

REMOTE SENSING-BASED ESTIMATION OF LAND SURFACE EMISSIVITY (LSE) IN A VOLCANIC CRATER ENVIRONMENT: THE CASE STUDY OF SAINT ANA LAKE

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ABSTRACT:

This study examines land surface emissivity (LSE) variability within the Saint Ana volcanic crater, part of the Ciomad volcanic complex in the Eastern Carpathians. Using Landsat 9 OLI-2/TIRS-2 data, emissivity was estimated through a vegetation-index-based approach to evaluate spatial relationships between lithology, vegetation density, and surface radiative properties. The analysis reveals measurable emissivity contrasts between densely forested crater slopes and exposed volcanic substrates dominated by silicate-rich materials. Lower emissivity values are associated with rocky outcrops and sparsely vegetated areas, whereas higher values correspond to vegetated and moisture-retaining surfaces. The results confirm the sensitivity of emissivity retrieval to geological and ecological controls and support its relevance for thermal characterization in heterogeneous volcanic environments.

1. INTRODUCTION

1.1 General information about the studied area

Saint Ana Lake is located within the Ciomad volcanic complex in the Eastern Carpathians (Figure 1), Romania, at approximately 46°07'35"N latitude and 25°53'13"E longitude E (WGS84), at an altitude of about 946 m above sea level.

Past geophysical and geochronological studies indicate that the Ciomad volcanic system remains potentially active, despite the absence of recent eruptions. Zircon geochronology and petrological analyses suggest that magma may still be present in a partially molten state beneath the volcanic edifice (Harangi et al., 2015).

Also, seismic tomography investigations have identified a low-velocity anomaly beneath the Ciomad complex, interpreted as a potential magma storage region or a zone of elevated temperature within the crust (Popa et al., 2012).

Recent comparative analyses of European volcanic systems previously classified as extinct indicate that several of these structures may still retain magmatic potential. In the case of Ciomad, the presence of long-lived magma and delayed eruptive behavior has been documented, suggesting that volcanic reactivation cannot be excluded (Harangi et al., 2015).

For many years, the Ciomatu–Puturosu Massif was regarded as an extinct volcanic structure, with Lake Saint Ana forming inside its crater and later becoming an important tourist destination in Harghita County. Earlier estimates placed the volcano's last eruption at approximately 30,000 years ago.

However, more recent research proposes a significantly later eruption, around 9,800 years ago. Additionally, new studies conducted by specialists from several European countries indicate signs of renewed internal volcanic activity.

Although no direct evidence of current eruptive activity exists, multiple geophysical and geochemical indicators suggest that the Ciomad volcanic system should be considered dormant, with ongoing subsurface processes.

1.2 Institutional and Conservation Framework of the region

According to the Management Plan of the ROSCI0248 Tinovul Mohoş – Lake Saint Ana site as showed in Figure 2 (approved on 14 November 2017), the Site of Community Importance (SCI) ROSCI0248 Tinovul Mohoş – Lake Saint Ana was designated under Order no. 1964/2007 of the Minister of Environment and Sustainable Development concerning the establishment of the protected status of Sites of Community Importance.



Figure 1. a) Saint Ana Lake (tinutulapelor.ro) / b) Lake view (zenivers.ro)

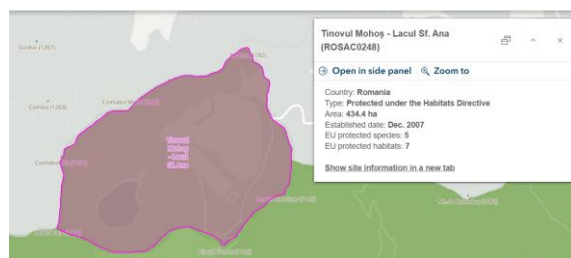


Figure 2. ROSCI0248 site (Natura2000.eea.europa.eu)

The designation was subsequently amended by Order no. 2387/2011 of the Minister of Environment and Forests.

