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Delineation of Groundwater Recharge Areas in High-Terrain Young Andesitic Volcano Geothermal Systems

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ABSTRACT

High-terrain young andesitic volcano geothermal systems are common in Indonesia. The surficial geology is often dominated by massive, non-fractured lava and welded tuff formations, which can act as aquitards. In contrast, some areas may be covered by unconsolidated tephra, agglomerates, or other reworked materials, forming unconfined aquifers or local recharge zones. Geothermal exploration in Indonesia is often hindered by the assumption that high-elevation areas on volcano flanks are groundwater recharge zones that must be protected. However, not all such areas function as recharge zones. In this paper, we discuss the common characteristics of groundwater recharge areas that may not be associated with the geothermal fluid system, meaning these areas can still be utilized for geothermal development, such as siting well pads for drilling targets. We analyzed slope (using DEMNAS data), LandSat 9, Landcover and geology data, integrating these factors in a GIS using Index Overlay Method to identify the most plausible recharge areas. This approach is considered a simple, semi-quantitative method that is sufficiently valid for locating groundwater recharge zones. Consequently, areas outside these recharge zones can be deemed suitable for geothermal development.

1 INTRODUCTION

The study area is a high-standing composite volcano classified as a Young Andesitic Volcano, located in East Java, Indonesia (Figure 1). Several warm springs emerge along the northern and western lower slopes of the volcano, indicating the presence of geothermal activity and potential resources (Figure 2). Consequently, the area has been designated as a geothermal working area. However, as is typical in tropical regions, the volcano is extensively covered by dense vegetation, which contributes to its function as a groundwater recharge and conservation area. This condition poses challenges for geothermal development. In particular, drilling activities are often constrained due to environmental concerns, including the potential risk of groundwater contamination, among other factors.

Hydrogeological systems in composite volcanoes are generally complex, primarily due to the heterogeneity of volcanic deposits, strong permeability contrasts, steep topography, and other controlling factors . Therefore, not all parts of such volcanic terrains serve as effective groundwater recharge zones. Furthermore, the presence of hydrothermal clay layers, which may act as impermeable cap rocks, can inhibit the hydraulic connection between deep geothermal fluids and shallow groundwater systems.

This study aims to identify and characterize groundwater recharge areas that are not hydraulically connected to the geothermal system. By delineating these zones, geothermal development activities—such as drilling site placement—can be optimized while minimizing interference with groundwater recharge processes.

The method mainly using GIS spatial analysis and remote sensing, geology data, with small discussions on fluid chemistry. It is considered as simple approach but sufficient to select the area for well targeting in particular at the early stage of exploration.

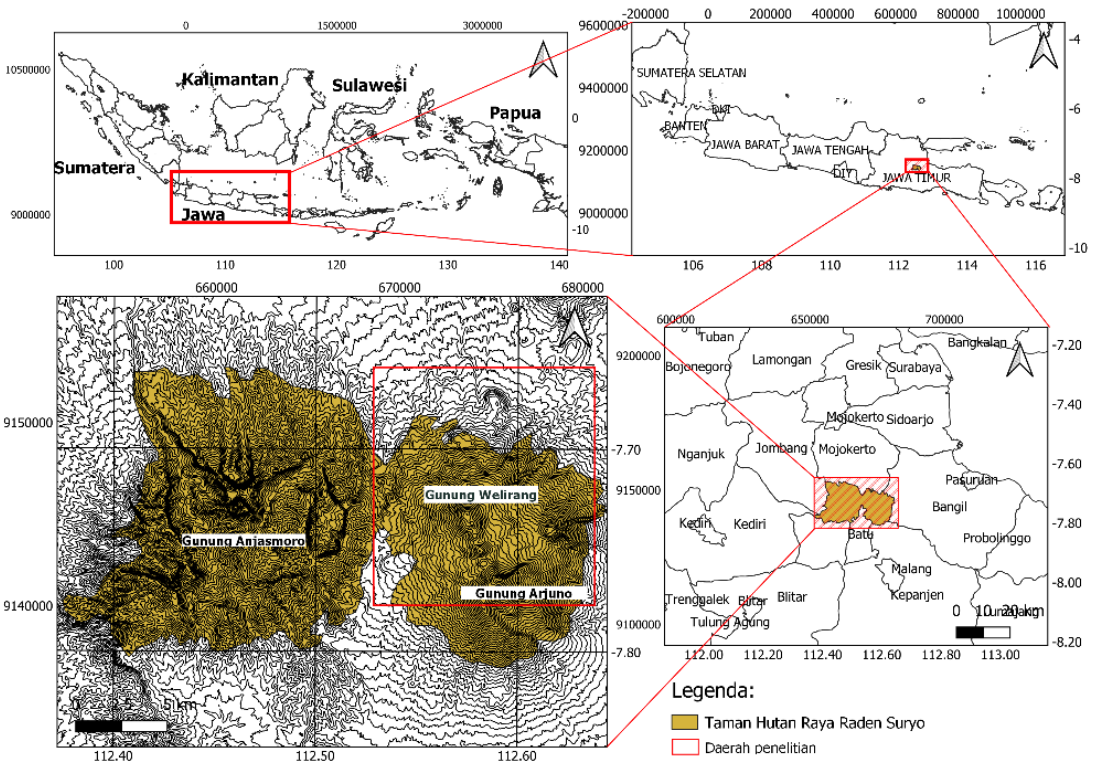


Figure 1. Location of study area.

