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Groundwater potential assessment for Penang mainland, Malaysia using remote sensing and Geographical Information System (GIS)

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Abstract: Penang mainland is identified as the most water-vulnerable region in Malaysia, with a substantial portion of its population dependent on agriculture, particularly rice cultivation. This reliance highlights the critical role of groundwater as an alternative water source, necessitating a comprehensive assessment of its potential. Despite its importance for sustainable land use and development planning, a systematic evaluation of groundwater potential in Penang mainland requires a more thorough investigation. Previous investigations have primarily focused on Penang Island, utilizing remote sensing and Geographic Information System (GIS) techniques to assess groundwater prospects based on geological and geomorphological parameters derived from satellite data and geological maps. This study presents a preliminary attempt to map groundwater potential across Penang mainland, with a focus on supporting agricultural activities, particularly in paddy cultivation zones. The main objective is to delineate areas of high and low groundwater potential using an integrated approach that combines remote sensing and GIS technologies. This methodology offers a cost-effective solution that minimizes the need for direct field access. Thematic layers derived from Landsat 9 imagery and Digital Elevation Model (DEM) data were analyzed and integrated using the Analytical Hierarchy Process (AHP) and weighted overlay techniques. Key parameters incorporated include land cover, drainage density, lineament density, soil type, geology, slope, elevation, and geomorphology. The results identify areas such as Kampung Tamban, Taman Bertam, Seberang Perai, Taman Bukit Juru, and Kampung Kepala Gajah as having “Very Good” groundwater potential. Conversely, regions including Bukit Mertajam Forest Park, Kampung Pelet, Kampung Lima Kongsi, and Bukit Jawi are classified as having “Very Poor” groundwater potential.

Keywords: Groundwater potential, remote sensing, GIS, Landsat 9, AHP, hydrogeology, Penang

INTRODUCTION

Groundwater is a vital natural resource, essential for human health and the maintenance of ecological diversity (Waikar & Nilawar, 2014). Safeguarding it from contamination and ensuring its efficient management are critical for sustaining both natural ecosystems and human activities. The movement of groundwater is largely governed by geological factors such as porosity and permeability. Recharge primarily occurs through precipitation and subsurface infiltration, while discharge takes place via effluent seepage, springs, evaporation, and anthropogenic extraction (Fetter, 2001). Globally, approximately one-third of the population relies on groundwater as a primary source of drinking water (Jose *et al*., 2012). Its significance is particularly pronounced in agriculture and domestic applications, with nearly 80% of rural populations depending on it for daily needs, compared to about 50% in urban areas (Food and Agriculture Organization, 2021; Khadka, 2022). This increasing dependence has raised concerns regarding the potential overexploitation of groundwater resources (Shakak, 2015). Sustainable groundwater management requires a comprehensive understanding of regional geological and geomorphological conditions. The use of remote sensing data and thematic maps, encompassing satellite imagery, soil types, geological structures, drainage networks, and precipitation patterns is essential for accurately delineating groundwater potential zones (Srivastava *et al*., 2012).

A survey commissioned by the Malaysian government has identified Penang state as the region most susceptible to water vulnerability in the country (Ranhill Consulting Sdn. Bhd., 2011), mainly because the majority of its water needs are met by a single common river system, the Muda River. In recent years, the incidence of low water level alerts for state dams has escalated, leading Penang to fund around RM500,000 in 2016 for cloud-seeding initiatives designed to stimulate precipitation to restore critically diminished dam water levels (Petrick *et al*., 2023). Due to its elevated population density and metropolitan status, it is essential to establish alternative water sources to ensure the state’s water security. Groundwater is defined as the water that fills the pore spaces in rocks and soil, starting from a specific depth below the surface (Famiglietti, 2014). It provides

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half of the world's population with their primary supply of drinkable water and contributes for 33% of global water usage (World Water Assessment Programme, 2009). This proposal seeks to investigate the potential of groundwater as a sustainable resource for Penang mainland, addressing the critical need for diversified water supply strategies to enhance the region's resilience against water scarcity.

Numerous studies on groundwater exploration have been conducted on Penang Island; however, there are no published studies for the Penang mainland. This study aims to identify areas with both favorable and unfavorable groundwater potential on the mainland as a preliminary step in assessing the availability of groundwater resources in the region. The assessment employed a combination of remote sensing and geographic information systems (GIS) techniques to develop a groundwater potential map (Kura *et al.*, 2018).

The combination of remote sensing data with Geographic Information System methodologies is especially effective in identifying groundwater potential across different geographical areas. This study illustrates that integrating thematic maps derived from both conventional and remote sensing techniques with GIS results in more accurate outcomes (Jose *et al.*, 2012). Groundwater forms as water permeates the earth's surface, where the underlying soil exhibits porosity (Hasan *et al.*, 2017). A decline in the groundwater table occurs when extraction rates exceed replenishment, leading to reduced groundwater zones and lower water levels in wells, lakes, and streams in areas with high withdrawal rates (Senanayake *et al.*, 2016).

Remote sensing serves as a crucial source of information regarding surface features pertinent to groundwater, encompassing aspects such as land use, landforms, and drainage density. This dataset can be effortlessly incorporated into GIS to enable the identification of groundwater zones (Oh *et al.*, 2011).

Numerous researchers have effectively employed an integrated approach that combines remote sensing and Geographic Information System techniques, yielding favorable results at the local level (Musa *et al.*, 2000; Manap *et al.*, 2013) and internationally (Srivastava & Bhattacharya, 2006; Pradhan, 2009; Mukherjee *et al.*, 2012; Kumar *et al.*, 2016; Saha, 2017). Several research have given their models specific weights and employed a variety of parameters. fffff Among the commonly utilised criteria are lithology, geomorphology, lineament density, precipitation, slope, drainage density, soil composition, and land use (Manap *et al.*, 2013). In Malaysia, specifically in the Langat Basin of Selangor, groundwater potential mapping has been carried out utilising remote sensing and GIS (Musa *et al*, 2000; Manap *et al.*, 2013), as well as in Kedah (Younger, 2009), Perlis (Younger, 2009), and Perak (Surip *et al.*, 2009).