The ROSCI0248 site covers a total surface area of 434.41 hectares and fully overlaps with two legally protected natural reserves: the Lake Saint Ana Natural Reserve (code 2486) and the Moho peat bog Natural Reserve (code 2487). The Lake Saint Ana reserve is classified as a mixed protected area (botanical, geological and landscape value) and extends over 201.38 hectares. It is entirely included within the boundaries of the ROSCI0248 Natura 2000 site. This institutional framework ensures the conservation of both the volcanic geomorphological features and the associated peatland ecosystems characteristic of the Ciomad volcanic complex.

1.3 Geomorphology and topography

The geomorphology of the area is dominantly volcanic and reflects the late-stage evolution of a stratovolcano edifice shaped by explosive eruptive processes and subsequent gravitational reworking. The lake basin is circular to slightly elliptical in plan view and is enclosed by a continuous crater rim with steep inner slopes and more gently inclined outer flanks. The crater diameter is approximately 950–1,000 m (Figure 3), while the lake itself covers roughly 0.19 km². The inner crater walls descend sharply toward the lake surface, indicating limited erosional degradation and preservation of the original explosive morphology. The relatively symmetrical geometry of the depression suggests formation during a high-energy eruptive phase, most likely involving phreatomagmatic or sub-Plinian activity (Figure 4).

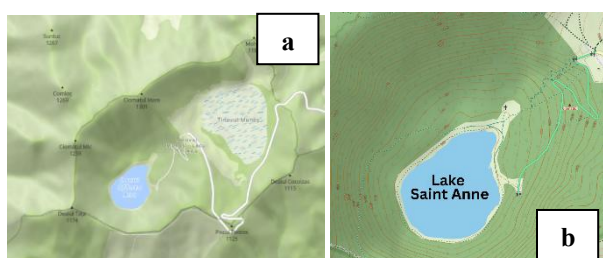


Figure 3. a) Topographic map of the area; b) Detailed view (OpenStreetMap)

The crater rim rises prominently above the lake surface, reaching elevations of approximately 1,300–1,400 m a.s.l., while the lake surface lies at about 946 m a.s.l. This pronounced relative relief enhances the enclosed character of the basin and contributes to its hydrological isolation. The slopes surrounding the lake are mantled by pyroclastic deposits, volcanic breccias, and lahar-derived materials, which locally display hummocky microrelief and evidence of gravitational mass movement.



Figure 4. 3D geomorphological representation of the Saint Ana – Ciomad volcanic system (Bing Maps)

The broader landscape of the Ciomad complex is characterized by dome-shaped volcanic structures, radial valleys, and dissected volcanic slopes. The surrounding terrain exhibits moderate to strong relief energy, with incision controlled by structural discontinuities and lithological contrasts between massive andesitic lava bodies and more erodible volcanoclastic units (Karátson et al., 2013; Seghedi et al., 2004).

The Saint Ana basin is a closed depression with no surface outflow, functioning as an endorheic system. Its morphology permit water retention, with precipitation and minor groundwater contributions serving as the primary hydrological inputs. The absence of fluvial breaching of the crater rim confirms both the structural integrity of the volcanic edifice and the relatively young geomorphological age of the system.

Overall, the morphology of the Saint Ana Lake area reflects the interaction between explosive volcanic construction, crater preservation, gravitational reworking of pyroclastic materials, and limited post-volcanic erosion. The result is a distinctive circular volcanic landform that represents the best-preserved crater morphology within the Harghita volcanic chain and the only crater lake in Romania (Karátson et al., 2013; Harangi et al., 2015). The well-preserved morphology of the Saint Ana crater further supports its relatively young geological age and limited erosional degradation, consistent with recent volcanic activity within the Late Pleistocene–Holocene interval (Karátson et al., 2013; Harangi et al., 2015).

1.4 Geological setting

The Ciomad volcanic complex (Figure 5), the latest and southern volcanic center of the Harghita Mountains in the Eastern Carpathians, has Saint Ana Lake inside one of its twin craters. The Neogene–Quaternary volcanic alignment that formed along the inner edge of the Carpathian arc and represents the last phases of post-collisional magmatic activity within the Carpathian–Pannonian region includes the South Harghita range.