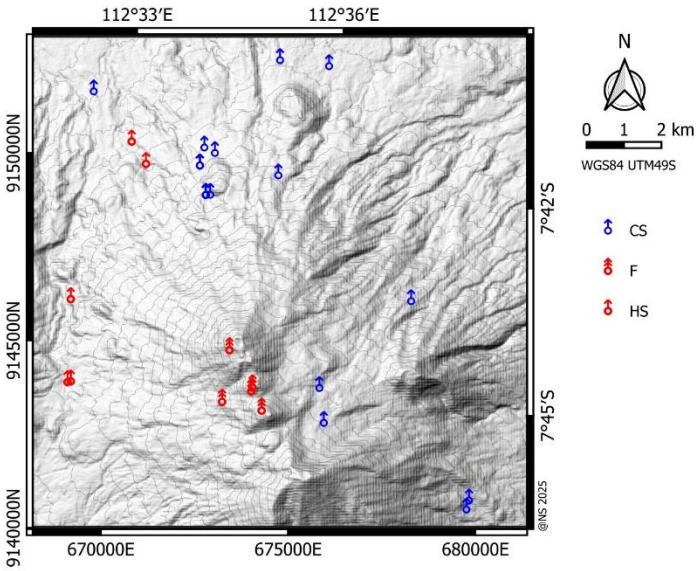


Figure 2. Distribution of thermal and cool springs in study area.

2 GEOLOGY

The study area comprises a Quaternary volcanic complex consisting of a stratovolcano and a caldera, collectively, in this study, referred to as the Arjuno-Welirang Volcanic Complex (AWVC). The volcanic evolution of this complex began with the activity of the older Anjasmara Volcanoe located in the western part of the study area. Volcanic products from Anjasmara are interpreted to underlie the younger AWVC deposits. The Anjasmara volcanic sequence consists primarily of lava and pyroclastic flows, which are exposed along the lower western flanks of the AWVC.

The evolution of the AWVC is interpreted to have begun with the eruption of the Ajuno Volcano, located at the southern part of the complex. Subsequent volcanic activity migrated progressively toward the north-northeast, forming the Welirang Volcano, and later shifted to the Kembar1 and Kembar2 edifices situated between Arjuno and Welirang. The surface deposits of the complex are dominated by lava flows with minor occurrences of

pyroclastic flow deposits. Around the eruptive craters of Welirang and Kembar1 and Kembar2, the youngest volcanic products are predominantly tephra deposits, composed various size from block, agglomerate, lapilli, tuff and ash-fall materials. The geological map of the study area, with minor modifications, is adapted from the Geological Agency of Indonesia (PSDMBP, 2010) and presented in Figure 3.

