STUDY OF SURFACE TEMPERATURE AND GEOMORPHOLOGY IN THE TIRIS GEOTHERMAL AREA, LAMONGAN VOLCANIC SYSTEM, EAST JAVA, INDONESIA

Dr. Rizwana M. Saktiani
Department of Geological Engineering, Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia

V0LUME 01 ISSUE 01 (2024)
Published Date: 23 December 2024 // Page no.: - 50-63

ABSTRACT

This research applied the remote sensing method to map the land surface temperature (LST) distribution and geomorphology of the Tiris geothermal area (TGA), situated within the broader Lamongan Volcano Complex. The investigation covered a 73 km^2 area, encompassing both the TGA and the Lamongan Volcanic Field (LVF). The distribution of LST was ascertained by processing thermal infrared images acquired by the Landsat-8 satellite. Geomorphological characterization of the study area was achieved through the analysis of 567-band composite multispectral Landsat-8 imagery in conjunction with Digital Elevation Model (DEM) data from the Shuttle Radar Topography Mission (SRTM). The geomorphological conditions were depicted through visual delineation applied to the 567-band composite map and a three-dimensional topographical model. The study's findings indicate that the LST across the area ranges from 15.84°C to 41.05°C. It was observed that the thermal hotspots within the study area were predominantly located in built-up areas and regions of bare land, rather than being directly correlated with known geothermal surface manifestations. No significant high-LST anomaly was detected in the immediate vicinity of the TGA hot springs. This is likely due to the confounding influence of the Tancak River, where the thermal signature of the hot springs is mixed with the ambient temperature of the river's water flow. The geomorphological investigation clarified the structural framework of the Lamongan Volcano, identifying two principal lineaments with northwest-southeast and northwest-east orientations. Furthermore, a distinct fault was identified within the TGA, trending northwest-southeast and spatially associated with the Tancak watershed, suggesting a structural control on the location of surface manifestations.

KEYWORDS: - Land Surface Temperature, Remote Sensing, Geomorphology, Fault, Lineament, Geothermal Manifestation, Lamongan Volcano.

Introduction

1.1. Broad Background and Historical Context

The global pursuit of sustainable and renewable energy sources has placed significant emphasis on the exploration and development of geothermal resources. Indonesia, situated along the tectonically active Pacific Ring of Fire, possesses an extraordinary endowment of geothermal potential, estimated to be among the largest in the world. This potential is a direct consequence of the region's intense volcanic and tectonic activity, which creates the necessary heat sources, reservoirs, and fluid pathways for the formation of geothermal systems. The government of Indonesia has recognized this vast potential as a cornerstone of its national energy strategy, aiming to reduce reliance on fossil fuels and mitigate greenhouse gas emissions. The exploration of these resources, however, is often fraught with challenges. Many promising geothermal fields are located in remote, mountainous regions with rugged terrain and dense tropical vegetation, making conventional ground-based geological and geophysical surveys both logistically difficult and prohibitively expensive.

One such area of significant interest is the province of East Java, which hosts several volcanic complexes with indications of geothermal activity. Among these, the Lamongan Volcano Complex in the Probolinggo Regency has been identified as a promising location for geothermal development [46]. The Tiris area, a small village situated on the northeastern flank of the Lamongan Volcano, has long been known for its surface geothermal manifestations, primarily in the form of hot springs [49, 48]. These manifestations serve as direct, tangible evidence of an active subsurface thermal system, prompting further investigation into its capacity for energy generation. Initial assessments have suggested a substantial geothermal potential for the Tiris area, with estimates ranging from approximately 74 MWe to 147 MWe, concentrated within a prospective area of about 11 km^2 [47]. The primary indicators supporting this assessment are the hot springs found along the Tancak River in Tiris, which exhibit temperatures significantly higher than the surrounding land and water bodies [1, 2]. Specifically, the hot springs register temperatures between 35°C and 45°C, which is a notable contrast to the ambient land water temperature of around 10°C [50]. This marked temperature differential strongly implies the upwelling of geothermally heated fluids from a deeper reservoir, making the area a prime candidate for detailed exploration.

The geological setting of the Lamongan Volcano Complex is complex and dynamic. The region is characterized by a landscape of steep terrains, numerous volcanic cones, and maars, which are low-relief volcanic craters often formed by phreatomagmatic eruptions—explosive events that occur when rising magma interacts with groundwater [56, 57]. The presence of these features points to a history of volatile volcanic activity. The geological structures, particularly faults and fractures, are considered critical components of the geothermal system. These structures, which are well-developed in the local Argopuro andesitic lava and Lamongan lava formations, are believed to act as primary conduits, or pathways, for the ascent of hot fluids from the subsurface reservoir to the surface [54, 55]. Regional structural analyses indicate that the Tiris geothermal area is controlled by major northwest-southeast and north-south trending structures, which are expressed morphologically as lineaments and faults [52]. These same structural trends appear to control the alignment of several maars in the Lamongan complex, further reinforcing the link between regional tectonics and the pathways of geothermal fluids [59]. However, the challenging physical environment of the Lamongan complex presents significant obstacles to traditional mapping and exploration. The steep topography, dense tropical vegetation cover, and extensive weathering of surface rocks—such as the intense lateralization of outcropping basaltic rocks—make direct geological mapping exceptionally difficult and often inconclusive [60, 61, 62]. These complex surface conditions obscure underlying geological structures and make it challenging to build a comprehensive model of the geothermal system based on surface observations alone. It is this combination of high geothermal potential and significant exploration challenges that necessitates the adoption of alternative, more efficient investigation methodologies.

1.2. Critical Literature Review

The need to overcome the limitations of terrestrial-based exploration in challenging terrains has led to the widespread adoption of remote sensing technologies in the field of geothermal science [65]. Remote sensing, defined as the science and art of acquiring information about objects, areas, or phenomena without direct physical contact, offers a powerful suite of tools for preliminary geothermal exploration [66, 9]. By utilizing data from satellite-borne sensors, researchers can analyze vast and inaccessible areas efficiently, identifying key surface indicators of subsurface geothermal activity. This approach is particularly valuable in the initial stages of exploration, as it allows for the rapid screening of large regions to pinpoint smaller, more promising areas for subsequent, detailed ground surveys. The application of remote sensing in geothermal exploration typically focuses on two primary indicators: thermal anomalies and geological structures. The rationale is that geothermal systems often manifest at the surface through elevated ground temperatures and are almost always controlled by permeable geological structures like faults and fractures.

The use of thermal infrared (TIR) data from satellites to map Land Surface Temperature (LST) is a cornerstone of remote sensing-based geothermal exploration. TIR sensors detect thermal energy radiated from the Earth's surface, which can then be algorithmically converted into temperature values. Several studies have successfully demonstrated the utility of this method for identifying geothermal hotspots. For instance, research in the Dieng volcanic complex utilized TIR-based satellite imagery to estimate LST and delineate thermal anomalies associated with geothermal activity [8]. Similarly, studies at the Aso volcanic area in Japan by Mia et al. used Landsat ETM+ images to explore and monitor geothermal activity, showcasing the effectiveness of LST mapping in a well-established volcanic geothermal setting [17, 18]. These studies have established robust methodologies for processing satellite thermal data to derive accurate LST maps, which can reveal subtle temperature variations indicative of subsurface heat flow. In Indonesia, this approach has been applied across various geothermal fields. Research by Utama et al. [10], Sukendar et al. [11], Azhari et al. [12], and Bakruddin et al. [13] has consistently affirmed that remote sensing methods are ideally suited for mapping LST distributions in Indonesian geothermal areas [68, 69]. These studies have provided a foundational framework for interpreting thermal data in the context of the country's unique tropical environment, highlighting the potential to identify prospective zones even under dense vegetation cover.