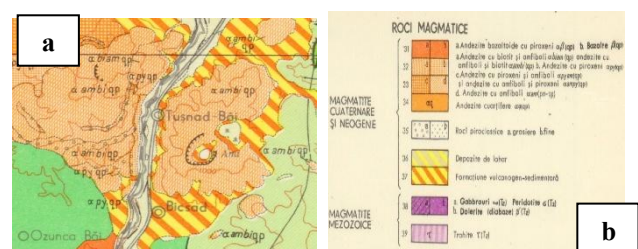


Figure 5. a) Geological map, b) Lithology (Romanian Geological Institute)

The volcanic structure surrounding Saint Ana Lake is primarily made up of amphibole–pyroxene andesites, which correlate to huge lava flows and extrusive bodies associated to domes, according to the geological map. These rocks, which make up the

structural core of the Ciomad complex (Figure 6), document the calc-alkaline magmatism characteristic of volcanic systems impacted by subduction.

Dome morphology and eruptive behavior are largely controlled by lava cooling and solidification processes (Zimbelman et al. 2000). Highly viscous Peléan domes may grow through extrusion and spreading but are also prone to gravitational collapse, producing block-and-ash flows, as documented at Mount Pelée, Unzen, and Puy-de-Dôme. Final dome geometry depends on multiple interacting factors, including magma composition, viscosity, yield strength, effusion rate, eruption duration, dome thickness, crystal and volatile content, cooling rate, and the inclination of the substrate (de Silva et al. 1994; Anderson et al. 1995; Fink and Bridges 1995; Stasiuk and Jaupart 1997; Watts et al. 2002; Lyman et al. 2004; Hale and Wadge 2008). The 1980–1986 dacitic dome growth at Mount St. Helens illustrates that similar magma composition can generate different dome morphologies, emphasizing that geochemistry alone does not determine final form (Zimbelman et al. 2000). Volcanic dome morphology results from complex interactions between magma rheology, extrusion dynamics, and cooling conditions. Rather than representing uniform edifices, lava domes display substantial variability in geometry and surface texture, ranging from compact, steep-sided structures to elongated coulées. This variability reflects differences in magma viscosity, crystallinity, volatile content, and effusion rate.

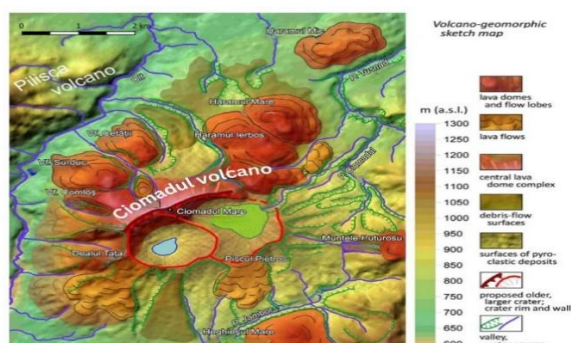


Figure 6. Ciomadul volcano sketch map (Karatson et al. 2013, Morphometrical and geochronological constraints on the youngest eruptive activity in East-Central Europe at the Ciomadul lava dome complex, East Carpathians)

Based on the height-to-diameter (H/D) ratio, Blake (1990) distinguished four dome types—upheaved plug, Peléan dome, coulée, and low dome—interpreted as reflecting progressively decreasing lava yield strength. Later refinements introduced additional morphological variants, including the lobate dome and the platy dome, the latter characterized by a fractured, plate-like surface texture (Fink and Griffiths 1998; Fink and Anderson 2000).

Seismic tomography studies indicate the presence of a vertically extended low-velocity zone beneath the Ciomad volcanic complex, interpreted as a hot magmatic structure that may represent a magma transport path or a crustal magma chamber beneath the volcano (Popa et al., 2012).

Older sedimentary layers, such as marls, sandstones, clay-rich deposits, and locally conglomeratic levels of Cretaceous to Neogene age, are found beneath the volcanic succession. The pre-volcanic structural structure that supported the Ciomad volcanic system is represented by these sedimentary units. The

change from basin sedimentation to volcanic construction during the late evolutionary stages of the Carpathian arc is demonstrated by the layering of volcanic products over this sedimentary substrate. The Saint Ana as shown in Figure 7 basin's morphologically distinct circular crater structure is thought to be the result of explosive eruptive periods that may have involved phreatomagmatic interactions.