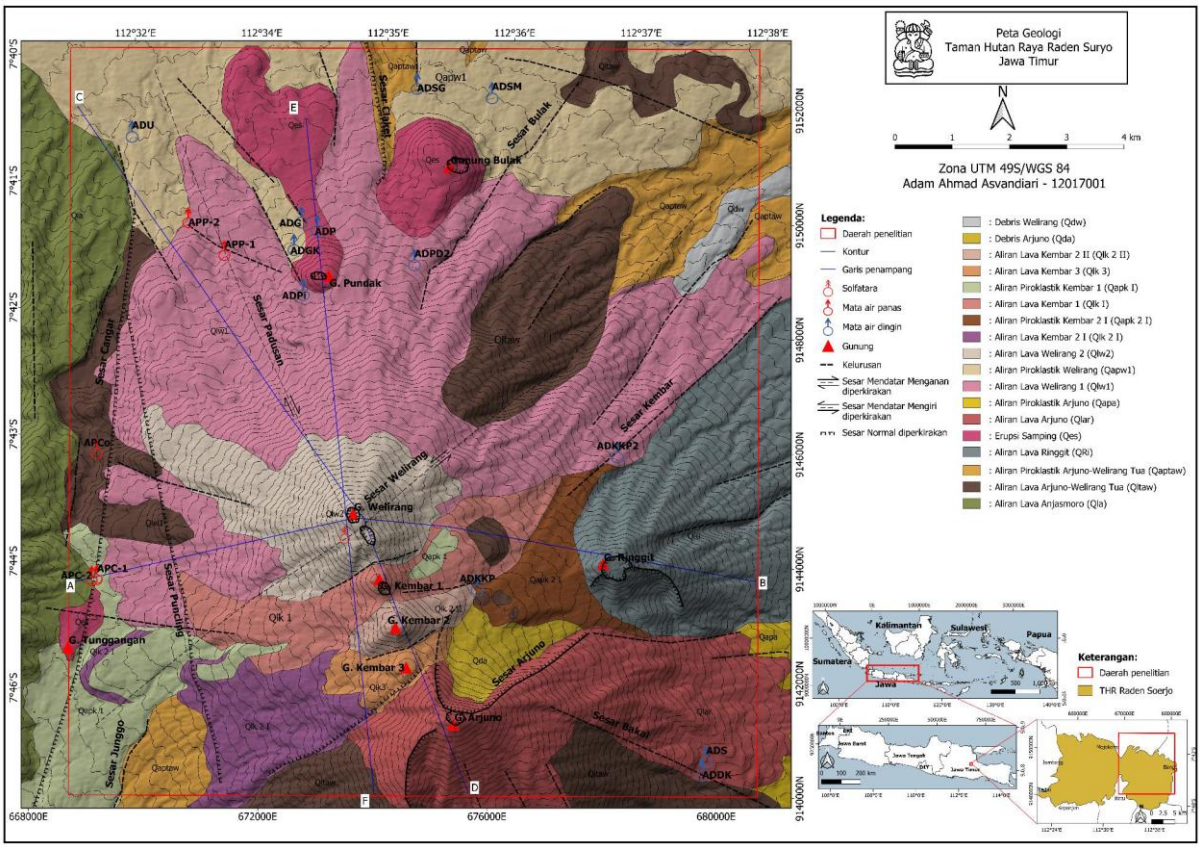


Figure 3. The geological map of the study area, with minor modifications, is adapted from the Geological Agency of Indonesia (PSDMBP, 2010, in Asvandiari 2022).

3 GROUNDWATER RECHARGE AREA

Ground Water Recharge Area (GWRA) is the area where water predominantly flows downward through the unsaturated zone to replenish an aquifer. (https://www.dws.gov.za/Groundwater/ Groundwater_Dictionary/ index.html?introduction_recharge_area.htm).

This recharge can be for shallow unconfined or deep confined aquifers. In unconfined aquifers, surface water moves down from the ground surface, or recharge area, and through an unsaturated zone until it reaches a saturated zone. The boundary between the two zones is called the water table. An unconfined aquifer's water table surface can be several feet or several hundred feet below the ground surface; the thickness of the unconfined aquifer can vary, and its lower boundary is commonly denoted by a confining bed, separating the confined aquifer below.

Replenishment of water in unconfined aquifers can take days, months, or years depending on the recharge pathway. Generally, water moves faster and easier through sand, gravel, and fractured rock than it does through silt and clay. The recharge area for a confined aquifer is generally located some distance from, or at a higher elevation than, the zone that is being used as a water supply. Replenishment of water in confined aquifers can take years or decades depending on the recharge pathway

There are several factors that determine the effectiveness of an area to be a ground water recharge area. Those factors are discussed as follows:

1. Slope, it has a major influence on groundwater percolation (the process by which water infiltrates and moves downward through the soil to recharge the aquifer). Gentle slopes promote higher infiltration and percolation because rainfall stays longer on the surface, giving more time for water to seep into the ground.

Steep slopes → encourage surface runoff rather than infiltration, since water flows downhill quickly before it can infiltrate.

2. Geology/lithology, lithology may act as aquifer or aquitard or aquiclude. This depend on the porosity and permeability of the rock formation. Loose material such as volcanic tephra have many pore spaces and allow rapid recharge. The occurrence of fracture and fault can enhance the rock permeability. Consolidated rocks may have good permeability if the rock is fractured or faulted. The better the permeability the better the recharge.

3. Lineament density, it is often assumed have similar role with fracture and faults density. The map reflects the connectivity of fracture and fault permeability, thus the denser the lineament the better the permeability, furthermore better opportunity as recharge area. Since the study area is covered by young volcanic product, the surface texture is smooth and rarely reflect lineaments. Therefore in this study this data is ignored.

4. Drainage density, it plays an important role in controlling groundwater recharge potential, as it reflects how surface water interacts with subsurface infiltration processes

5. Soil permeability, it is the ability of soil to transmit water through its pore spaces and fractures. This data is rarely available. In this study it is not included.

6. Landcover, It determines how rainfall interacts with the ground surface and affects infiltration, evapotranspiration, and runoff. In volcanic area, the area cover by dense big trees are the better recharge area compare to the area cover by grass, shrub or built up. Bareground cover by loose tephra can be a good recharge area because it permits rains water to percolate to the aquifer.

7. Rainfall intensity, the rainfall provides the primary source of recharge, but intensity affects how effectively water infiltrates. The data is rarely available. In this research it is not included.

4 DATA AND METHOD

In this study the data being used are shown in the Tabel 1.

Table 1. Data Source for the study.