Conventional methods of evaluating groundwater, such as field-based hydrogeological studies and geophysical resistivity surveys, are usually costly and time-consuming (Ibrahim-Bathis & Ahmed, 2016). Groundwater, which occupies pore spaces in geological formations below the water table, flows through aquifers to discharge points like wells, oceans, and lakes. Globally, about 60% of freshwater is groundwater, with only approximately 0.6% classified as fresh water. Conversely, remote sensing and GIS provide precise identification of groundwater zones utilising several approaches, such as the Weighted Linear Combination (WLC) (Lakshmi & Reddy, 2018), the Analytical Hierarchical Process (AHP) (Saranya & Saravanan, 2020), and the Index Overlay Method (Lakshmi & Reddy, 2018).

These methods are notably cost-effective for the exploration of groundwater resources, especially when considering the substantial financial implications associated with drilling activities, which can often be a significant expense. A groundwater potential map serves as a valuable tool in this regard, efficiently narrowing down the number of viable drilling locations by identifying regions that exhibit both low and high groundwater potential. By highlighting these areas, the map allows for a more targeted approach, ultimately saving time and resources. However, it is important to recognize that while such maps provide valuable insights, the collection of in situ data remains a critical component of the investigation process. This data is essential for validating the conclusions drawn from remotely sensed data, ensuring that the findings are accurate and reliable. Without this ground-truthing, there is a risk that the interpretations made based on the maps could be misleading. Therefore, a comprehensive approach that combines both remote sensing and in situ data collection is necessary for effective groundwater management and exploration (Jha *et al.*, 2007). Well yield (Srivastava & Bhattacharya, 2006; Machiwal *et al.*, 2011; Mukherjee *et al.*, 2012; Manap *et al.*, 2013) is the primary parameter utilised for validation; nevertheless, indicators such as depth to the water table (Thomas *et al.*, 2009; Kumar *et al.*, 2016; Saha, 2017) and unvalidated maps (Kumar *et al.*, 2007; Vijith, 2007) are also documented in the literature.

LOCATION AND GEOLOGY OF THE STUDY AREA (SEBERANG PERAI)

On the Malaysian peninsula's northwest coast is the state of Penang. It is bordered to the north and east by Kedah, to the south by Perak, and to the west by the Straits of Malacca and the island of Sumatra in Indonesia (Figure 1). Penang is made up of the island of Penang as well as Province Wellesley, a strip of coastline on the mainland. The mainland is geographically isolated from the island by a waterway and spans 1,049 km². Although there is a noticeable increase in rainfall from September to November, precipitation in this area is dispersed equally throughout the year (Lee, 2005). The population of Penang mainland is approximately 947,400 individuals. The foundational geology of the research region mostly comprises clay, silt, sand, gravel, and granite (Lee, 2005).

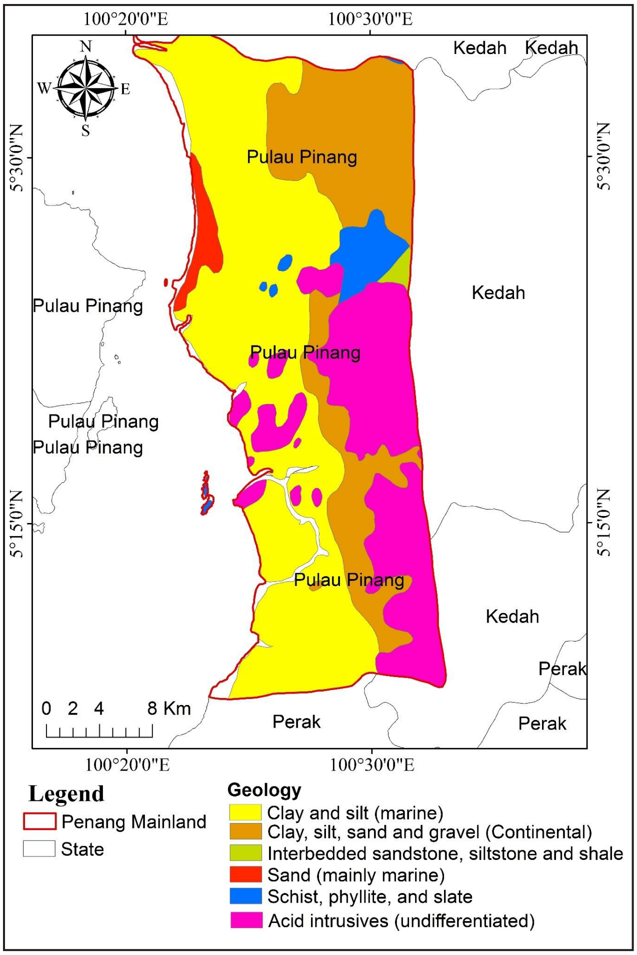

Figure 1: Geologic map of Penang mainland, Malaysia (Modified from JMG, 2010).

The area is underlain by granite basement rocks, metasediments and sedimentary rock types (Courtier, 1974). The granitic basement rocks comprise of medium to coarse grained muscovite-biotite granite (Courtier, 1974). Hassan (1990) has classified the granites of Penang Island to illustrate the early and late phases of the same magmatic event. Two closely related intrusive episodes, i.e., late Triassic to early Jurassic periods resulted in the granitic intrusions within the area (Kwan, 1984). The metasedimentary rocks comprise of schist, phyllite, and slate. While the sedimentary rocks comprise of sand, interbedded sandstone, siltstone, and shale of marine and continental origin. The details of the geological evolution of the study area can be found in (Hassan, 1990).

METHODOLOGY

Remote sensing, Geographic Information Systems (GIS), and Analytic Hierarchy Process (AHP) methodologies were employed to systematically identify potential groundwater zones within the Penang mainland district. The process begins with the crucial first step of preparing individual thematic layers, which are essential for conducting an effective overlay analysis. Each thematic layer or map is designed to represent a specific parameter related to groundwater potential, such as land use/land cover, rainfall patterns, and geological features. This detailed mapping allows for a comprehensive understanding of the factors influencing groundwater availability in the region.