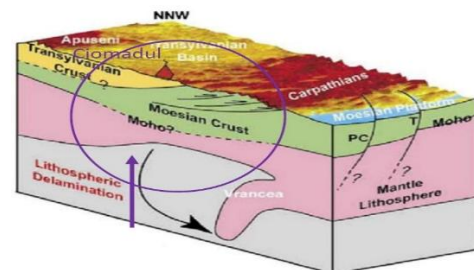


Figure 7. Geodynamic model of Vrancea (Knapp et al., 2005, Tectonophysics)

In comparison to other parts of the Harghita chain, the crater's geometry and the little amount of erosional modification suggest a relatively early volcanic age.

1.5 Thermal Hot Spots in Volcanic and Geothermal Contexts

Hot spots are commonly interpreted as localized zones of enhanced surface radiative behavior that may reflect subsurface heat transfer or hydrothermal alteration. While temperature anomalies are often emphasized, variations in land surface emissivity (LSE) can also provide important diagnostic information, as emissivity is strongly controlled by material composition, surface roughness, porosity, and moisture content (Dash et al. 2002; Li et al. 2013).

In volcanic systems, emissivity contrasts may be associated with altered lava domes, fractured surfaces, degassing zones, or hydrothermally affected deposits rather than active lava extrusion. Because volcanic rocks exhibit distinct spectral emissivity signatures depending on silica content and degree of alteration, LSE analysis can contribute to identifying subtle surface expressions of residual geothermal processes (Salisbury and D'Aria 1992; Dash et al. 2002). However, interpretation requires discrimination from emissivity variations caused by vegetation cover, soil moisture, and topographic effects.

2. METHODOLOGY AND DATA ACQUISITION

2.1 The method used

Land Surface Emissivity (LSE) is a key radiative parameter describing the efficiency with which natural surfaces emit thermal radiation relative to a blackbody.

As an intrinsic property of materials, it provides valuable information regarding surface composition, particularly for silicate-dominated lithologies. Nevertheless, LSE is not invariant; it is affected by surface roughness, structural heterogeneity, and sensor viewing geometry (Li et al., 2012).

In the context of satellite-based thermal remote sensing, accurate emissivity retrieval is essential for reliable land surface temperature (LST) estimation and for reducing systematic uncertainties in radiative transfer calculations (Figure 8).

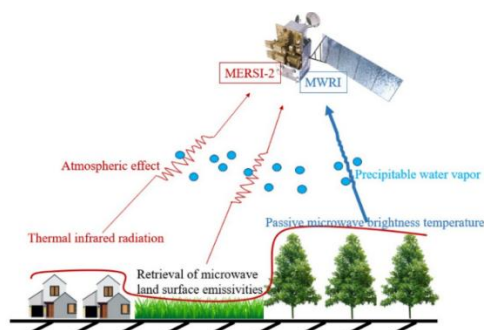


Figure 8. Graphical abstract illustrating land surface emissivity retrieval (from Li et al. 2024, Remote Sensing 16(2): 352)

Beyond temperature retrieval, LSE supports investigations of pedogenetic processes, soil erosion, vegetation cover dynamics in sparsely vegetated environments, lithological discrimination, and mineral exploration. Furthermore, it plays a critical role in improving surface energy balance modelling and related climatological applications (Li et al., 2012).

Emissivity a wavelength-dependent quantity defined as the ratio of the radiance actually emitted by an isothermal, homogeneous body and the radiance emitted by a black body at the same thermodynamic temperature (Norman and Becker 1995, https://lpvs.gsfc.nasa.gov/LSTE/LSTE_home.html)

2.2 Data acquisition: Satellite Data and Pre-Processing

A Landsat 9 OLI/TIRS Collection 2 Level-2 scene (Path 183/Row 028), acquired on 20 January 2026, was downloaded from the United States Geological Survey (USGS) Earth Explorer platform. The Level-2 Surface Temperature product includes atmospherically corrected land surface temperature and surface emissivity data derived from the thermal infrared Band 10. In this study, the surface emissivity (ST_EMIS) band was used to analyze the spatial variability of land surface emissivity in the Saint Ana – Ciomad volcanic area.