Alongside thermal analysis, the identification of geological structures is equally critical. Faults and fracture networks provide the necessary permeability for geothermal fluids to circulate and ascend to the surface [55]. Remote sensing techniques, particularly the analysis of multispectral imagery and Digital Elevation Models (DEMs), are highly effective for mapping lineaments—linear features on the landscape that often represent the surface expression of underlying faults or fracture zones. Putri and Purwanto [6] demonstrated the interpretation of geological structure and lithology using Landsat 8 and SRTM imagery, showing how different band combinations can enhance the visibility of structural features. In the context of geothermal exploration, Azhari et al. [12] specifically investigated the link between geological structures identified from Landsat-8 data and LST patterns in the Blawan geothermal field. Their work highlighted the spatial correlation between faults and elevated surface temperatures, reinforcing the concept that these structures act as conduits for heat and fluid flow. Bakruddin and Utama [13] also utilized Landsat-8 imagery for fault analysis in the Arjuno-Welirang geothermal field, further establishing the satellite's utility for structural mapping in East Java. Sukendar et al. [11] combined LST, vegetation indices, and geomorphology to analyze the Mount Salak geothermal area, proposing that zones with high lineament density are weak zones that facilitate the flow of hot fluids to the surface, creating surface manifestations. This integrated approach, which combines thermal and structural analysis, provides a more comprehensive picture of the geothermal system than either method could alone.

The Lamongan volcanic field itself has been the subject of previous geological and geochemical studies. The work by Carn [4] provided a detailed account of the physical volcanology, historical activity, and associated hazards of the field, establishing a fundamental understanding of its geological context. More recently, Deon et al. [3] conducted a geochemical and hydrochemical evaluation of the geothermal potential of the Lamongan field. Their research confirmed the likely existence of a geothermal system based on the chemistry of the hot spring waters, but also noted challenges in mapping due to the complex surface conditions [62]. An early remote sensing study in the area by Utama et al. [10] used Landsat ETM+ imagery for a preliminary investigation of geothermal potential, successfully identifying lineaments in the Lamongan Volcano and faults in the Tiris area. This work laid the groundwork for the current study by demonstrating the applicability of remote sensing to this specific location. The present research builds directly upon this body of work, leveraging the more advanced capabilities of the Landsat-8 satellite and integrating thermal, land cover, and detailed geomorphological analysis to provide a more nuanced and comprehensive assessment.

1.3. The Identified Research Gap

Despite the acknowledged geothermal potential of the Tiris area [47] and the foundational remote sensing work previously conducted [10], a comprehensive and integrated analysis that combines modern high-resolution satellite data for both Land Surface Temperature and detailed geomorphological mapping was lacking. Previous studies either focused on broader geological or geochemical aspects [3, 4] or conducted preliminary remote sensing analyses with older satellite data [10]. A significant gap existed in leveraging the enhanced capabilities of newer sensors, like those on Landsat-8, to perform a detailed, multi-faceted investigation. Specifically, while hot springs in Tiris were known to exist [1, 2], their relationship with regional LST patterns had not been systematically mapped and analyzed. It was unclear whether the hot springs produced a distinct, detectable thermal anomaly at the land surface or if their thermal signature was obscured by environmental factors. The influence of land cover, such as vegetation, built-up areas, and water bodies, on the LST distribution had not been quantitatively assessed for this specific area.

Furthermore, while previous work had identified major structural trends [52, 10], a detailed delineation of lineaments and faults using a combination of multispectral band composites and 3D topographic modeling had not been undertaken. The precise spatial relationship between these delineated structures and the location of geothermal manifestations (hot springs) and other volcanic features (maars) required further clarification. Understanding this relationship is crucial, as it directly pertains to the structural controls of the geothermal system—a key element for targeting future exploration and drilling efforts. The challenging terrain and dense vegetation cover [60] remained a primary obstacle, meaning that a research approach that could effectively "see through" these challenges to map both thermal and structural characteristics over a wide area was needed to fill this gap. The current study was therefore designed to address this gap by applying a synergistic remote sensing methodology to concurrently map the LST distribution and the detailed geomorphological and structural setting of the Tiris geothermal area.

1.4. Study Rationale, Objectives, and Hypotheses

The rationale for this study is rooted in the need for an efficient, cost-effective, and comprehensive method to advance the preliminary exploration of the Tiris geothermal area. Given the logistical challenges posed by the Lamongan Volcano Complex's terrain [60, 61], a remote sensing-based approach is the most logical first step to gain a synoptic overview of the key surface indicators of geothermal activity [64, 65]. The availability of free, high-quality data from the Landsat-8 satellite, with its improved thermal and multispectral sensors [5], and DEM SRTM data provides an unprecedented opportunity to conduct such an investigation. By integrating LST analysis with geomorphological mapping, this research aims to produce a more holistic interpretation of the surface characteristics of the geothermal system than could be achieved by focusing on a single indicator.

The primary objective of this research is to map and analyze the distribution of Land Surface Temperature and the geomorphological conditions of the Tiris geothermal area and the surrounding Lamongan Volcano Complex. This overarching goal is broken down into the following specific objectives:

1. To process Landsat-8 thermal and multispectral data to derive accurate maps of land cover (using NDVI), land surface emissivity, and Land Surface Temperature (LST) for the study area across multiple acquisition dates.

2. To identify and delineate the locations of thermal anomalies (hot spots) and assess their spatial relationship with different land cover types, including vegetated areas, bare land, built-up areas, and known geothermal manifestations.

3. To utilize Landsat-8 multispectral band composites and 3D modeling of DEM SRTM data to perform a visual delineation of key geomorphological features, specifically faults, lineaments, and maars.

4. To analyze the spatial correlation between the delineated geomorphological structures (faults and lineaments) and the locations of geothermal manifestations to infer the structural controls of the geothermal system.

Based on these objectives and the existing literature, the study was guided by the following hypotheses:

1. It was hypothesized that distinct high-LST anomalies would be detectable within the study area, but that these anomalies might not directly coincide with the hot spring locations due to the masking effects of the river

and vegetation. Instead, the highest LST values would be associated with areas of low vegetation cover, such as bare land and artificial surfaces (built-up areas).

2. It was hypothesized that a network of lineaments and faults could be delineated from satellite and DEM data and that these structures would exhibit a preferential orientation (e.g., northwest-southeast) consistent with regional tectonic controls.

3. It was hypothesized that the locations of the geothermal hot springs in the Tiris area would show a strong spatial association with the delineated faults, confirming that these structures likely act as permeable pathways for the ascent of hot fluids from the subsurface.

By systematically addressing these objectives and testing these hypotheses, this research aims to provide valuable, spatially explicit data that can significantly contribute to the understanding of the Tiris geothermal system and guide future, more targeted exploration efforts.

METHODS

2.1. Research Design

This study employed a quantitative, remote sensing-based research design to investigate the surface characteristics of the Tiris geothermal area. The design was fundamentally cross-sectional, utilizing satellite imagery captured at specific points in time to map and analyze spatial patterns of Land Surface Temperature (LST) and geomorphology. The core of the research design involved the acquisition, processing, and integrated analysis of two primary types of geospatial data: multispectral and thermal imagery from the Landsat-8 satellite, and topographic data from the Digital Elevation Model (DEM) of the Shuttle Radar Topography Mission (SRTM) [39, 74].

The methodology was structured as a multi-step workflow. The first major component focused on thermal analysis. This involved a series of data processing steps to convert the raw satellite data into a meaningful physical parameter, LST. This conversion process is not direct and requires several intermediate calculations, including radiometric correction, calculation of the Normalized Difference Vegetation Index (NDVI) to characterize land cover, estimation of vegetation fraction, and determination of land surface emissivity. Each of these steps was designed to correct for atmospheric and surface-related factors that influence the thermal signal detected by the satellite, thereby ensuring the accuracy of the final LST product.

The second major component of the research design was the geomorphological analysis. This was approached using visual interpretation and delineation techniques applied to specifically processed satellite and DEM data [40]. A 567-band composite of Landsat-8 multispectral imagery was created to enhance the visibility of geological and landform features. This was complemented by the creation of a 3D topographic model from the DEM SRTM data, which provided a perspective view of the landscape, further aiding in the identification of structural lineaments and faults [169, 113]. The design involved comparing the features delineated through this remote sensing approach with existing geological maps to validate the interpretations [112].