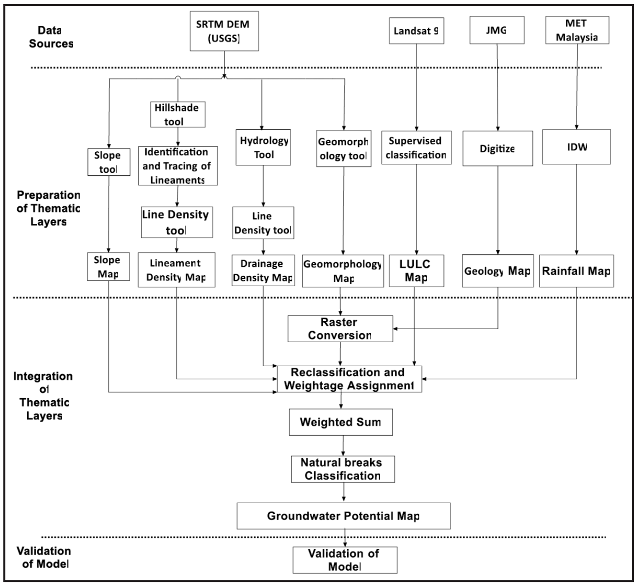

Figure 2: Methodological flow of the study.

Once the thematic layers are created, they are then integrated through a weighted overlay system, which combines the various parameters based on their relative importance. This integration process is critical for producing the final groundwater potential map, which visually represents areas with varying levels of groundwater potential. Below is a summary of the data sources and methods used to achieve this objective, as illustrated in Figure 2. This approach not only enhances the accuracy of groundwater zone identification but also provides valuable insights for stakeholders involved in water resource management and planning in the region.

Data sources and thematic layer development

In order to assess groundwater potential across the Penang mainland, a series of thematic layers were generated using various geospatial datasets and analytical methods. These layers include lineament density, geomorphological, rainfall, geology, drainage density, slope and land use/land cover (LULC). These parameters were selected based on their relevance in previous hydrogeological studies (Magesh *et al*., 2012; Jha *et al*., 2007) and their established role in influencing groundwater potential zones. Integrating them in a GIS-based multi-criteria analysis allows for a comprehensive and spatially explicit assessment of groundwater potential. All thematic layers were projected to the Universal Transverse Mercator (UTM) Zone 47 North coordinate system and processed within the ArcGIS environment.

Topographic and slope analysis

Topographic information was derived from the Shuttle Radar Topography Mission Digital Elevation Model (SRTM-DEM) with a 30-meter spatial resolution. Slope maps were generated from the DEM using the Spatial Analyst extension in ArcGIS. These maps are critical for identifying areas of potential groundwater recharge, as flatter regions tend to favor infiltration over runoff.

Geological mapping

Geological maps of the study area were obtained from the Malaysian Department of Minerals and Geoscience (JMG). These maps were scanned, georeferenced, and digitized using ArcGIS to create a rough stratigraphic sequence. This stratigraphic sequence provides information on rock types, structural formations, and fault zones, which is essential for identifying groundwater-bearing formations.

Geomorphological mapping

Geomorphological features, such as river terraces, alluvial plains, and structural hills, were extracted utilizing a Digital Elevation Model (DEM) in lieu of traditional topographic maps or satellite imagery. The DEM data facilitated the precise delineation and classification of landforms, which serve as significant indicators of surface processes and potential groundwater recharge zones. This geomorphological layer was subsequently processed and integrated into a GIS environment for spatial analysis.

Lineament extraction and density mapping

Lineaments were extracted from Landsat 9 Operational Land Imager (OLI) satellite images using edge detection and directional filters in PCI Geomatica and ArcGIS. The lineament density layer was then produced using the Line Density tool in ArcGIS, which helps identify areas with higher fracture concentrations that may enhance secondary porosity and permeability.

Drainage density mapping

Drainage networks were delineated from the SRTM-DEM through hydrological processing techniques including filling sinks, flow direction, and flow accumulation modeling. The drainage density map was derived by calculating the total length of drainage lines per unit area using ArcGIS. Areas with lower drainage density are generally more favorable for groundwater recharge.

Land use/land cover classification

LULC maps were developed using supervised classification techniques on Landsat 9 imagery (14/01/2024). Ground truthing and high-resolution reference data were used to train and validate the classification. Different land cover types were assigned weights based on their influence on groundwater recharge (forests and agricultural areas generally support better recharge compared to impervious urban surfaces).

Rainfall mapping

Rainfall data for Penang mainland for the period from 2014 to 2023 were obtained from three local meteorological stations and interpolated using the inverse distance weighting (IDW) method to create a continuous rainfall surface (Table 1). This enabled analysis of long-term rainfall trends.

The monitoring stations used in this study are as follows:

- Station 1 Mardi Bertam, located in the northwest of Penang mainland.
- Station 2 Butterworth, located in the central part of Penang mainland.
- Station 3 Prai, located in the southwest of Penang mainland.

Data from these stations were interpolated using spatial interpolation methods to create a continuous rainfall surface distribution for the study area. IDW interpolation was applied, a technique commonly used in hydrological studies due to its ability to provide an accurate representation of spatial data with variability over distance.

The rainfall distribution map indicates that the northwest region of the mainland experienced the highest rainfall, ranging from 2,250 to 2,680 mm, while the southwest region recorded the lowest rainfall, ranging from 1,530 to 1,620 mm (Table 1). The overall variation in rainfall across the Penang mainland was limited, with a total difference of only 720 mm between the highest and lowest rainfall levels recorded.

Figure 3 shows annual rainfall distribution (2014–2023) for the three stations: Butterworth, Mardi Bertam, and Prai. Butterworth and Mardi Bertam stations exhibit relatively stable rainfall data throughout the period from 2014 to 2023, with only minor fluctuations observed across the years. In contrast, the Prai station recorded a significant peak in annual rainfall in 2017 but presents missing data for several subsequent years, particularly after 2019, which affects its reliability for continuous analysis. Similarly, Mardi Bertam

Table 1: Rainfall distribution (2014-2023).