Data	Source	Remark
DEMNAS	https://tanahair.indonesia.go.id/	Spatial resolution: 0.27 arc-seconds (approximately 8.1 meters)
Geology Map 1:100 000	Geological Agency (PSDMBP, 2010)	Digitize from jpg map
River	https://tanahair.indonesia.go.id/	RBI 25K Kab. Pasuruan (2022)
LandSat 9 (2,3,4,5,6)	https://earthexplorer.usgs.gov/	Landsat 8 Collection 2 Level-2 LST acquired on August 19, 2024
Landcover	https://esa-worldcover.org/en/data-access	ESA WorldCover 10 m 2021
Spings and fumaroles coordinate	Asvandiari, 2022	In spread sheet format

5 PREPARATION OF FACTOR MAPS

All preparatory processes for generating the factor maps were carried out using QGIS. Each factor map was subsequently assigned a weight according to its relative significance. The final stage of the analysis involved the development of a Groundwater Recharge Potential Map through the application of the Index Overlay Method (IOM) (Bonham-Carter, 1994; Shrestha et al., 2017), in which the weighted factor maps were integrated using the following equation:

$$S = \frac{\sum W_i S_{ij}}{\sum W_i} \quad (1)$$

where *Wi* is the weight of ith factor map, *Sij* is the *i*th spatial class weight of the *j*th factor map, and *S* is the weighted spatial unit value in output map. In this study, the final formula is shown in the equation:

$$Potential\ recharge = (slope \times 15) + (lithology \times 15) + (drainage\ density \times 5) + (land\ cover \times 5) + (NDVI \times 10) + (distance\ from\ active\ crater \times 25) + (distance\ from\ fumarole \times 25) \quad (2)$$

The flow chart of spatial analysis is shon in Figure 4.

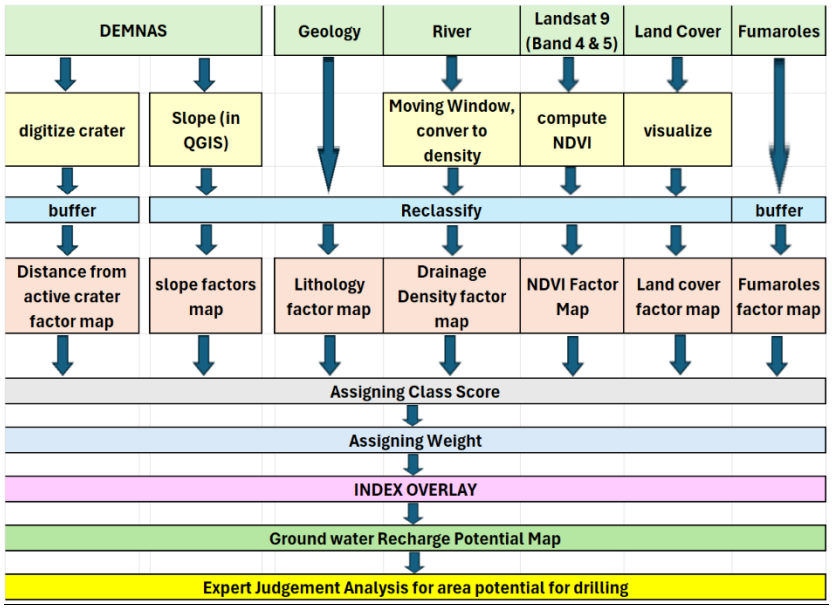


Figure 4. Flow chart methodology.

The DEMNAS dataset was utilized to generate the distance-to-active-crater map. In active craters, upflow of magmatic and hydrothermal fluids is dominant; hence, these areas are considered impermeable to rainfall percolation and do not contribute to groundwater recharge. This factor was assigned a high weight (25; Table 2), with areas closer to the crater exhibiting lower recharge potential. This pattern is analogous to that observed in the distance-from-fumaroles factor map. The DEMNAS data were also employed to derive slope information, where steeper slopes correspond to reduced potential for rainwater infiltration and groundwater recharge.

Lithology was categorized into three classes. Class 3 represents lithologies located near the volcanic summit or crater, typically composed of tephra deposits. Class 2 corresponds to relatively younger lithologies than Class 3, commonly consisting of loose materials or fractured lava. Class 1 denotes the older lithologies, which are generally more compact and less permeable.

The assignment of class scores and map weights was determined through expert judgment, reflecting the relative importance of each factor in influencing groundwater recharge potential.