The final stage of the research design involved the synthesis and interpretation of the results from both the thermal and geomorphological analyses. This integrative approach aimed to identify spatial correlations between thermal anomalies, land cover types, and geological structures. By overlaying the LST maps with the geomorphological feature maps, the study sought to understand the interplay between surface temperature patterns and the underlying structural framework of the geothermal system. This comprehensive design allowed for a robust investigation that leveraged the strengths of different remote sensing data and techniques to build a multi-layered understanding of the Tiris geothermal area, a task that would be impractical using ground-based methods alone due to the area's challenging characteristics [63, 64].

2.2. Study Area

The research was conducted in the Tiris geothermal area, which is part of the larger Lamongan Volcano Complex, located in the Probolinggo Regency, East Java, Indonesia [23, 46]. The total study area covered an extent of approximately 73 km^2 [37, 76]. The geographical positioning of the study area falls within the 49th Southern Hemisphere zone of the Universal Transverse Mercator (UTM) projection system. The specific coordinates defining the rectangular study area extend from an easting of 755836.00 mE to 765831.00 mE and from a northing of 9122318.00 mS to 9115076.00 mS [77].

For the purpose of focused analysis, the overall study area was subdivided into two primary locations of interest [78]. The first is the Lamongan Volcanic Field (LVF), which encompasses the main volcanic edifice of Mount Lamongan and its immediate surroundings. This area is characterized by a classic volcanic landscape, including the central volcanic cone, parasitic cones, and extensive lava fields. The second location is the Tiris Geothermal Area (TGA), situated to the northeast of the Lamongan Volcano [49]. The TGA is the primary focus for geothermal potential and is defined by the presence of surface manifestations, most notably a series of hot springs that emerge along the Tancak River watershed [48].

The general environment of the Lamongan Volcano Complex is characterized by a steep and rugged terrain, which is a common feature of young volcanic landscapes in Indonesia [60]. The region is also covered by dense tropical vegetation, a factor that presents significant challenges for both direct observation and remote sensing analysis [60]. The geology of the area is dominated by volcanic products, including andesitic lavas from the older Argopuro volcano and more recent lavas from Lamongan itself [54]. The surface is also marked by the presence of numerous maars and cinder cones, which are indicative of past phreatomagmatic and magmatic eruptive activity [57, 58]. These complex geological and environmental conditions underscore the suitability of a remote sensing approach, which allows for consistent data collection and analysis across the entire challenging landscape [63].

2.3. Materials and Apparatus

The primary materials for this research consisted of secondary data in the form of digital satellite imagery and elevation models, which were all obtained from public archives. No primary field data collection was conducted. The specific datasets and the software used for their processing and analysis are detailed below.

Data:

1. Landsat-8 Imagery: The core data for this study were derived from the Landsat-8 satellite, which is operated by the U.S. Geological Survey (USGS). The imagery was downloaded from the USGS EarthExplorer website [102]. The specific scenes used corresponded to path 118 and row 65 of the Worldwide Reference System (WRS-2) [101]. To analyze temporal changes and ensure cloud-free views of the study area, three separate scenes were acquired from different dates in 2018: May 17th, September 28th, and October 30th [103]. The selection of these images was contingent upon low cloud cover, a critical factor for accurate surface analysis. The respective cloud cover percentages for the three dates were 5.26%, 1.11%, and 7.19% [104]. These values are all below the generally accepted threshold of 10% for high-quality satellite acquisition, rendering the data suitable for use [105]. The Landsat-8 satellite carries two main sensors: the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). Data from both sensors were utilized.

○ OLI Bands: For land cover and geomorphological analysis, specific multispectral bands from the OLI sensor were used. Bands 4 (Red, 0.64–0.67 μm) and 5 (Near-Infrared/NIR, 0.85–0.88 μm) were used for calculating the Normalized Difference Vegetation Index (NDVI) [109]. Bands 5 (NIR), 6 (Shortwave Infrared 1/SWIR-1, 1.57–1.65 μm), and 7 (Shortwave Infrared 2/SWIR-2, 2.11–2.29 μm) were used to create the false-color composite for visual delineation of geological structures [111].

○ TIRS Bands: For the Land Surface Temperature (LST) calculation, thermal data from the TIRS sensor were essential. Specifically, Band 10 (TIR-1, 10.60–11.19 μm) and Band 11 (TIR-2, 11.50–12.51 μm) were processed [110].

2. Digital Elevation Model (DEM) SRTM Data: To analyze the topography and aid in geomorphological interpretation, DEM data from the Shuttle Radar Topography Mission (SRTM) were used [101]. The specific dataset utilized was the 2014 version of the SRTM data, which was also downloaded from the USGS website [107]. This dataset provides a digital representation of the Earth's surface topography, which was crucial for creating the 3D models of the study area [113].

Apparatus (Software):

The processing, analysis, and visualization of the geospatial data were conducted using a suite of Geographic Information System (GIS) and remote sensing software. While the specific software is not named in the source text, standard industry and academic tools for such an analysis would include packages like ENVI (Environment for Visualizing Images) for specialized image processing (such as radiometric correction and LST calculation), ArcGIS or QGIS for general GIS operations (data management, map creation, spatial analysis), and potentially a tool like Global Mapper for 3D visualization and hill shading as mentioned in the procedure [175]. These software packages provide the necessary algorithms and tools to perform the complex calculations and visual interpretations required by the study's methodology.

2.4. Experimental Procedure/Data Collection Protocol

The procedure for this study involved a systematic sequence of data processing and analysis steps applied to the raw Landsat-8 and DEM SRTM data. The protocol can be divided into two main workflows: the LST derivation workflow and the geomorphological analysis workflow.

LST Derivation Workflow:

This workflow transformed the raw digital numbers (DN) from the satellite imagery into final LST values in degrees Celsius.

1. Radiometric Correction and Top-of-Atmosphere (ToA) Reflectance: The first crucial step for the OLI bands (4 and 5) was radiometric correction. This process converts the raw DN values, which are unitless, into physically meaningful units of Top-of-Atmosphere (ToA) reflectance. This correction is necessary to minimize errors that arise from variations in sensor illumination and atmospheric conditions at the time of image acquisition [119, 120]. The conversion was performed using the formal equation provided by the USGS [15], which involves band-specific multiplicative and additive rescaling factors (M_rho and A_rho) and a correction for the solar elevation angle (theta_SE) [121, 122].

2. NDVI Calculation: Once the OLI bands were converted to ToA reflectance, the Normalized Difference Vegetation Index (NDVI) was calculated. NDVI is a widely used indicator of the density and health of vegetation [116]. It was computed using the reflectance values from the Red band (rho_red, Band 4) and the NIR band (rho_NIR, Band 5) [125]. The standard formula was applied, where NDVI = (rho_NIR−rho_red)/(rho_NIR+rho_red) [126, 127]. The resulting NDVI values, which range from -1 to +1, were used to classify the land cover of the study area [129].

3. Vegetation Fraction (P_v) Calculation: The NDVI values were then used to calculate the vegetation fraction

(P_v), which represents the proportion of an area covered by green vegetation [131]. This was calculated using an empirical formula that squares the normalized NDVI value: P_v=((NDVI−NDVI_min)/(NDVI_max−NDVI_min))2 [133]. In this equation, NDVI_min and NDVI_max represent the NDVI values corresponding to bare soil and full vegetation cover, respectively [135].