All scenes were imported into ArcGIS Pro and organized within a mosaic dataset created in a file geodatabase to ensure spatial consistency and unified radiometric handling. The mosaic dataset was defined in the Universal Transverse Mercator (UTM) projection corresponding to the study area. The Landsat 9 product definition was applied to preserve the original band configuration and wavelength properties.

3. RESULTS AND ANALYSIS

3.1 Map outputs

All data processing, raster handling, and cartographic layout design were performed in ArcGIS Pro. The emissivity layer was visualized using a continuous color scale ranging between 0.95 and 0.98 in order to highlight subtle spatial contrasts as showed in Figure 9. Base reference layers, including hydrography, settlements, transportation network, scale bar, and north arrow, were incorporated to ensure proper spatial contextualization.

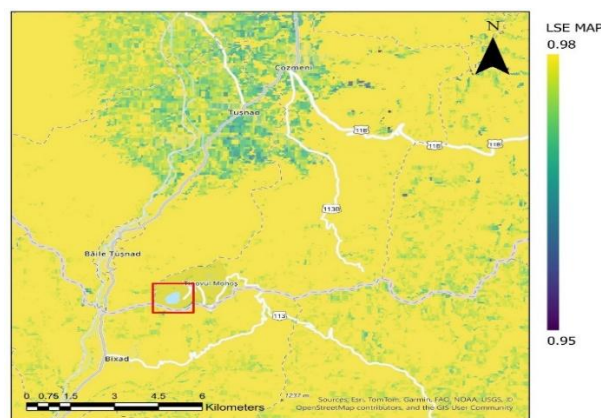


Figure 9. Land Surface Emissivity (LSE) map of the Saint Ana–Ciomad volcanic area derived from Landsat 9

The area of interest, corresponding to the Saint Ana–Mohoș crater sector, is emphasized within a defined frame to facilitate local-scale analysis. Although the emissivity distribution appears relatively homogeneous across the broader region, localized variations can be observed and may reflect differences in lithology, vegetation cover, surface roughness, or soil moisture conditions. The resulting cartographic output therefore provides a first-order spatial assessment of emissivity patterns within the Ciomad volcanic complex.

3.2 Spatial Distribution of NDVI and Vegetation Cover

The spatial distribution of NDVI across the Saint Ana Lake area reflects the strong ecological gradients characteristic of volcanic crater environments. High NDVI values are predominantly associated with forested slopes surrounding the crater rim, while reduced values correspond to exposed volcanic deposits and erosion-prone sectors. The northern and western crater margins exhibit dense vegetation cover, consistent with the relatively stable geomorphological conditions described in Section 1.3. In contrast, localized areas of sparse vegetation align with rocky outcrops and blocky lava surfaces linked to the volcanic evolution of the Ciomad massif (Karátson et al., 2013).

The derived Fractional Vegetation Cover (FVC) map emphasizes the contrast between vegetated crater slopes and exposed silicate-rich substrates. These findings correspond with previous observations that volcanic terrains often present sharp vegetation–lithology transitions due to substrate composition and soil development stages (Harangi et al., 2015).

3.3 Spatial Variability of Land Surface Emissivity

The Landsat 9 - based emissivity retrieval reveals spatial variability controlled primarily by vegetation density and lithological composition. Higher emissivity values are concentrated in densely forested zones surrounding the crater rim and in moist soils adjacent to the lake shoreline. Lower emissivity values are systematically observed over exposed volcanic rock formations and sparsely vegetated surfaces, where silicate mineral dominance influences thermal infrared behavior.

Silicate-rich volcanic materials typically exhibit emissivity values between 0.94 and 0.97 in the thermal infrared region (Sobrino et al., 2004; Li et al., 2013). The emissivity values retrieved in the present study fall within this expected interval,

confirming the geological control over thermal radiative properties.

The spatial agreement between emissivity variations and mapped geological structures (Section 1.4) suggests that LSE retrieval provides meaningful information regarding surface composition in volcanic crater environments.