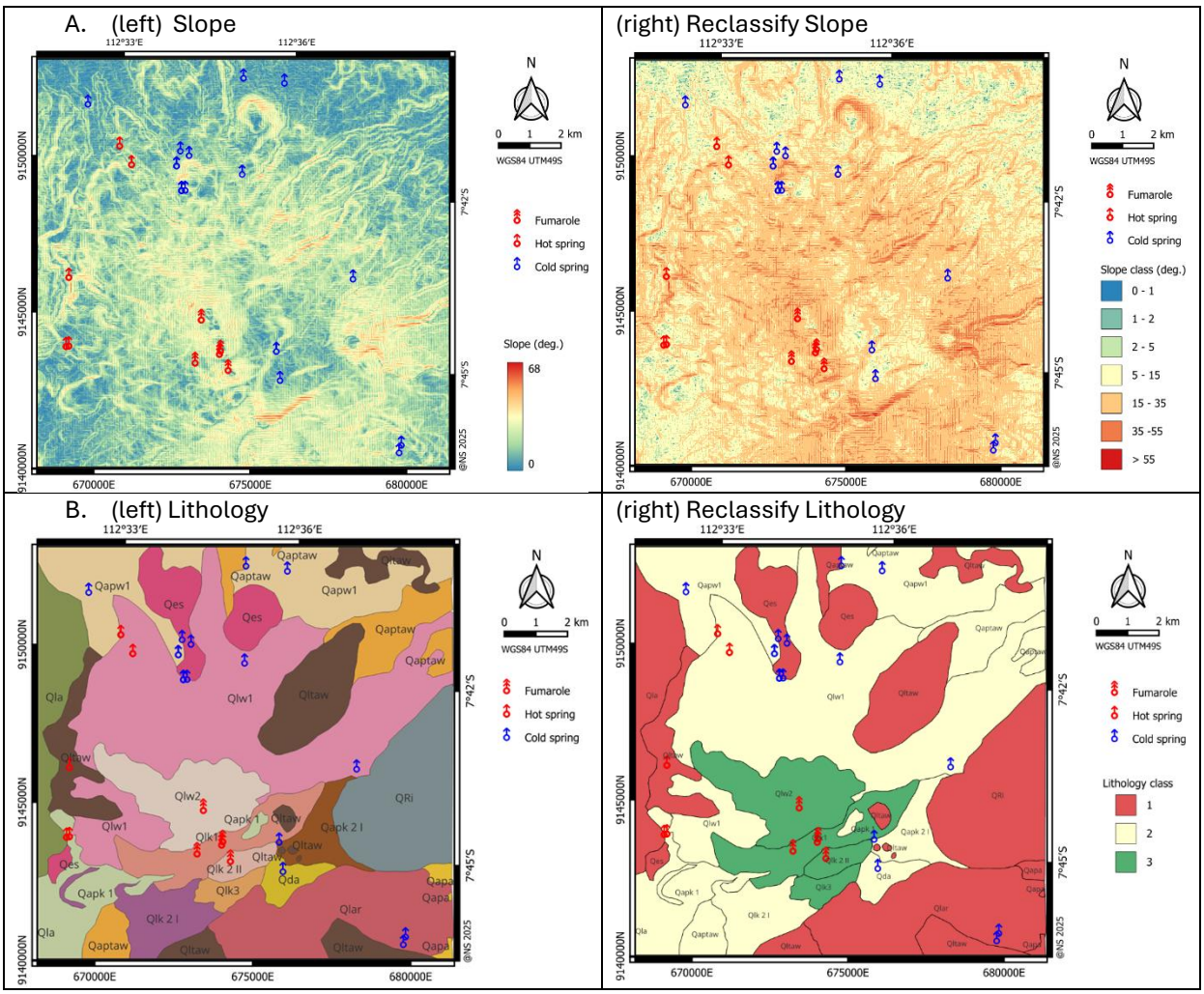
6 RESULT

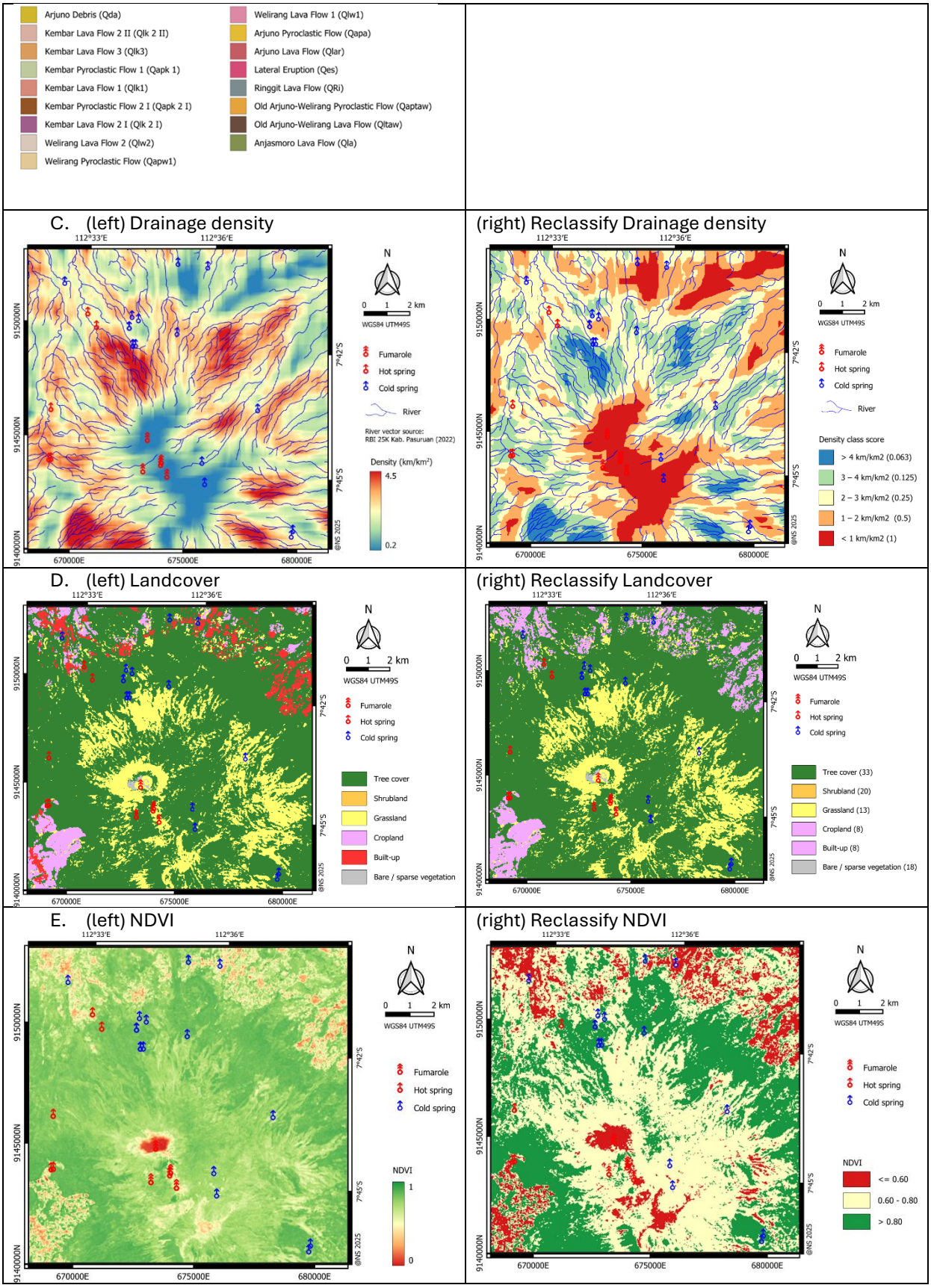
The factor maps and the weight is shown in the Tabel 2 and Figure 5.