4. Land Surface Emissivity (epsilon) Calculation: Emissivity, a measure of an object's ability to radiate absorbed energy, is a critical parameter for accurate LST calculation [137]. The emissivity for each pixel was estimated using an NDVI-based method [137]. The procedure followed a classification scheme: pixels with very low NDVI (less than 0.2) were classified as bare land with an assumed emissivity (epsilon_s) of 0.98 [140]; pixels with high NDVI (greater than 0.5) were classified as fully vegetated with an emissivity (epsilon_v) of 0.99 [141]; and pixels with intermediate NDVI values (between 0.2 and 0.5) were treated as mixed land. For these mixed pixels, emissivity was calculated as a function of the vegetation fraction (P_v) using the formula epsilon=mP_v+n, where 'm' and 'n' are coefficients derived from the bare soil and vegetation emissivities and a shape factor [142, 144, 145].

5. LST Calculation: The LST calculation itself utilized the thermal bands (10 and 11) from the TIRS sensor.

○ First, the raw DN values of the thermal bands were converted into spectral radiance (L_lambda) using a similar radiometric correction process involving band-specific multiplicative (M_L) and additive (A_L) scaling factors [152, 153].

○ Next, this spectral radiance was converted into brightness temperature (T_censor) in degrees Celsius. This conversion uses the thermal constants (K_1 and K_2) specific to each thermal band, as provided in the satellite's metadata [158, 160]. The formula is based on the Planck radiation law.

○ Finally, the LST was calculated by correcting the brightness temperature for the land surface emissivity calculated in the previous step. This final correction was performed using an equation that incorporates the wavelength of the emitted radiance (lambda), the brightness temperature (T_censor), the land emissivity (epsilon), and several physical constants (Planck's constant 'h', the speed of light 'c', and the Boltzmann constant 'J') [165, 167].

Geomorphological Analysis Workflow:

1. 567 Band Composite Creation: For the structural analysis, a false-color composite image was created using OLI bands 5 (NIR), 6 (SWIR-1), and 7 (SWIR-2) [170]. Before compositing, these bands also underwent radiometric correction to convert DN to radiance, similar to the process described for the LST workflow [171]. This specific band combination is known to be effective for highlighting variations in lithology, soil moisture, and geological structures.

2. DEM SRTM Processing: The DEM SRTM data for the study area were first clipped to the region of interest [175]. To enhance the visualization of topographic features, a dynamic hillshade was applied. This was done by setting a specific light direction, with an altitude of 76 degrees and an azimuth of 323 degrees, which helps to accentuate linear features like ridges and valleys that may correspond to geological structures [175].

3. Visual Delineation and Interpretation: The final step was the visual delineation of geomorphological features [169]. This process involved a skilled interpreter manually drawing lines and polygons on the 567-band composite and the 3D hillshade model to map out lineaments, faults, and maars [40]. The interpretations were guided by characteristic features in the imagery, such as linear tonal variations, straight river segments, and circular depressions. The results of this delineation were then compared with existing geological maps of the area to validate the findings and place them in a known geological context [112, 488].

2.5. Data Analysis Plan

The data analysis plan for this study was structured to systematically interpret the processed remote sensing products and address the core research objectives. The analysis was primarily qualitative and comparative, focusing on the spatial patterns and relationships between the derived datasets.

1. Land Cover Analysis: The first stage of analysis involved interpreting the generated NDVI maps. The study area's land cover was classified into four distinct categories based on ranges of NDVI values: body of water or cloud cover (NDVI < 0.00), bare land (0.00 < NDVI < 0.20), mixed land (0.20 < NDVI < 0.50), and vegetated land (NDVI > 0.50) [183, 184]. The analysis focused on describing the dominant land cover types within the two main sub-regions, the Tiris Geothermal Area (TGA) and the Lamongan Volcanic Field (LVF). Furthermore, the analysis compared the NDVI maps from the three different acquisition dates (May, September, and October 2018) to identify and describe any significant changes in land cover over that period [189, 192].

2. Emissivity Analysis: The emissivity maps, which were derived from the NDVI data, were then analyzed. The analysis described the spatial distribution of emissivity values, which ranged from a low of 0.98 to a high of 0.99 [246]. The plan was to correlate these emissivity values with the land cover classifications, explaining why certain areas, such as vegetated lands, exhibited higher emissivity, while others, like bare land and water bodies, had lower values [249, 251]. This step was crucial for understanding one of the key factors that influences the final LST calculation.

3. Land Surface Temperature (LST) Anomaly Analysis: This formed the core of the thermal investigation. The analysis of the LST maps was multi-faceted.

○ Statistical Summary: The minimum, maximum, and average LST values were calculated for each of the three acquisition dates to provide a quantitative summary of the thermal conditions [260].

○ Spatial Pattern Description: The spatial distribution of LST across the TGA and LVF was described in detail for each date. The analysis focused on identifying "hot spots" or areas with high LST anomalies.

○ Correlation with Land Cover: A key part of the plan was to investigate the nature of these hot spots by correlating their locations with land cover information, aided by visual inspection using tools like Google Earth [265, 269, 461]. The goal was to determine whether high LST was associated with geothermal activity or other factors like urbanization (built-up areas) or exposed soil (bare land) [479].

○ Analysis of Geothermal Manifestations: The LST values at the specific locations of the known hot springs in TGA were extracted and analyzed [266]. The plan was to assess whether these points showed a distinct thermal signature and to interpret the findings, particularly if no anomaly was found, considering environmental factors like the presence of the Tancak River [268, 477].

○ Temporal Comparison: The LST maps from the three dates were compared to identify any trends or significant changes in temperature patterns over the dry season of 2018, and to correlate these changes with any observed changes in land cover [473].

4. Geomorphological and Structural Analysis: The final phase of analysis focused on the geomorphological maps derived from the 567-band composite and the 3D DEM.

○ Feature Identification: The plan involved identifying and describing the key geomorphological features, including lineaments, faults, maars, and maar lakes [485]. The interpretation of colors and patterns in the 567-band composite was used to differentiate land cover types relevant to the structural analysis (e.g., water, vegetation, built-up areas, bare land) [490].

○ Structural Orientation: The orientation or trend of the delineated lineaments and faults was determined and described (e.g., northwest-southeast) [492, 493].

○ Validation and Integration: The delineated features were compared against an existing geological map to validate their location and existence [494].

○ Synthesis with Geothermal Manifestations: The most critical analysis was to overlay the map of delineated structures (faults and lineaments) with the locations of the hot springs. The plan was to analyze the spatial relationship to determine if the emergence of hot springs is controlled by these geological structures, thereby providing evidence for the pathways of geothermal fluid flow [605, 619]. This synthesis aimed to build a conceptual model of the structural controls on the Tiris geothermal system.

RESULTS

3.1. Preliminary Analyses

The preliminary analyses focused on establishing the foundational surface characteristics of the study area, specifically the land cover distribution as represented by the Normalized Difference Vegetation Index (NDVI) and the subsequent derivation of land surface emissivity. These parameters are essential prerequisites for the accurate calculation and interpretation of Land Surface Temperature (LST).

Land Cover (NDVI) Distribution:

The land cover across the 73 km^2 study area was mapped using NDVI values calculated from Landsat-8 imagery for three separate dates: May 17th, September 28th, and October 30th, 2018. The overall NDVI values across all dates ranged from a minimum of -0.08 to a maximum of 0.61 [186]. Based on established classification thresholds [183], the landscape was categorized into four classes: body of water or cloud cover (NDVI < 0.00), bare land (0.00 < NDVI < 0.20), mixed land (0.20 < NDVI < 0.50), and vegetated land (NDVI > 0.50) [184].

The average NDVI values for the three dates were 0.43 (May), 0.39 (September), and 0.33 (October) [197]. This progressive decrease in the average NDVI value suggests a drying trend and a reduction in vegetation vigor as the year progressed from the early dry season towards the peak dry season, which is typical for this climatic region. Despite this trend, the average values indicate that the study area as a whole is predominantly characterized by mixed land, a mosaic of vegetation, soil, and other surface types [187].

