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Unveiling the Crucial Challenges and Potential of Remote Sensing in Geothermal Exploration: A Case Study from the Northwest Himalayas

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INTRODUCTION

India is emerging as a high-potential geothermal frontier, supported by extensive hot springs and favourable Enhanced Geothermal System prospects. The Himalayan geothermal province alone hosts ~150 thermal springs (up to >90 °C) and reservoirs temperature exceeding 150 °C, energized by active tectonics and radiogenic heat flow.

While conventional geological and geophysical assessments exist, geothermal exploration in India lacks sufficient remote sensing (RS) integration (Figure1). RS approaches are crucial particularly in high-altitude environments where extreme climate and complex topography restrict field surveys. Satellite-based RS offers a scalable, cost-effective approach for preliminary detection of geothermal surface expressions prior to ground deployment.

This study demonstrates that elevation-induced challenges, including topographic shadows, high background temperature from exposed mafic rocks, vegetation coverage, and coarse spatial resolution, can suppress land surface temperature (LST) anomalies, even from ~90 °C springs. The outcomes define critical detection constraints and highlight future avenues to enhance RS-based reconnaissance for high-altitude geothermal assessment before detailed subsurface investigations.

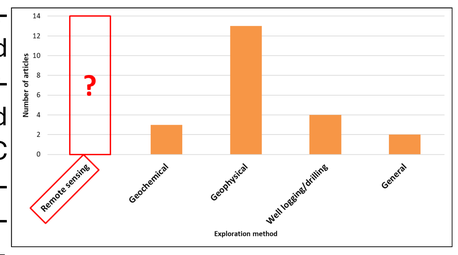


Figure 1. Bibliometric analysis of geothermal exploration approaches in India.

METHODS AND MATERIALS

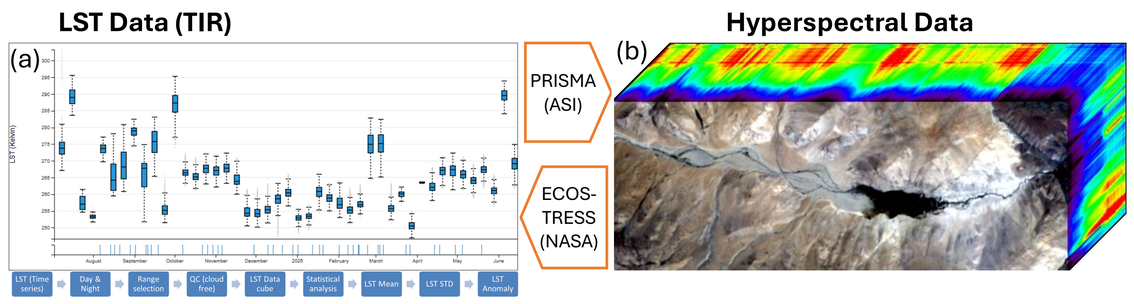
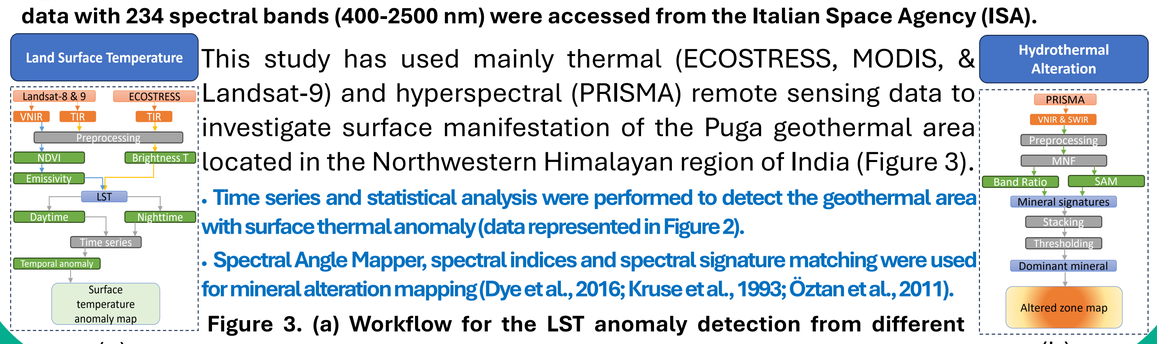


Figure 2. (a) ECOSTRESS (LST) data (July 2024—Jun 2025) accessed from NASA LP DAAC, (b) PRISMA (L2D) data with 234 spectral bands (400-2500 nm) were accessed from the Italian Space Agency (ISA).