Table 2. Factor maps and the weight for Index Overlay Analysis.

No.	Factor Maps	Map Weight	Map Class	Class Score
1.	Slope	15	Flat (0 – 1°)	1
			Very gentle (1 – 2°)	0.333
			Gentle (2 – 5°)	0.111
			Strongly sloping (5 – 15°)	0.037
			Moderately steep (15 – 35°)	0.012
			Steep (35 – 55°)	0.004
			Very Steep (> 55°)	0.001
2.	Lithology	15	QRi, Qltaw, Qapa, Qlar, Qes, Qla,	1
			Qapk 1, Qaptaw, Qapw1, Qda, Qlk 2 l, Qlw1	2
			Qlw2, Qlk1, Qlk3	3
3.	Drainage density	5	< 1 km/km^2	1

No.	Factor Maps	Map Weight	Map Class	Class Score
			1 – 2 km/km^2	0.5
			2 – 3 km/km^2	0.25
			3 – 4 km/km^2	0.125
			> 4 km/km^2	0.063
4.	Land cover	5	Tree cover	33
			Shrubland	20
			Grassland	13
			Cropland	8
			Built-up	8
			Bare / sparse vegetation	18
5.	NDVI	10	<= 0.6	1
			0.6 – 0.8	3
			> 0.8	6
6.	Distance from active crater	25	<= 250 m	0
			250 – 500 m	1
			500 – 750 m	2
			750 – 1000 m	3
			> 1000 m	4
7.	Distance from fumarole	25	<= 500 m	0
			500-1000 m	1
			> 1000 m	2




Arjuno Debris (Qda)
Kembar Lava Flow 2 II (Qlk 2 II)
Kembar Lava Flow 3 (Qlk3)
Kembar Pyroclastic Flow 1 (Qapk 1)
Kembar Lava Flow 1 (Qlk1)
Kembar Pyroclastic Flow 2 I (Qapk 2 I)
Kembar Lava Flow 2 I (Qlk 2 I)
Welirang Lava Flow 2 (Qlw2)
Welirang Pyroclastic Flow (Qapw1)
Welirang Lava Flow 1 (Qlw1)
Arjuno Pyroclastic Flow (Qapa)
Arjuno Lava Flow (Qlar)
Lateral Eruption (Qes)
Ringgit Lava Flow (QRi)
Old Arjuno-Welirang Pyroclastic Flow (Qaptaw)
Old Arjuno-Welirang Lava Flow (Qltaw)
Anjasmoro Lava Flow (Qla)
C. (left) Drainage density
(right) Reclassify Drainage density
D. (left) Landcover
(right) Reclassify Landcover
E. (left) NDVI
(right) Reclassify NDVI
112°33'E
112°36'E
7°42'S
7°45'S
9150000N
9145000N
9140000N
670000E
675000E
680000E
N
0 1 2 km
WGS84 UTM49S
Fumarole
Hot spring
Cold spring
River
River vector source:
RBI 25K Kab. Pasuruan (2022)
Density (km/km²)
4.5
0.2
Density class score
> 4 km/km2 (0.063)
3 – 4 km/km2 (0.125)
2 – 3 km/km2 (0.25)
1 – 2 km/km2 (0.5)
< 1 km/km2 (1)
Tree cover
Shrubland
Grassland
Cropland
Built-up
Bare / sparse vegetation
Tree cover (33)
Shrubland (20)
Grassland (13)
Cropland (8)
Built-up (8)
Bare / sparse vegetation (18)
NDVI
1
0
<= 0.60
0.60 - 0.80
> 0.80
@NS 2025