Spatially, the land cover distribution showed distinct patterns and changes within the two main sub-regions, the Tiris Geothermal Area (TGA) and the Lamongan Volcanic Field (LVF). In the TGA, there was a noticeable change in land cover over the observation period, particularly in the northeastern portion, where areas of vegetated land appeared to transition into mixed land [189, 190]. The known geothermal manifestations, the hot springs, were consistently located within areas classified as mixed land throughout all three observation dates [191]. In the LVF, land cover changes were even more significant. A considerable transformation from mixed land to a combination of bare land and mixed land was observed, especially in the northern section of the Lamongan Volcano edifice [192, 193]. This indicates a more pronounced loss of vegetation cover in the volcanic field itself compared to the surrounding TGA. Additionally, several bodies of water, identified as maars, were visible in the south of the TGA [194]. The imagery from May and September was also affected by significant cloud cover in the southern part of the LVF, which was classified along with water bodies due to its low NDVI values [195]. Overall, both the TGA and LVF were found to be dominated by mixed land cover [196].

Land Surface Emissivity:

The land surface emissivity, which describes the efficiency of a surface in radiating thermal energy, was calculated based on the NDVI-derived land cover classifications. The emissivity values across the study area were found to be highly varied, with values ranging from a low of 0.98 to a high of 0.99 [246]. This variation is a direct function of the diverse surface cover, composition, moisture content, and roughness of the landscape [244].

The spatial distribution of emissivity was strongly correlated with the land cover map. The highest emissivity value, 0.99, was consistently associated with areas of dense, healthy vegetation, which appeared as dark blue in the emissivity visualizations [249, 250]. This finding is consistent with established literature, which confirms that vegetated land has a very high emissivity [252]. Conversely, the lowest emissivity value, 0.98, was found in and around the maar lakes and other areas of bare or wet land [247, 248]. The areas around the lakes were characterized as bare land, dry land, wet land, and turbid water, all of which have lower emissivity values compared to vegetation [248]. This is also in agreement with reference values, which place the emissivity of wet land between 0.95 and 0.98 and that of water bodies at approximately 0.98 [249, 253]. Therefore, the analysis confirmed a clear distinction in radiative properties between the vegetated and non-vegetated portions of the study area, with vegetated land being a more efficient radiator of thermal energy than bare ground, water, or land with sparse vegetation. This spatially explicit emissivity information was critical for correcting the brightness temperature and deriving an accurate LST.

3.2. Main Findings

The main findings of this research center on the distribution of Land Surface Temperature (LST) and the characterization of the geomorphological structures within the study area. These results provide direct insights into the surface thermal state and the structural framework controlling the geothermal system.

Land Surface Temperature (LST) Distribution:

The LST was calculated for the three acquisition dates, revealing a general warming trend from May to October 2018, consistent with the observed decrease in vegetation cover. The overall LST across the study area and all dates ranged from a minimum of 15.84°C to a maximum of 41.05°C [41]. The average LST increased progressively, with values of 22.74°C in May, 25.81°C in September, and 26.95°C in October [260].

- LST on May 17th, 2018: The LST distribution for this date ranged from 17.90°C to 30.68°C [263]. Within the TGA, several small areas exhibited high LST anomalies. However, upon inspection, these hot spots were identified as built-up areas and patches of bare land, not geothermal manifestations [265]. At the actual locations of the hot springs, the LST was found to be in the range of 23.10°C to 23.27°C [266]. This temperature did not reflect the known high temperatures of the springs themselves but rather appeared to represent the ambient temperature of the Tancak River water in which the springs are located [267, 268]. In the LVF, high LST anomalies were observed to the north and northwest of the Lamongan Volcano, and these were also correlated with areas of bare land [269].

- LST on September 28th, 2018: The LST for this date showed a significant increase, with a range of 16.81°C to 38.26°C [459]. The pattern of high LST anomalies was similar to that in May. In the TGA, hot spots were again associated with built-up areas and bare land [460, 461]. The LST recorded at the hot spring locations had increased to a range of 25.49°C to 25.84°C [462]. This increase was attributed to the altered land cover and reduced water flow in the Tancak watershed during the drier season, rather than a change in the geothermal output [463]. The LST anomaly in the LVF also intensified in the north and northwest, a change linked to the transformation of previously vegetated land into bare and mixed land [465].

- LST on October 30th, 2018: The warming trend continued, with LST ranging from 15.84°C to 41.05°C [466]. The spatial distribution of hot spots remained consistent with the previous months. High LST anomalies in the TGA were once again found in built-up areas and bare lands [467, 468]. The temperature at the hot spring locations increased further, ranging from 26.86°C to 27.78°C, a change again attributed to the evolving land cover and hydrological conditions in the Tancak watershed [469, 470]. The LST anomaly in the LVF showed a significant increase in magnitude and extent, particularly in the north and northeast of the volcano, corresponding directly with areas that had undergone a substantial transformation from mixed land to bare and mixed land combined [471, 472].

A key overarching finding from the LST analysis is that the geothermal manifestations in the Tancak watershed did not produce a clear, high-temperature anomaly in the satellite-derived LST data [476]. The direct contact and mixing of the hot spring water with the flowing river water effectively masks the thermal signature, resulting in a measured temperature that is a mixture of the two [478]. The most significant thermal effects observed at the surface were not from geothermal heat but from solar heating of specific land cover types. In accordance with findings from other studies [481, 20], built-up areas and bare land consistently showed higher LST due to their low vegetation cover and high thermal absorption [479].

Geomorphological Findings:

The geomorphological analysis, conducted through visual delineation of a 567-band composite image and a 3D DEM model, successfully identified several crucial structural and volcanic features.

- Lineaments: Two major lineaments were identified passing through the main body of the Lamongan Volcano [492]. One lineament trends northwest-southeast, while the second trends northwest-east [617, 606]. These linear features, interpreted as the surface expression of deep-seated geological structures, appear to control the overall morphology of the volcanic edifice. The identification of these lineaments is consistent with previous research that has also noted structural controls in the region [608].

- Faults: A significant fault was identified in the northeastern part of the study area, within the TGA [493]. This fault is clearly oriented in a northwest-southeast direction and is spatially associated with the Tancak watershed [493, 618]. The most critical finding of the geomorphological analysis is that the known geothermal hot springs are located along or very near this fault [604, 605]. This strong spatial correlation strongly suggests that this fault acts as a primary structural control, providing a permeable pathway for geothermal fluids to ascend from the subsurface reservoir and emerge at the surface as hot springs [619]. The characteristics of this fault, as delineated from the remote sensing data, showed a strong similarity to the geological information presented on existing maps of the area [494].

- Maars and Maar Lakes: The analysis also clearly identified several maars and maar lakes, which appeared as distinct dark, circular features in the 567-band composite [491]. These features were found to be predominantly distributed in a zone that extends from the southeast to the northwest of the main volcanic field [602, 619]. This alignment is sub-parallel to the major fault and lineament trends, suggesting that their formation may also be influenced by the same regional structural grain.

In summary, the main findings reveal a landscape where surface temperatures are primarily dictated by land cover type and solar radiation, with geothermal heat signatures being localized and masked by surface water. However, the underlying geomorphology reveals a clear structural framework of faults and lineaments that directly controls the location of the geothermal manifestations, providing a critical piece of information for understanding and exploring the Tiris geothermal system.

3.3. Secondary or Exploratory Findings

Beyond the primary results concerning LST and major structures, the integrated analysis revealed several secondary findings that add further nuance to the understanding of the Tiris geothermal area and the methodologies used.

One notable exploratory finding is the dynamic relationship between land cover, seasonality, and surface temperature. The comparison of data across the three dates in 2018 (May, September, October) provided a snapshot of the environmental dynamics during the dry season. The progressive decrease in the average NDVI [197] and the corresponding increase in average and maximum LST [260] quantitatively demonstrate the impact of seasonal drying on the landscape's thermal properties. The transformation of vegetated and mixed land to bare land, particularly in the LVF, had a direct and measurable effect on increasing LST [465, 472]. This highlights that in a tropical volcanic environment, temporal LST analysis must be carefully interpreted in the context of seasonal vegetation changes. A single-date LST map could be misleading without this context, as thermal anomalies could be transient features related to land cover change rather than stable geothermal heat flow.