Station	Location	Minimum Annual Rainfall (mm)	Maximum Annual Rainfall (mm)
Mardi Bertam	North-west Penang mainland	2250	2680
Butterworth	Central Penang mainland	1800	2150
Prai	South-west Penang mainland	1530	1620

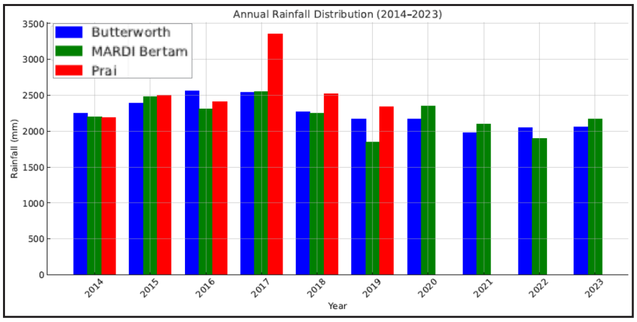

Figure 3: Annual rainfall distribution (mm) at Butterworth, Mardi Bertam, and Prai stations, 2014–2023.

has incomplete records during 2017 and 2018. Among the three stations, Butterworth provides the most complete and consistent dataset, making it the most dependable source for rainfall assessment in the study area.

Groundwater potential mapping

To generate the groundwater potential map, multiple thematic layers were prepared, including geology, slope, land use/land cover, rainfall, slope, drainage density, and lineament density (Table 2). Each thematic layer was derived from relevant data sources and processed using GIS tools. The Analytic Hierarchy Process (AHP) scale introduced by (Saaty & Vargas, 1980) was applied to assign relative weights to each layer based on its influence on groundwater recharge and storage. Within each layer, sub-classes were also ranked accordingly. References such as and previous groundwater potential studies (Rani *et al.*, 2015) were consulted to guide the assignment of weights and rankings.

The weighted overlay analysis was then performed in ArcGIS, where all standardized layers were combined based on their assigned weights. The result is a composite Groundwater Potential Index (GPI), which categorizes the study area into zones ranging from very low to very high groundwater potential. This approach allows for a spatially integrated assessment that supports effective water resource planning.

Use of Well Data in Groundwater Potential Analysis to support and validate this classification, groundwater well location data were obtained from the MYGEMS platform provided by the Department of Minerals and Geoscience Malaysia (https://mygems.jmg.gov.my), which offers only the spatial distribution of wells without detailed attributes.

Therefore, official reports from JMG were consulted to acquire more accurate and comprehensive information on well characteristics, including their operational status (active or inactive), depth, and other relevant parameters. These wells were then overlaid on the groundwater potential map to assess the consistency between actual well conditions and the classified zones. This integration enhances the reliability of the results and provides a better understanding of groundwater distribution in the study area.

Analytic Hierarchy Process (AHP) method

The Analytic Hierarchy Process, developed by (Saaty & Vargas, 1980), is a widely recognized decision-making framework. It helps experts evaluate and compare various attributes systematically, especially in complex scenarios where multiple criteria need consideration. This method is beneficial for addressing inconsistencies in human judgment by providing a structured approach through a systematic weighting process. The AHP methodology involves two main steps. The first step is creating a hierarchical framework that organizes decision criteria into different levels, with the main goal positioned at the top. This structure includes main criteria and sub-criteria, capturing the complexity of decision-making. The hierarchical representation clarifies interactions between factors and enhances the understanding of attribute relationships. The second step of the AHP is assessing the relative importance of each criterion through pairwise comparisons. Experts evaluate the significance of one attribute over another using a scale from 1 to 9 (Saaty, 2008) (Table 3). Pairwise comparisons help derive weights that reflect the relative importance of each attribute. A consistency check, the Consistency Ratio (CR), ensures the reliability and validity of results. A CR value below 0.1 is acceptable, indicating consistent judgments. If the CR is above 0.1, judgments may need review to enhance reliability. In a recent study, AHP was used to quantify weights assigned to thematic layers and attributes influencing groundwater potential. The systematic quantification of weights on a scale from 1 to 9 allows a

Table 2: Data used for each thematic map produced.

Map	Data type and Source
Lineament density map	SRTM DEM (USGS)
Geomorphology map	SRTM DEM (USGS)
Drainage density map	SRTM DEM (USGS)
Slope map	SRTM DEM (USGS)
Geology map	Department of Minerals and Geoscience Malaysia (JMG)
Rainfall map	Malaysian Meteorological Department (MET Malaysia) between 2014 and 2023
Land use/Land cover map	United States Geological Survey Landsat 9

Table 3: Fundamental scale of Analytic Hierarchy Process (AHP) (Saaty & Vargas, 1980).

Intensity of importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective.
3	Moderate importance	Experience and judgment slightly favor one element over another.
5	Strong importance	Experience and judgment strongly favor one element over another.
7	Very strong importance	One element is favored very strongly over another; its dominance demonstrated in practice.
9	Extreme importance	The evidence favoring one element over aother is of the highest possible order of affirmation.
2,4,6,8	Can be used to express intermediate values	

rigorous analysis of each attribute's importance. By using AHP in this way, we aim to provide a solid framework for assessing groundwater potential, leading to more informed resource management decisions essential for sustainable environmental practices. Several previous studies have successfully used this method for groundwater assessment, demonstrating its effectiveness in areas with limited field data and complex hydrogeological conditions, such as (Rahmati *et al*., 2015). Its ability to handle both qualitative and quantitative data makes AHP a powerful tool in geospatial analysis and water resource management planning.

Assigning weights and normalization

Weight assignment and normalization constitute crucial steps in the analysis process. This study established the allocation of weights to various theme layers and their specific properties by evaluating numerous prior studies and expert insights. This method complied with Saaty's scale (Saaty & Vargas, 1980). Higher scores are allocated to elements considered more influential, while lower scores are assigned to those having lesser influence. The eigenvector method and Analytic Hierarchy Process (AHP) were employed to standardize these weights to ensure fairness. This normalization approach aims to reduce any bias related to the weights assigned to the thematic layers and their associated attributes (Machiwal *et al*., 2011). The normalised weight functions as a metric for multiparameter analysis, an essential component of groundwater mapping (Lakshmi & Reddy, 2018) (Table 4).