This study has used mainly thermal (ECOSTRESS, MODIS, & Landsat-9) and hyperspectral (PRISMA) remote sensing data to investigate surface manifestation of the Puga geothermal area located in the Northwestern Himalayan region of India (Figure 3).

- Time series and statistical analysis were performed to detect the geothermal area with surface thermal anomaly (data represented in Figure 2).
- Spectral Angle Mapper, spectral indices and spectral signature matching were used for mineral alteration mapping (Dye et al., 2016; Kruse et al., 1993; Öztan et al., 2011).

Figure 3. (a) Workflow for the LST anomaly detection from different thermal sensors, (b) Workflow for mineral (alteration) detection.

RESULTS

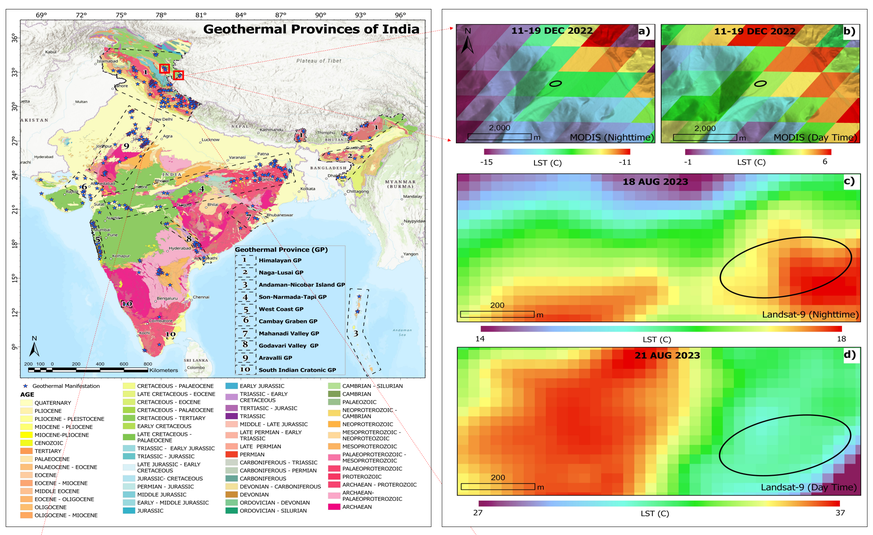


Figure 4. Left: Geothermal Province Map of India (Daqiq et al., 2025). Right: Night and Day time LST (challenging) of Demchok geothermal area (black ellipse) from different satellites; (a) and (b) from MODIS, (c) and (d) from Landsat-9.