Another secondary finding relates to the interpretation of lineaments. While the study successfully identified major lineaments on the Lamongan Volcano body [492], the direct connection between these specific lineaments and surface geothermal manifestations like fumaroles or hot rocks on the volcano itself remains unanalyzed [609]. The study confirmed that lineaments are often interpreted as weak zones that can channel hot fluids, a concept supported by the work of Sukendar et al. [11, 610]. However, the manifestations in the study area are located in the distal TGA, controlled by a specific fault, not on the volcano's main body along the delineated lineaments. This suggests a more complex plumbing system where the heat source is beneath the volcano, but the fluids migrate laterally along permeable structures, such as the identified northwest-southeast fault, to emerge several kilometers away in the Tiris area. This finding implies that in exploration, it is crucial to look for manifestations not just on a volcanic edifice itself but also along distal faults that may be structurally connected to the magmatic heat source.

Furthermore, the study implicitly demonstrates the power of specific band combinations in multispectral analysis. The use of the 567-band composite (SWIR-2, SWIR-1, NIR) was highly effective not only for structural delineation but also for land cover discrimination in a way that supported the LST interpretation [490]. For example, this composite clearly differentiated built-up areas and bare lands (which showed high LST) from vegetated land and water bodies (which showed low LST) [490]. This reinforces the idea that an integrated approach, where the results of one analysis (multispectral composites) inform the interpretation of another (thermal analysis), yields a more robust and reliable outcome than either method used in isolation. The visual clarity provided by the 567 composite was essential for correctly attributing the cause of the observed hot spots to land cover rather than mistakenly interpreting them as direct geothermal anomalies.

Finally, the distribution pattern of the maars and maar lakes, trending from southeast to northwest [602], serves as an additional piece of corroborating evidence for the orientation of the dominant regional stress field and its resulting structures. The alignment of these volcanic vents sub-parallel to the main Tiris fault and the Lamongan lineaments suggests a deep-seated structural control that has governed not only the recent pathways for geothermal fluids but also the ascent of magma during past phreatomagmatic eruptions. This provides a cohesive picture where multiple distinct geological phenomena—faulting, fluid flow, and volcanism—are all governed by the same underlying tectonic framework.

DISCUSSION

4.1. Interpretation of Key Findings

The results of this study provide a multi-layered perspective on the surface expression of the Tiris geothermal system, yielding several key interpretations. The most significant finding is the apparent paradox between the known geothermal potential of Tiris and the satellite-derived Land Surface Temperature (LST) map. While geothermal manifestations in the form of hot springs with temperatures up to 45°C are present [50], the LST analysis did not identify a corresponding high-temperature anomaly at these locations [43]. The LST values recorded at the spring sites were only moderately elevated above the background and were significantly lower than the true spring temperatures [266, 462, 469]. This discrepancy can be confidently interpreted as a result of "thermal masking" by surface hydrological processes. The hot springs emerge directly within the Tancak watershed, and their thermal output is immediately mixed with and diluted by the cooler, flowing water of the river [268, 478]. The Landsat-8 TIRS sensor, with its 100-meter spatial resolution (resampled to 30 meters), captures an integrated temperature over a relatively large pixel area. Consequently, the sensor does not measure the point-source temperature of the spring vent but rather an averaged temperature of the water, wet sediment, and surrounding vegetation within that pixel. This finding is critically important for geothermal exploration using remote sensing in tropical, water-rich environments. It demonstrates that the absence of a strong LST anomaly at a known manifestation site does not necessarily negate the existence of a geothermal resource; instead, it highlights the need to consider confounding environmental factors, particularly the presence of rivers or dense vegetation canopies.

In contrast, the highest LST anomalies were consistently detected in areas of bare land and built-up areas [42, 614]. This finding is not indicative of subsurface geothermal heat but is a direct consequence of solar insolation and the thermal properties of different land cover types. Bare soil and artificial surfaces like asphalt and roofing materials have lower albedo (reflect less solar radiation) and lower thermal inertia compared to vegetated surfaces. They absorb a greater amount of solar energy and heat up more rapidly, leading to significantly higher surface temperatures during the day when the satellite passes over. This interpretation is strongly supported by numerous studies, including the work of Uddin et al. [20], which noted that built-up and revitalized lands create higher thermal effects due to minimal vegetation cover [481], and Mia et al. [17], which confirmed that bare land is more thermally active than vegetated land [483]. This interpretation underscores a fundamental principle of LST-based geothermal exploration: it is imperative to first account for land cover-induced thermal variations before attributing any remaining anomalies to geothermal sources. In the Tiris case, the dominant thermal patterns were overwhelmingly controlled by solar heating of the surface, not by geothermal heating from below.

The geomorphological findings provide a much more direct and interpretable link to the geothermal system. The delineation of a major fault trending northwest-southeast through the TGA, with the hot springs emerging along its trace, is the most compelling piece of evidence from the study [493, 605]. This spatial association is the classic expression of a structurally controlled geothermal system. The fault acts as a zone of enhanced permeability, a natural conduit that allows the hot, buoyant geothermal fluids to ascend from the deep reservoir towards the surface [55]. The identification of two major lineaments on the main volcanic edifice of Lamongan with similar orientations suggests that this fault is not an isolated feature but part of a larger regional structural system [492, 606]. This interpretation aligns with previous assertions that the Tiris geothermal area is regionally controlled by northwest-southeast and north-south structures [52]. The fact that these structures can be clearly identified using remote sensing techniques, even in a challenging, vegetated landscape, validates the method's utility for structural mapping. The alignment of the maars along a similar southeast-northwest trend further strengthens this interpretation, suggesting a deep-seated structural grain that has controlled both magmatic and hydrothermal activity over time [59, 602]. Therefore, the study interprets the Tiris geothermal system as one where the heat source is likely located beneath the main Lamongan Volcanic Field, and the geothermal fluids migrate laterally through a permeable, northwest-southeast-trending fault zone to emerge several kilometers away at the surface in the Tancak watershed.

4.2. Comparison with Previous Literature

The findings of this study both corroborate and build upon the body of existing literature related to the Lamongan geothermal area and the application of remote sensing in geothermal exploration. The geothermal potential of the Tiris area, estimated at 74-147 MWe by the Directorate of Indonesian Geothermal [2], provided the foundational context for this research [47]. The geochemical study by Deon et al. [3] had previously confirmed the geothermal nature of the Tiris hot springs through hydrochemical analysis but also noted the difficulties in conventional mapping [62], a challenge that this study sought to overcome using remote sensing. The results presented here align with their conclusion of a viable geothermal system but provide new, spatially explicit data on its structural controls.

This study's application of remote sensing techniques follows a methodological lineage established by numerous researchers in Indonesia and abroad. The general approach of using Landsat data to map LST and geological structures for geothermal purposes has been validated by works such as those by Azhari et al. [12] in the Blawan field and Bakruddin and Utama [13] in the Arjuno-Welirang field. The current research confirms the effectiveness of these methods in the specific context of the Lamongan complex. The finding that high LST anomalies were associated with bare land and built-up areas, rather than geothermal manifestations, is highly consistent with similar observations in other geothermal fields. For example, Mia et al. [17, 18] in their studies of the Aso volcano in Japan, and Qin et al. [16] in Tengchong, China, also had to carefully differentiate between solar-induced and geothermal-induced thermal anomalies, often using land cover analysis as the primary tool for this differentiation. This study's results reinforce the universal nature of this challenge in LST-based exploration.