FINDINGS AND ANALYSIS

Thematic strata

Lineament density map

To generate the lineament density map, remote sensing techniques were employed using Landsat 9 imagery in conjunction with Digital Elevation Model (DEM) data from the Shuttle Radar Topography Mission (SRTM). The process began with image pre-processing, including geometric correction and enhancement, to improve feature visibility. Lineaments were extracted using PCI Geomatica, a remote sensing and image analysis software that provides advanced tools for automated lineament detection through image enhancement and filtering techniques. The extraction process was based on tonal variation, linear alignment of vegetation, drainage disruptions, and topographic breaks observed in both satellite imagery and DEM data. Compared to manual digitization, PCI Geomatica reduced subjectivity and improved accuracy in delineating structural features. The extracted lineaments were subsequently imported into ArcGIS, where they were processed, refined, and integrated with other thematic layers for map production.

Following extraction, the digitized lineaments were vectorized and converted into a raster format using the Line Density tool in ArcGIS. This tool calculates the length of lineaments per unit area (m/m^2), thereby producing a continuous lineament density surface across the Penang mainland. The raster resolution was maintained at 30 meters to match the resolution of the input DEM and satellite data.

The results revealed that lineaments predominantly exhibit a northeast-southwest (NE-SW) orientation (Figure 4a), with higher densities concentrated in the central hilly region. This area is geologically characterized by undifferentiated acidic intrusions and active fault lines. The maximum lineament density recorded in the study area was 0.00253 m/m^2, with a secondary peak at 0.00203 m/m^2. In contrast, lower densities were observed in coastal zones dominated by alluvial deposits and flat terrain, where structural features are less prominent (Figure 5a).

This spatial distribution of lineaments is crucial in assessing groundwater potential, as zones with higher lineament density often indicate increased secondary porosity

Table 4: Weights and scores used for each thematic map utilized in the overlay of the groundwater potential map.

No.	Theme	Percentage (%)	Class	Score (s)
1	Lineament density, LD (m/m^2)	38	0.00204–0.00253	5
			0.00153–0.00203	4
			0.00102–0.00152	3
			0.000507–0.00101	2
			0–0.000506	1
2	Geomorphology, GM	24	Lowland	5
			Hills	4
3	Geology, g	13	Sand (mainly marine)	5
			Clay, silt, sand and gravel-undifferentiated (Continental)	4
			Clay and silt (marine)	3
			Schist, phyllite, slate and limestone. Minor intercalations of sandstone and volcanics	2
			Interbedded sandstone, siltstone and shale	1
4	Rainfall, R (mm)	9	2080–2250	5
			1920–2070	4
			1800–1910	3
			1690–1790	2
			1530–1680	2
5	Slope, S (°)	7	0–1.94	5
			1.95–5.98	
			5.99–12.6	
			12.7–21.3	
			21.4–41.2	
6	Drainage density, DD (m/m^2)	5	0–0.000521	5
			0.000522–0.00104	4
			0.00105–0.00156	3
			0.00157–0.00209	2
			0.0021–0.00261	1
7	Land use/Land cover, LULC	4	Water bodies	5
			Agriculture	4
			Forest	3
			Urban	2

and permeability, enhancing groundwater infiltration and storage (Moore, 1982; Arulbalaji *et al*., 2019; Kabeto *et al*., 2022).

Geomorphology map

The geomorphology of a region is of paramount importance when assessing its potential and prospects for groundwater. This is due to its direct influence on the subsurface movement of groundwater. Geomorphology significantly influences groundwater movement through several critical factors. Steep slopes generally increase surface runoff, whereas valleys promote aquifer recharge. The specific types of soil and rock present dictate permeability, which subsequently affects both water flow and aquifer storage capacity. Furthermore, both natural and artificial drainage patterns can have a substantial impact on water levels. Vegetation contributes to this dynamic by affecting humidity levels and enhancing soil infiltration processes. Changes in land use/land cover, particularly urbanization, typically lead to a reduction in groundwater recharge, while agricultural practices may produce varied effects on the hydrological system. Geological structures, such as faults, create pathways for groundwater movement, and karst topography alters traditional drainage patterns. In summary, a comprehensive understanding of geomorphology is essential for the effective management of groundwater resources (Magesh *et al*., 2012). A visual representation of the geomorphological features can be observed in Figure

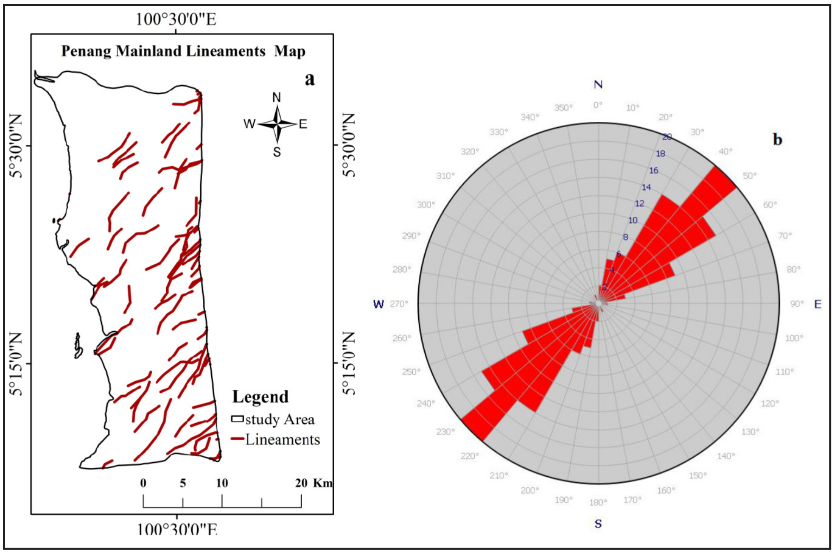

Figure 4: (a) Study area with lineaments and (b) Rose diagram showing the general trends of the lineaments on the Penang mainland. The lineaments run mainly from northeast to southwest.

5b where a map highlights the hilly terrain present in the eastern and southeastern regions of Penang mainland, while the remaining area is primarily characterized by lowlands.

Geology map

The geological features of the study area are illustrated in Figure 5c, which delineates six distinct lithological characteristics: undifferentiated acid intrusives; marine clay and silt; undifferentiated continental clay, silt, sand, and gravel; interbedded sandstone, siltstone, and shale; predominantly marine sand; and schist, phyllite, slate, and limestone, with minor intercalations of sandstone and volcanic materials.