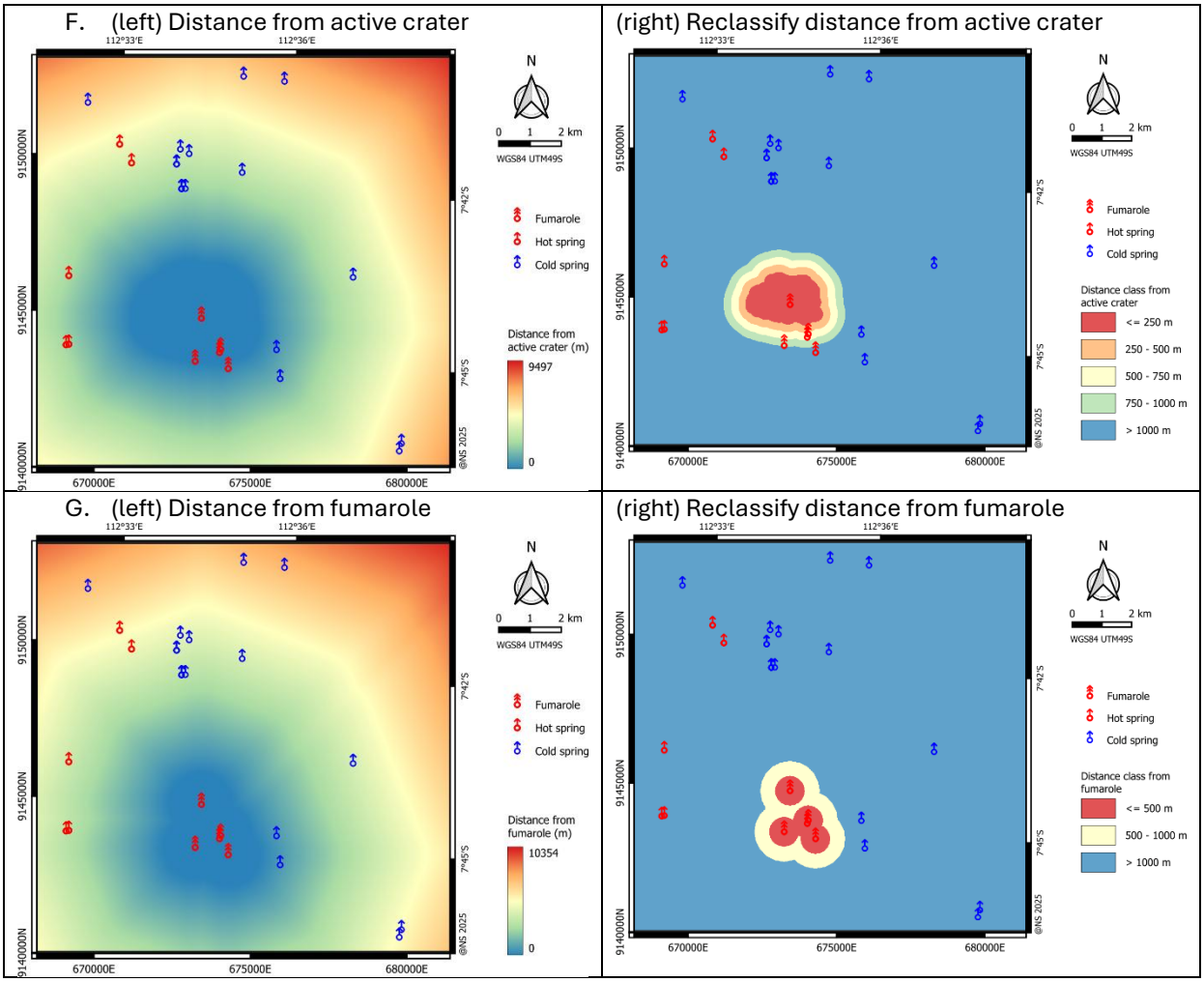


Figure 5. A to G is the map and the respective factor map as the product of reclassification and scoring.

7 GROUND WATER POTENTIAL RECHARGE MAP VS POTENTIAL AREA FOR GEOTHERMAL DRILLING

The final groundwater recharge potential map generated using the index overlay method is presented in Figure 6. The map illustrates areas of lower recharge potential, indicated by red and orange colors, predominantly located near the volcanic summit. These zones correspond to the upflow regions of volcano-associated geothermal systems and may serve as suitable targets for siting geothermal exploration or production wells.

