 1 km grid (ValidFlag = 1)

| <b>Class</b> | <b>Grid Count</b> | <b>Area (km<sup>2</sup>)</b> | <b>Area (%)</b> | <b>Mean</b> |
|--------------|-------------------|------------------------------|-----------------|-------------|
| Very Good    | 174               | 167.80                       | 17.26           | 48.37       |
| Good         | 301               | 289.44                       | 29.78           | 43.75       |
| Moderate     | 212               | 206.89                       | 21.29           | 38.87       |
| Low          | 222               | 210.58                       | 21.66           | 33.46       |
| Poor         | 103               | 97.29                        | 10.01           | 26.90       |

**Table 3.** Percentage distribution of recharge potential classes across river-buffer distance.

| <b>River buffer distance</b> | <b>Poor (%)</b> | <b>Low (%)</b> | <b>Moderate (%)</b> | <b>Good (%)</b> | <b>Very Good (%)</b> |
|------------------------------|-----------------|----------------|---------------------|-----------------|----------------------|
| 0-500 m                      | 0.12            | 0.18           | 45.92               | 29.57           | 24.21                |
| 500-1000 m                   | 0.86            | 0.51           | 51.15               | 40.12           | 7.36                 |
| >1000 m                      | 17.63           | 20.12          | 35.29               | 24.70           | 2.26                 |

**Table 4.** Distribution of recharge potential classes by sub-district, expressed as class percentages and potential area.

| <b>Sub-district</b> | <b>Poor (%)</b> | <b>Low (%)</b> | <b>Moderate (%)</b> | <b>Good (%)</b> | <b>Very Good (%)</b> | <b>Potential Area (%)</b> |
|---------------------|-----------------|----------------|---------------------|-----------------|----------------------|---------------------------|
| Baitussalam         | 0.96            | 1.55           | 48.75               | 28.52           | 20.23                | 48.74                     |
| Blang Bintang       | 27.25           | 14.29          | 21.11               | 36.77           | 0.58                 | 37.36                     |
| Darul Imarah        | 22.64           | 17.89          | 45.41               | 11.14           | 2.93                 | 14.06                     |
| Darul Kamal         | 12.39           | 36.15          | 44.00               | 7.46            | 0.00                 | 7.46                      |
| Darussalam          | 15.47           | 17.64          | 36.95               | 25.95           | 3.99                 | 29.94                     |
| Indrapuri           | 18.47           | 27.14          | 23.37               | 26.48           | 4.53                 | 31.02                     |
| Ingin Jaya          | 0.00            | 0.04           | 39.55               | 54.60           | 5.80                 | 60.41                     |

|                       |       |       |       |       |       |       |
|-----------------------|-------|-------|-------|-------|-------|-------|
| Kuta Baro             | 14.41 | 10.27 | 33.74 | 39.25 | 2.33  | 41.58 |
| Kuta Cot Glie         | 16.30 | 14.96 | 42.25 | 23.22 | 3.27  | 26.50 |
| Krueng Barona<br>Jaya | 0.00  | 0.00  | 79.05 | 14.16 | 6.79  | 20.95 |
| Kuta Malaka           | 0.92  | 8.66  | 33.42 | 52.93 | 4.06  | 57.00 |
| Montasik              | 26.13 | 8.28  | 25.26 | 38.46 | 1.86  | 40.32 |
| Simpang Tiga          | 15.08 | 48.52 | 27.78 | 8.62  | 0.00  | 8.62  |
| Suka Makmur           | 15.55 | 37.69 | 27.16 | 18.55 | 1.05  | 19.59 |
| Bandar Raya           | 2.80  | 0.00  | 96.57 | 0.64  | 0.00  | 0.64  |
| Jaya Baru             | 6.95  | 0.89  | 88.22 | 1.93  | 2.01  | 3.94  |
| Lueng Bata            | 0.00  | 0.40  | 92.63 | 5.21  | 1.76  | 6.97  |
| Baiturahman           | 0.00  | 0.56  | 95.90 | 2.87  | 0.67  | 3.55  |
| Ulee Kareng           | 0.00  | 0.00  | 90.49 | 7.43  | 2.09  | 9.51  |
| Meuraxa               | 0.00  | 0.00  | 80.64 | 6.02  | 13.34 | 19.36 |
| Kuta Raja             | 0.00  | 0.00  | 15.17 | 13.12 | 71.71 | 84.83 |
| Kuta Alam             | 0.00  | 0.13  | 70.21 | 8.24  | 21.41 | 29.66 |
| Syiah Kuala           | 0.00  | 0.00  | 59.94 | 9.00  | 31.06 | 40.06 |

**Table 5.** Comparison between GIS-RS-derived recharge potential classes and shallow MT resistivity (0–300 m) at MT stations.

| <b>MT Site</b> | <b>MT resistivity<br/>(0-300 m, <math>\Omega</math>m)</b> | <b>Groundwater<br/>recharge potential<br/>interpretation</b> |
|----------------|-----------------------------------------------------------|--------------------------------------------------------------|
| IDP-2          | 15                                                        | Very Good                                                    |
| IDP-3          | 25                                                        | Low-Moderate                                                 |
| IDP-4          | 40                                                        | Moderate-Good                                                |
| IDP-1          | 80                                                        | Low                                                          |