Rainfall map

The rainfall map depicted in Figure 5d provides an overview of the precipitation distribution in Penang mainland. It is evident that the north-western region experienced the greatest amount of rainfall, ranging from 2250 to 2680 mm. Conversely, the south-western part exhibited the lowest precipitation levels, ranging from 1530 to 1620 mm. The spatial variability of precipitation in Penang Mainland was limited, with just a 720 mm variation between the highest and lowest recorded figures. This map was created by interpolating precipitation data gathered from three monitoring stations between 2014 and 2023.

Slope map

The regions exhibiting the steepest inclines (up to 41.2°) are located in the centre mountainous section of the state (Figure 6a). The gradient of the surface displays a declining pattern. The most level and least steep inclines, ranging from 0 to 1.94°, can be found along the northwest coast. The core portions of the island exhibit slope between 1.95 and 5.98°, as well as slopes ranging from 5.99 to 12.6°, according to (Jhariya *et al*., 2016). The variation in height across a specific surface is known as the slope (Manap *et al*., 2013) further describe how the slope of the surface, which is mostly caused by gravity, is essential for regulating the flow of surface water. Due to reduced surface runoff, moderate slopes ranging from 0 to 5 degrees facilitate groundwater infiltration by enabling water to percolate into the subsurface. In contrast, steeper slopes hinder direct recharge. Additionally, groundwater extraction becomes challenging on slopes exceeding 35°, as access for vehicles and drilling equipment is greatly restricted (Thomas *et al*., 2009). Furthermore, it is asserted that slight inclines promote the retention of stagnant water.

Drainage density map

By measuring the proximity of stream channels, drainage density analysis provides information about the average length of these channels across the basin (Strahler, 1964; Singh *et al*., 2017). This metric demonstrates an inverse correlation with aquifer permeability and is essential in ascertaining runoff distribution and the degree of infiltration. Using a DEM with a resolution of 30 m x 30 m and the ArcGIS platform, the drainage density of Penang mainland was calculated for this study (Figure 6c). The analysis identified regions characterized by the highest drainage density, reaching levels of up to 0.00261 m/m².

Land use/Land cover map

The land use/ land cover map (Figure 6d) was generated utilizing a satellite image acquired from USGS Earth Explorer in January 2024. Subsequently, the image underwent supervised classification using ArcGIS. The study area encompasses four discrete land cover categories, namely water bodies, agriculture, forest, and urban area.

Groundwater potential map

The integration of remote sensing, GIS, and the Analytic Hierarchy Process (AHP) in this study provided a systematic

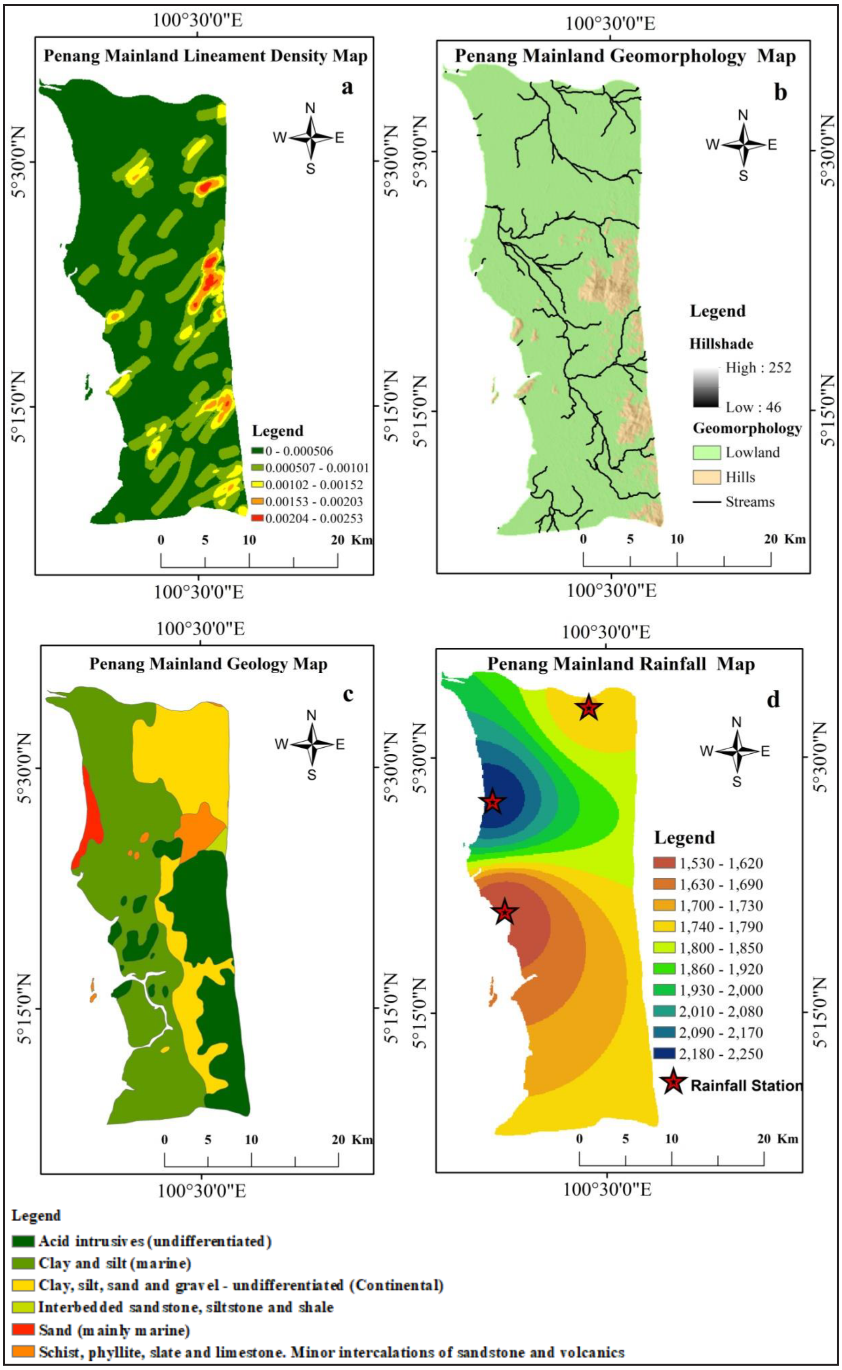

Figure 5: Thematic layers of (a) Lineament Density Map (m/m²), (b) Geomorphology Map, (c) Geology Map, (d) Rainfall Map (mm) of Penang mainland.

and efficient approach to delineating groundwater potential zones in Penang mainland. The resulting groundwater potential map, illustrated in Figure 7, offers important insights into the spatial distribution and availability of groundwater resources across the study area. The thematic layers and criteria used, such as slope, drainage density, lineament density and LULC, were selected based on their relevance to groundwater occurrence and recharge mechanisms.