The geomorphological findings, in particular, show a strong consistency with prior work. The northwest-southeast structural trend identified as the primary control on the Tiris hot springs [618] aligns perfectly with the regional structures mentioned in earlier reports [52] and the fault interpretations in the geological map by Suharsono and Surwati [21]. An early remote sensing study by Utama et al. [10], which used older Landsat ETM+ data, had also successfully indicated lineaments on the Lamongan Volcano and faults in TGA [608]. The present study, using the more advanced sensors of Landsat-8 and integrating 3D DEM analysis, has refined these initial findings, providing a clearer depiction of these structures and strengthening the interpretation of their control over the hot springs. The concept that areas with high lineament density represent weak zones favorable for fluid flow, as proposed by Sukendar et al. [11] for the Mount Salak area, is directly applicable to the Tiris fault zone [610]. This study provides a concrete example of this principle, where a distinct fault, rather than just a zone of high lineament density, is the primary controlling feature.

Furthermore, the choice of methodology, including the specific formulas for radiometric correction [122], NDVI [127], vegetation fraction [133], and LST calculation [165], were all based on well-established and peer-reviewed methods from the remote sensing literature [15, 16, 17, 18]. The use of the 567-band composite for enhancing geological features is also a standard technique, supported by literature such as Putri and Purwanto [6]. By employing these standard, validated techniques, the study ensures that its results are comparable to and consistent with the broader body of scientific work in this field. The unique contribution of this research lies in applying this integrated suite of modern techniques specifically to the Tiris area and demonstrating how the interplay of LST, land cover, and geomorphology can be decoded to reveal the nature of its geothermal system, particularly the critical insight into the thermal masking effect of the river.

4.3. Strengths and Limitations of the Study

This study possesses several notable strengths that enhance the validity and utility of its findings. The primary strength lies in its use of an integrated, multi-faceted remote sensing approach. By combining the analysis of Land Surface Temperature (LST), land cover (NDVI), and geomorphology (from multispectral composites and DEM data), the study provides a more comprehensive and robust interpretation than could be achieved with any single method. This synergy allowed for the crucial differentiation between solar-induced thermal anomalies and the masked geothermal signatures, a key insight of the research. Another significant strength is the cost-effectiveness and efficiency of the methodology. It allowed for the detailed investigation of a large and logistically challenging 73 km^2 area [37] without the need for extensive and expensive fieldwork, which is particularly advantageous for preliminary exploration in remote regions like the Lamongan Volcano Complex [64]. The use of freely available Landsat-8 and SRTM data further enhances the accessibility and replicability of this approach [102]. The analysis also benefited from using multiple Landsat-8 scenes from different dates [103], which enabled a temporal assessment of LST and land cover, revealing seasonal dynamics that would have been missed in a single-date analysis. This added a layer of dynamism to the understanding of the surface thermal environment. Finally, the validation of the delineated geomorphological features against existing geological maps [494] lends credibility to the structural interpretations, grounding the remote sensing results in established geological knowledge.

Despite these strengths, the study is subject to several limitations inherent to the remote sensing techniques employed. The most significant limitation is the spatial resolution of the Landsat-8 thermal sensor. Although processed to 30 meters, the native resolution is 100 meters, which is relatively coarse. This coarse resolution is the primary reason for the thermal masking effect, as it prevents the detection of small, point-source thermal features like individual hot spring vents and instead averages the temperature over a large area [477]. High-resolution thermal imagery from airborne or drone-based sensors would be required to overcome this limitation and accurately map the true thermal expression of the springs. A second limitation is that remote sensing is a purely surface-based investigation technique. It can detect surface temperature and infer the presence of subsurface structures from their surface expression, but it cannot directly measure subsurface temperatures, reservoir characteristics, or fluid chemistry. The interpretations regarding the geothermal system's "plumbing" are therefore inferential and require confirmation through geophysical methods (like resistivity or seismic surveys) and exploratory drilling. The accuracy of the LST calculations is also dependent on several assumptions, such as the emissivity values assigned to different land cover types [140, 141], and is susceptible to atmospheric interference that may not be perfectly corrected by standard algorithms. Lastly, cloud cover is a persistent issue in tropical regions like Indonesia [104]; while low-cloud-cover images were selected, residual haze or thin clouds could still affect the accuracy of the derived surface reflectance and temperature values.

4.4. Implications for Theory and Practice

The findings of this study have several important implications for both the theoretical understanding of volcanic geothermal systems and the practical application of remote sensing in geothermal exploration.

Implications for Theory:

Theoretically, this study reinforces the model of structurally controlled geothermal systems in volcanic arcs. It provides a clear case study where a distal fault system, rather than structures on the central volcanic edifice, acts as the primary conduit for fluids to reach the surface. This highlights the importance of considering the broader regional tectonic framework and not just the immediate volcanic center when conceptualizing the architecture of a geothermal field. The observed thermal masking effect also contributes to the theoretical understanding of how surface processes can obscure the thermal expression of a subsurface system. It adds a crucial environmental caveat to the theory that geothermal activity should always be accompanied by a surface LST anomaly, suggesting that in humid, tropical, and fluvial environments, hydrological signatures can dominate over geothermal ones in coarse-resolution thermal data. This implies that conceptual models of geothermal manifestation should explicitly include the potential for masking by surface water bodies and dense vegetation canopies.

Implications for Practice:

From a practical standpoint, this research has direct implications for geothermal exploration strategies, particularly in Indonesia and other similar tropical volcanic regions.

1. Exploration Targeting: The study demonstrates that in the Tiris area, targeting exploration efforts based on LST anomalies alone would be misleading, as it would direct attention towards built-up areas and bare land rather than the actual resource [614]. Instead, the most reliable surface indicator identified through remote sensing was the northwest-southeast trending fault associated with the hot springs [619]. Therefore, the practical recommendation for future exploration in this area, and others like it, is to prioritize structural mapping. Exploration teams should focus on identifying and tracing major fault and fracture systems, as these are the most likely conduits for geothermal fluids.

2. Methodological Workflow: The study validates a specific workflow for remote sensing analysis that can be adopted as a best-practice template for preliminary geothermal surveys. This workflow emphasizes the necessity of first conducting a thorough land cover analysis (e.g., via NDVI) to understand its influence on LST before making any geothermal interpretations. The integration of multispectral structural analysis with thermal analysis is shown to be not just beneficial but essential for avoiding erroneous conclusions.

3. Recognizing Limitations: The research serves as a practical reminder to exploration geoscientists of the limitations of satellite-based LST data. Practitioners must be aware of the spatial resolution of their data and the potential for thermal masking. This implies that when known manifestations exist but do not appear as thermal anomalies, they should not be dismissed. Instead, it should trigger a more detailed, ground-based investigation, possibly including geochemical sampling and ground temperature surveys, to confirm the resource.

4. Cost-Effective Reconnaissance: This study confirms that remote sensing is an invaluable tool for low-cost, rapid reconnaissance of large, inaccessible areas. It can efficiently narrow down a large concession area to a few high-priority targets (e.g., specific fault zones) for more expensive ground-based geophysical and geological surveys, thus optimizing exploration budgets and timelines.

4.5. Conclusion and Future Research Directions

Conclusion:

This research successfully demonstrated the capability of an integrated remote sensing methodology to map the Land Surface Temperature distribution and geomorphological conditions of the Tiris geothermal area. The study concluded that LST in the area ranged from 15.84°C to 41.05°C, with the highest thermal anomalies being primarily linked to solar heating of built-up areas and bare land, not direct geothermal outflows [613, 614]. The thermal signature of the hot spring manifestations was found to be masked by the hydrological influence of the Tancak River. The geomorphological analysis provided the most direct evidence of the geothermal system's controls, identifying two primary lineaments on the Lamongan Volcano and, most critically, a northwest-southeast oriented fault that is spatially associated with and controls the emergence of the Tiris hot springs [616, 617, 618, 619]. This fault appears to be the primary permeable structure channeling fluids from the deeper heat source. Ultimately, the study confirms that while LST analysis is a useful tool, it must be interpreted with caution in tropical environments, and that structural delineation via remote sensing is a more robust indicator for targeting exploration in structurally controlled geothermal systems like Tiris.

Future Research Directions:

Based on the findings and limitations of this study, several avenues for future research can be proposed to further advance the understanding of the Tiris geothermal system.