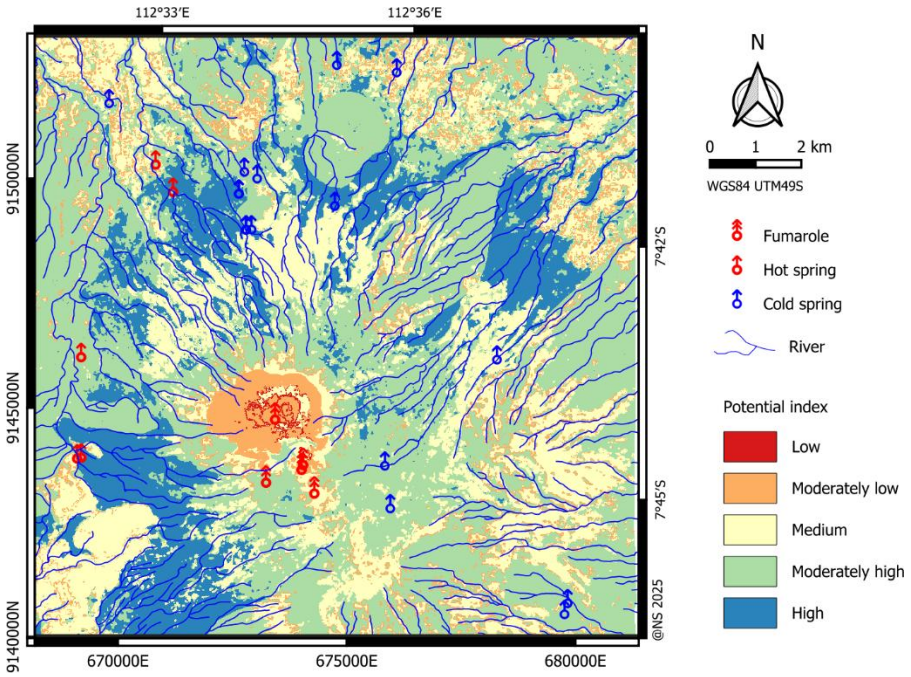


Figure 6. Ground water recharge potential zone. Low and Moderately low of Potential index areas are less potential for ground water recharge and maybe use for sitting geothermal well.

The resulting map was subsequently compared with the geothermal potential map produced by the Geological Agency (PSDMBP, 2010), as shown in Figure 7. A comparison between the geothermal potential zones and the groundwater recharge potential map (Figure 6) reveals areas of agreement, indicating that geothermal drilling may still be feasible within zones classified as having low recharge potential.

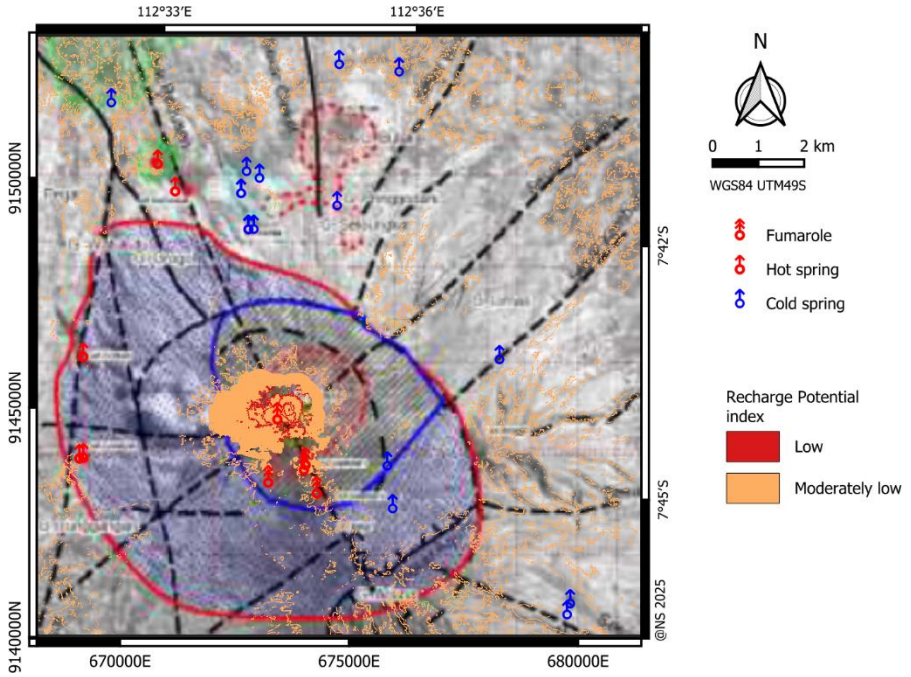


Figure 7. Geothermal potential map (PSDMBP, 2010) (low to moderately low recharge potential zone overlaid).

8 CONCLUSIONS

The groundwater recharge potential map developed in this study can support geothermal well siting and planning. It serves as a useful tool to identify areas with a lower risk of groundwater contamination from geothermal activities. The approach applied in this study represents a simple, semi-quantitative method that provides a sufficiently reliable means of delineating groundwater recharge zones.

Nevertheless, the groundwater recharge potential map produced in this study should be regarded as preliminary. Further investigations are required to refine its accuracy, including the integration of additional datasets such as isotopic analyses, detailed fault mapping, and field surveys to validate and characterize soil permeability.

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