As shown in Table 5, areas such as Kampung Tamban, Taman Bertam, Seberang Perai, Taman Bukit Juru, and Kampung Kepala Gajah exhibited high groundwater potential. These regions are characterized by low slope angles, low drainage density, and high lineament density, which are likely associated with favorable geological and hydrological settings that support recharge and groundwater storage. This observation is further validated by the presence of a cluster of productive wells in these areas, with depths ranging from 56 to 88 meters and consistent water levels between 1.6 and 2.4 m³. This data supports targeted investments in water infrastructure, such as boreholes and wells, for enhancing groundwater extraction and conservation practices.

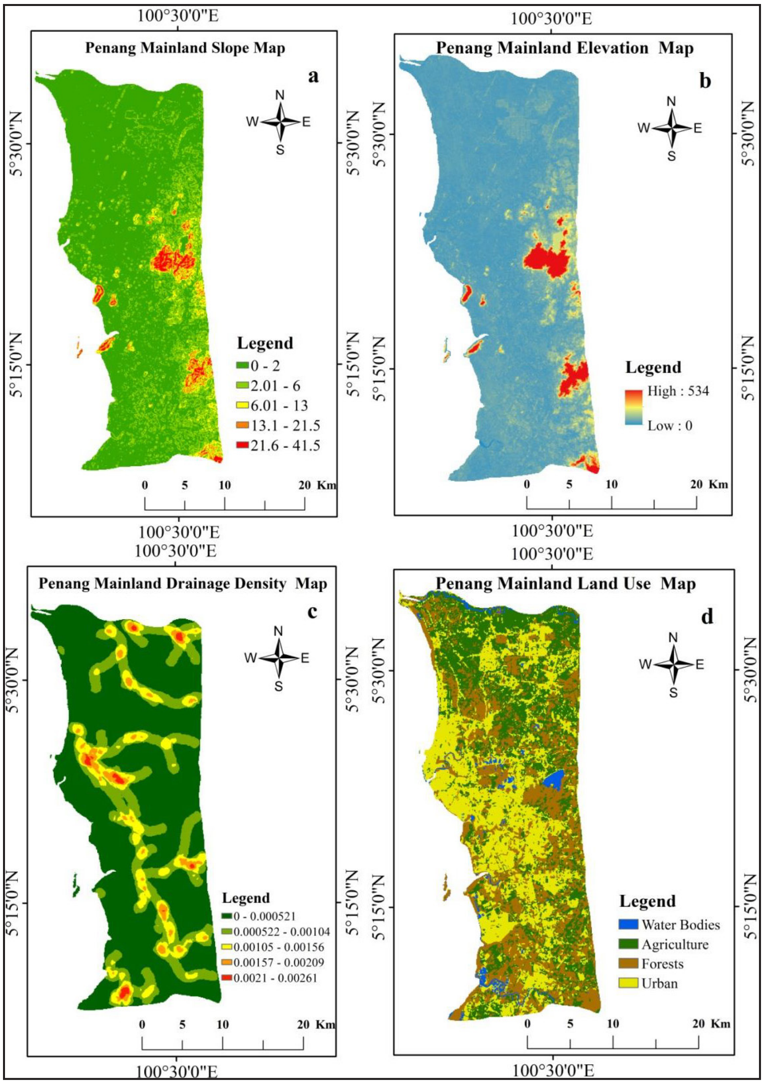

Figure 6: Thematic layers of (a) Slope Map (°), (b) Elevation Map (m), (c) Drainage Density Map (m/m²), and (d) Land Use/Land Cover Map) of Penang mainland.

In contrast, areas such as Bukit Mertajam Forest Park, Kampung Pelet, Kampung Lima Kongsi, and Bukit Jawi show the lowest groundwater potential, where several wells remain inactive. These findings raise concerns about groundwater availability and highlight the necessity for alternative water supply solutions, including rainwater harvesting, surface water utilization, or even desalination where feasible.

In this study, groundwater well data were used as validation points to support the delineation of groundwater potential zones derived from remote sensing and GIS analyses. While the majority of the wells fall within the shallow aquifer system (typically <50 m depth), a subset of wells ranges between 56 and 88 meters in depth. Although they may not strictly represent the shallow aquifer system, they were used to validate the presence of groundwater-bearing formations and to enhance the spatial reference coverage across the study area. A clear distinction was made during interpretation to account for the depth differences, and their inclusion did not significantly influence the delineation of shallow groundwater potential zones.

However, one of the key limitations of this study was the absence of direct groundwater table data. This limitation stemmed from the restricted availability and inconsistent coverage of groundwater level measurements across the study area. As a result, the current analysis primarily relied on surface indicators derived from satellite imagery and thematic mapping.

To address this limitation and improve assessment accuracy, it is acknowledged that river water levels can serve as a valuable proxy for groundwater table conditions, particularly in hydraulically connected shallow aquifer systems. Incorporating river stage data in future models may aid in estimating subsurface water availability and improve the delineation of recharge zones. This approach not only enhances the robustness of groundwater assessments but also offers a practical alternative when direct measurements are not available.