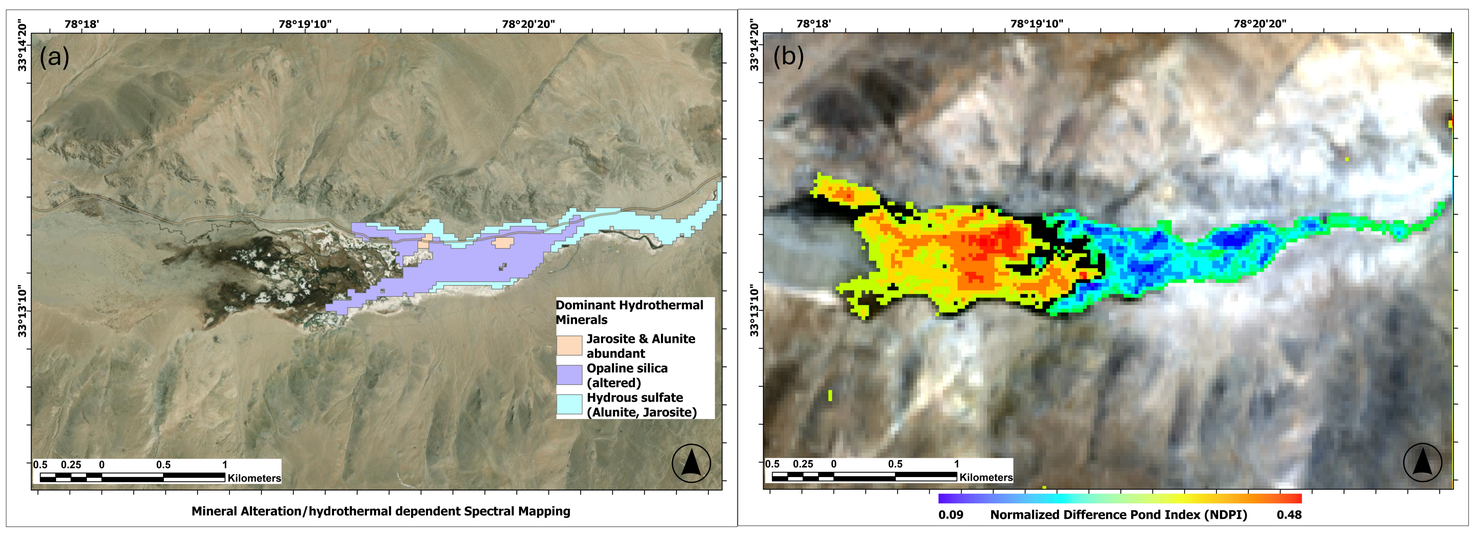


Figure 6. (a) Dominant hydrothermal indicating minerals mapped using hyperspectral remote sensing data and verified with in-situ spectral data acquired by Sarkar et al. (2022). (b) Normalized Difference Pond Index with higher value (red color) indicating hot water ponds surrounding the hot springs, while lower values (blue color) indicating no water pond in downstream of the Puga valley.

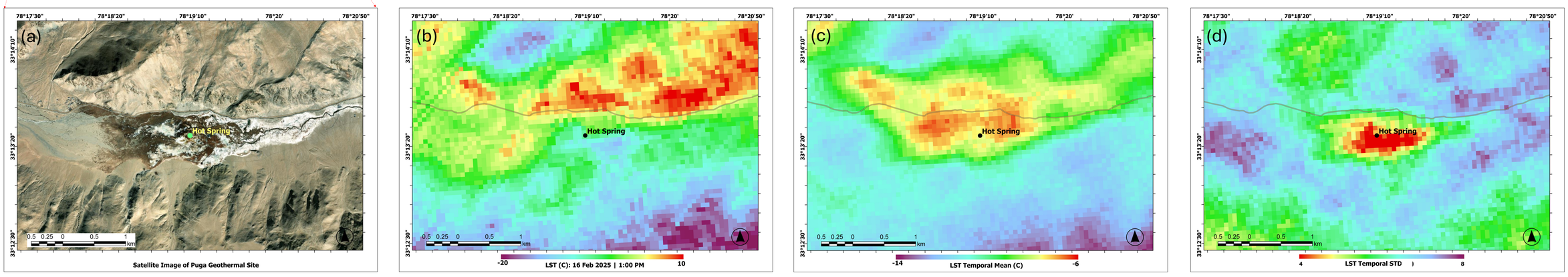


Figure 5. (a) Satellite image of Puga geothermal field showing combination of wetland, grass, and white sediments. (b) A Traditional LST map showing high background temperature (from exposed rocks) that suppress the geothermal surface temperature. (c) Land surface temperature anomaly has detect the Puga geothermal surface temperature with higher anomaly around the hot springs. (d) Geothermal area showing a constant surface temperature throughout the year).

DISCUSSION

The results indicate that Himalayan hot springs are not readily detectable from spaceborne thermal surveys due to coarse spatial resolution, steep terrain shadows, surface occlusion from vegetation, and constrained heat exposure at vent margins. This is a likely contributing factor to the limited adoption of thermal RS studies in the Himalaya.

Mineral and spectral index mapping show strong potential as indirect proxies for geothermal surface manifestations in thermally active province of the Himalaya, offering a cost-effective pathway to reduce reconnaissance effort in inaccessible valleys, including Demchok and Nubra regions of Ladakh.

Confidence in mineral abundance mapping remains constrained by the sparsity of validated reference spectra and region-specific spectral libraries, limiting detection to documented minerals. This defines a key methodological and confidence limitation of the present study, which can be improved through expanded spectral field campaigns and regional reference library development.

CONCLUSION

- This study evaluated the capabilities and constraints of remote sensing for NW Himalayan geothermal exploration, where applications in India remain limited despite strong resource potential. Using open-access spaceborne observations, we successfully mapped the Puga geothermal field through both direct surface temperature anomalies and indirect hydrothermal signatures.
- Our results demonstrate the first RS-based detection of geothermal temperature anomalies in Puga Valley, along with hydrothermal mineral zones verified using field spectra. We further show that surface temperature alone cannot delineate all geothermal systems, especially in rugged region wetlands affected by terrain shadowing and elevated background signals.
- Importantly, we confirm that hydrothermally active zones can be identified indirectly using vegetation and mineral indices, providing a reliable pathway for preliminary geothermal reconnaissance in the areas with evaporitic sedimentation.
- These findings establish a transferable, cost-effective framework for high-altitude and inaccessible areas geothermal assessment prior to detailed field subsurface investigations.

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