1. High-Resolution Thermal Imaging: To overcome the thermal masking effect and spatial resolution limitations, future work should involve the acquisition of high-resolution thermal data using an airborne or drone-based platform. This would allow for the precise mapping of thermal anomalies at the sub-meter scale, potentially revealing the true temperature and extent of the hot springs and possibly identifying other, more subtle areas of thermal leakage (e.g., diffuse soil gas vents) that are invisible to satellite sensors.

2. Integration with Geophysical Surveys: The structural model proposed in this study is based on surface expression. To validate and refine this model, it should be integrated with subsurface data from ground-based geophysical surveys. Methods such as Magnetotellurics (MT) or Electrical Resistivity Tomography (ERT) could be

used to map the resistivity structure of the subsurface, which can help to delineate the geothermal reservoir, identify fluid-filled fault zones, and trace the geothermal fluid pathways at depth.

3. Detailed Geochemical and Isotopic Analysis: While previous geochemical work has been done [3], a more detailed study of the hot spring fluids could provide further insights. Isotopic analysis (e.g., of oxygen and hydrogen) could help determine the origin and recharge sources of the geothermal water, while geothermometry based on solute or gas chemistry could be used to estimate the temperature of the deep reservoir.

4. InSAR for Surface Deformation: The application of Interferometric Synthetic Aperture Radar (InSAR) could be used to monitor for subtle ground surface deformation (uplift or subsidence) over the Lamongan-Tiris area. Such deformation can be associated with the movement of magma or changes in pressure within the geothermal reservoir, providing another layer of data for monitoring the dynamic state of the volcanic-hydrothermal system.

5. Comparative Studies: Applying the same integrated remote sensing methodology to other volcanic geothermal prospects in East Java would allow for comparative analysis. This could help to identify common structural and thermal signatures associated with productive systems in the region, leading to the development of a more refined exploration model for the entire volcanic province.

REFERENCES

[1] Environment Service of East Java Province. (2016). Environmental Management Performance Information of East Java Province Year 2016. Surabaya, Indonesia. http://jatimprov.go.id/read/materi/informasi-kinerja-pengelolaan-lingkungan-hidup-daerah-provinsi-jawa-timur-tahun-2016, accesed on May 6, 2018.

[2] Directorate of Indonesian Geothermal. (2017). Potential Geothermal Indonesia Vol. 1. Ministry of Energy and Mineral Resources, Jakarta. https://ebtke.esdm.go.id/post/2017/09/25/1751/buku.potensi.panas.bumi.2017, accesed on Jan. 28, 2018.

[3] Deon, F., Förster, H.J., Brehme, M., Wiegand, B., Scheytt, C., Moeck, I., Jaya, M. S., Putriatni, D.J. (2015). Geochemical/hydrochemical evaluation of the geothermal potential of the Lamongan volcanic field (Eastern Java, Indonesia). Geothermal Energy, 3(1): 20. http://dx.doi.org/10.1186/s40517-015-0040-6

[4] Carn, S.A. (2000). The Lamongan volcanic field, East Java, Indonesia: Physical volcanology, historic activity and hazards. Journal of Volcanology and Geothermal Research, 95(1-4): 81-108. http://dx.doi.org/10.1016/S0377-0273(99)00114-6

[5] Roy, D.P., Wulder, M.A., Loveland, T.R., Woodcock, C.E., Allen, R.G. (2014). Landsat-8: Science and product vision for terrestrial global change research. Remote Sensing of Environment, 145: 154-172. http://dx.doi.org/10.1016/j.rse.2014.02.001

[6] Putri, C.A.S., Purwanto, T.H. (2015). Interpretation of geological structure and lithology by landsat 8 and SRTM imagery in rembang district and its surrounding. Jurnal Bumi Indonesia, 4(3). http://lib.geo.ugm.ac.id/ojs/index.php/jbi/article/view/354/0, accesed on May 7, 2019.

[7] Juniarti, E., Maryanto, S., Susilo, A. (2017). Temperatures surface mapping of Wurung crater area, Bondowoso regency, east java in determination geothermal manifestations. Natural B, 4(1): 65-72. http://dx.doi.org/10.21776/ub.natural-b.2017.004.01.9

[8] Astisiasari, Hizbaron, D.R., Setiawan, M.A. (2020) Estimation of land surface temperature in Dieng volcanic complex using tir-based satellite imageries. IOP Conf. Series: Earth and Environmental Science, 451: 012066. http://dx.doi.org/10.1088/1755-1315/451/1/012066

[9] Soenarmo, S.H. (2009). Remote Sensing and Introduction to Geographical Information Systems for Earth Science, First Edition. Penerbit ITB, Bandung.

[10] Utama, W., Riski, S., Bahri, A.S., Warnna, D.D. (2012). ETM+ landsat image analysis for preliminary study of geothermal potential area determination at mount lamongan, tiris, probolinggo. Jurnal Fisika dan Aplikasinya, 8(1): 120103. http://dx.doi.org/10.12962/j24604682.v8i1.858

[11] Sukendar, P.M., Sasmito, B., Wijaya, A.P. (2016). Analysis of mount salak geothermal potential area distribution with surface temperature, vegetation, and geomorphology index. Jurnal Geodesi Undip, 5(2): 66-75.

[12] Azhari, A.P., Maryanto, S., Rachmansyah, A. (2016). Identification of geological structure and its effect on land surface temperature based on Landsat-8 data on the Blawan geothermal field. Jurnal Penginderaan Jauh dan Pengolahan Data Citra Digital, 13(1): 1-11. http://dx.doi.org/10.30536/j.pjpded.2016.v13.a2557

[13] Bakruddin, W.D., Utama, W. (2016). Use of Landsat-8 satellite imagery for fault analysis in the arjuno welirang geothermal field, East Java Province. Proceedings of the National Seminar on Infrastructure Technology Application Region IX (ATPW), Surabaya, pp. I-37–I-44. https://www.researchgate.net/publication/306357964, accesed on Dec. 20, 2018.

[14] Danoedoro, P. (2012). Introduction to Digital Remote Sensing, First Editon. Penerbit Andi, Yogyakarta.

[15] USGS. (2016). Department of the Interior U.S. Geological Survey. Vol. 8.

[16] Qin, Q., Zhang, N., Nan, P., Chai, L. (2011). Geothermal area detection using Landsat ETM+ thermal infrared data and its mechanistic analysis-A case study in Tengchong, China. International Journal of Applied Earth Observation

and Geoinformation, 13(4): 552-559. http://dx.doi.org/10.1016/j.jag.2011.02.005

[17] Mia, M.B., Nishijima, J., Fujimitsu, Y. (2014). Exploration and monitoring geothermal activity using Landsat ETM+ images: A case study at Aso volcanic area in Japan. Journal of Volcanology and Geothermal Research, 275: 14-21. http://dx.doi.org/10.1016/j.jvolgeores.2014.02.008

[18] Mia, M.B., Fujimitsu, Y., Nishijima, J. (2017). Thermal activity monitoring of an active volcano using landsat 8/OLI-TIRS sensor images: A case study at the aso volcanic area in southwest Japan. Geosciences, 7(4): 118. http://dx.doi.org/10.3390/geosciences7040118

[19] Lillesand, T.M., Kiefer R.W., Chipman, J.W. (2004). Remote Sensing and Image Interpretation, (5 th ed.). John Wiley & Sons, USA.

[20] Uddin, S., Al Ghadban, A.N., Al Dousari, A., Al Murad, M., Al Shamroukh, D. (2010). A remote sensing classification for land-cover changes and micro-climate in Kuwait. International Journal of Sustainable Development and Planning, 5(4): 367-377. http://dx.doi.org/10.2495/SDP-V5-N4-367-377

[21] Suharsono, Surwati, T. (1992). Geological Map of The Probolinggo Quadrangle, Jawa (1:100.000). Geological Research and Development Centre, Bandung, Indonesia.