3.4 Emissivity–Lithology: Relationship in the Ciomad Volcanic Context

The Ciomad volcanic complex represents one of the youngest volcanic systems in the Carpathian–Pannonian region (Harangi et al., 2015). Its lithological diversity, including lava domes, pyroclastic deposits, and weathered volcanic materials, generates heterogeneous surface properties.

Within the Saint Ana crater, emissivity contrasts correspond to variations in surface roughness and mineralogical composition. Blocky lava deposits and exposed volcanic formations exhibit lower emissivity compared to vegetated and weathered surfaces.

This pattern indicates that emissivity retrieval from Landsat 9 is sensitive to both biological and geological surface characteristics. In volcanic systems where geothermal or post-volcanic manifestations occur, accurate emissivity estimation becomes essential for reliable thermal analysis.

3.5 Implications for Thermal Characterization

The incorporation of pixel-based emissivity into the land surface temperature workflow reduces potential bias associated with constant emissivity assumptions.

In heterogeneous volcanic terrain such as Saint Ana, emissivity variability may significantly influence brightness temperature correction. The results demonstrate that areas characterized by exposed volcanic rock would be subject to temperature overestimation if uniform emissivity values were applied.

Therefore, spatially explicit emissivity retrieval enhances the reliability of thermal interpretation in crater lake environments.

3.6 Interpretation of Land Surface Emissivity Patterns

The land surface emissivity (LSE) pattern observed within the Saint Ana – Ciomad volcanic system reveals predominantly high values (0.97–0.98), consistent with dense vegetation and moisture-influenced substrates typical of mountainous volcanic terrains. From a geothermal perspective, emissivity constitutes a critical thermophysical parameter, as it governs the radiative efficiency of surface materials and directly influences the interpretation of satellite-derived thermal signals.

In volcanic and post-volcanic settings, spatial variations in emissivity may reflect changes in surface composition, hydrothermal alteration processes, soil moisture redistribution, or exposure of mineral substrates affected by subsurface heat flux. Although the present analysis does not reveal pronounced low-emissivity anomalies at Landsat spatial resolution, the uniformly elevated emissivity values may partly result from the masking effect of forest cover, which can obscure subtle geothermal manifestations at the surface.

The Ciomad volcanic complex is widely regarded as a dormant system with documented post-volcanic manifestations (e.g., CO₂

emissions and mofettes), suggesting the persistence of subsurface geothermal processes. In this context, the observed LSE distribution provides an important baseline for evaluating surface thermophysical stability. The absence of strong emissivity discontinuities indicates that any existing geothermal influence is either spatially limited, thermally diffuse, or concealed beneath vegetative cover.

Consequently, while the current LSE assessment does not independently confirm active surface geothermal anomalies, it remains directly relevant to geothermal investigations. The emissivity field establishes the radiative framework necessary for detecting subtle energy balance perturbations and supports the hypothesis that latent geothermal processes, if present, require integrated multi-parameter analysis (thermal, structural, and geochemical) for comprehensive characterization.

4. CONCLUSIONS

The results confirm that emissivity variability over Saint Ana Lake is governed by both ecological and geological controls. The strong correspondence between NDVI patterns and emissivity values supports the applicability of the NDVI-threshold method in forested volcanic settings.

Furthermore, the alignment between low-emissivity zones and silicate-rich volcanic formations reinforces the known spectral behavior of such materials in the thermal infrared domain (Li et al., 2013).

Given that the Ciomad volcanic complex is considered dormant but not extinct (Harangi et al., 2015), accurate thermal surface characterization remains relevant for environmental and geophysical monitoring.

The study highlights the importance of emissivity correction in volcanic crater systems where surface heterogeneity is pronounced.

The present work represents a preliminary methodological assessment of Land Surface Emissivity as an observational tool in dormant volcanic environments. The spatial patterns identified within the Ciomad crater may reflect subtle residual geothermal influences and justify further multidisciplinary investigation.

Accordingly, the study highlights the potential advantages of LSE-based remote sensing in volcanic terrain analysis and provides a framework for future integration with thermal, geochemical, and structural datasets.

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