In addition to the current study, previous research by Petrick *et al*. (2023) provides valuable insights into the applicability of integrated approaches for groundwater

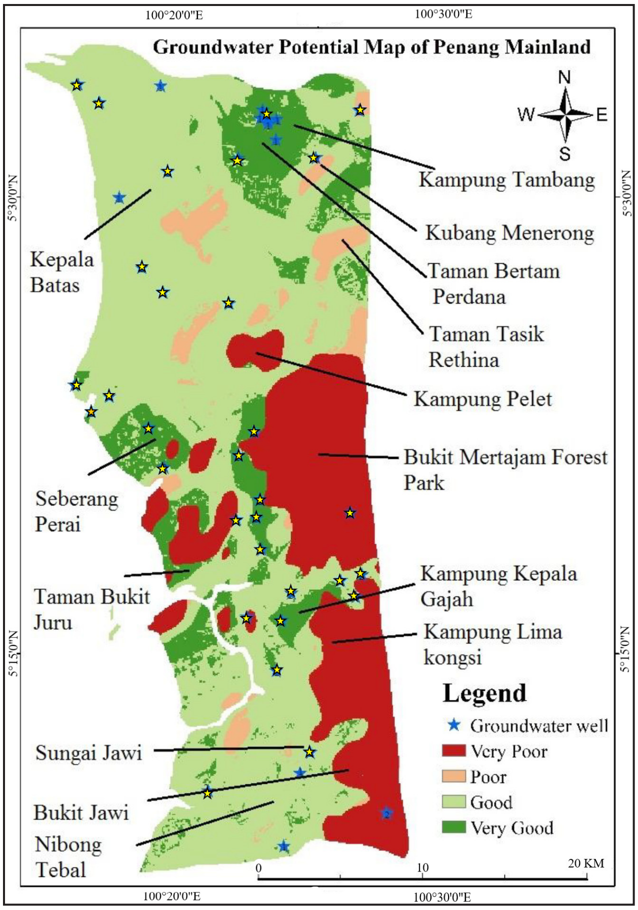

Figure 7: Groundwater potential map of Penang mainland and groundwater wells obtained from https://mygems.jmg.gov.my. The ★ indicates active wells and the ☆ indicates inactive wells. The map was divided into four classes based on the groundwater potential score of each cell.

exploration of Penang island. The authors employed remote sensing and GIS techniques similar to those used in this research but also validated their findings using 2D Electrical Resistivity Tomography (ERT), which enhanced the subsurface interpretation of aquifer presence and characteristics. Although their focus was on Penang Island rather than the mainland, the methodological parallels and successful use of geophysical validation underscore the robustness of using multi-source data integration for delineating groundwater potential zones. This highlights the potential for incorporating geophysical methods such as 2D ERT in future extensions of the current study to validate the remotely sensed groundwater predictions and improve subsurface confidence levels.

While the present study focused on remote sensing and GIS-derived indicators, previous research has demonstrated the value of including subsurface data. For instance, Hairudin *et al*. (2022) integrated lineament density into the DRASTIC model and included groundwater table depth as a key parameter. Their work in the Tampin District showed improved model accuracy and highlighted the importance of incorporating both surface and subsurface data. This comparison suggests that the future incorporation of water table and river level data could significantly strengthen groundwater potential assessments in Penang mainland.

Despite these data constraints, the applied methodology demonstrated strong potential for identifying favorable groundwater zones in Penang mainland. These findings underscore the need for tailored groundwater management strategies that reflect regional variations in aquifer characteristics. Furthermore, enhancing the model with additional hydrological data, such as water table measurements and river stages, would strengthen its utility for groundwater planning and climate resilience strategies.

Table 5: Results of the groundwater potential mapping.

Groundwater potential class	Total percentage (%)	Area (km²)	Location
Very Good	13.8	99.4275	Kampung Tamban, Taman Bertam, Seberang Perai, Taman Bukit Juru and Kampung Kepala Gajah
Good	59.1	425.5537	Kepala Batas, Sungai Jawi and Nibong Tebal
Poor	4.5	32.63625	Kubang Menerong and Taman Tasik
Very Poor	22.6	163.1588	Bukit Mertajam Forest Park, Kampung Pelet, Kampung Lima Kongsi and Bukit Jawi

CONCLUSION

This study presents a groundwater potential map for Penang mainland, developed through the preparation and integration of seven hydrogeologically relevant thematic layers: lineament density, geomorphology, geology, rainfall, slope, drainage density and land use/land cover. Areas classified as "Very Poor" potential, including Bukit Mertajam Forest Park, Kampung Pelet, Kampung Lima Kongsi, and Bukit Jawi, are characterized by alluvial lithology and undifferentiated acid intrusives. Conversely, areas designated as "Very Good" potential, such as Kampung Tamban, Taman Bertam, Seberang Perai, Taman Bukit Juru, and Kampung Kepala Gajah, exhibit alluvial lithology, marine clay, and silt, in addition to undifferentiated continental clay, silt, sand, and gravel.

This study addresses the existing knowledge gap regarding the limited number of groundwater studies conducted on Penang mainland, offering valuable preliminary guidance for the selection of suitable locations for groundwater well drilling in the region. Given that Penang is recognized as the most water-insecure state in Malaysia, the effective exploitation of groundwater resources has become imperative to ensure the availability of this vital resource. The scarcity of water in the region highlights the urgent need for comprehensive studies and strategic planning to manage groundwater supplies sustainably.

Furthermore, this map will serve as an invaluable tool for relevant stakeholders, including policymakers, environmental agencies, and local communities, in promoting the sustainable development and management of groundwater resources. By providing clear insights into potential drilling sites, the map can facilitate informed decision-making and encourage collaborative efforts aimed at safeguarding and optimizing groundwater use for both current and future generations. In this way, the study not only contributes to the scientific understanding of groundwater resources in Penang but also supports broader initiatives for water security and sustainable resource management in the region.

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AUTHORS CONTRIBUTION

BAM: data analysis, drafting the manuscript, experimental design, writing-original draft preparation, investigation, methodology and writing-final draft. IAA: supervision, writing-review & editing, and validation. KAK: writing-review & editing, and validation. AF: writing-review & editing.

CONFLICT OF INTEREST

The authors wish to clarify that they have no conflicts of interest to disclose regarding this submission. This statement affirms that there are no financial, personal, or professional relationships that could be perceived as influencing the research or the interpretation of the findings presented in this article. The authors are committed to maintaining transparency and integrity in their work and ensure that their research is conducted and reported without any undue influence or bias.

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