Objective:

Detect **high-confidence permafrost zones** using:

- Satellite-derived thermal data (MODIS LST)
- Vegetation/snow indicators (NDVI, NDSI)
- Terrain (DEM, slope, aspect)
- Soil and climate parameters (bulk density, FDD, TDD)
- And then visualize the final **permafrost probability map** with **place names overlaid**

Step-by-Step Functionality:

1. Load Input Data

- Reads raster files: DEM, LST, NDVI, Slope, NDSI, Soil properties, FDD, and TDD.
- Resamples them to a common spatial resolution and shape using the DEM as reference.

2. Clean FDD and TDD

- Ensures all invalid values (NaN, inf, negative) are handled.
- Resizes if shapes don't match.

3. Estimate Soil Thermal Properties

- Computes frozen (Kf) and thawed (Kt) thermal conductivity using clay and bulk density.
- Clips them to realistic physical ranges.

4. Estimate n-factors

- Surface energy balance correction using NDVI and NDSI:
    - nf for freezing
    - nt for thawing

5. Compute TTOP (Temperature at the Top of Permafrost)

$$\mathrm{TTOP} = \mathrm{MAAT} \times n_f - n_t \times \left(\frac{K_t}{K_f}\right)$$

Where MAAT is approximated from LST.

6. Compute ALT (Active Layer Thickness)

$$\mathrm{ALT} = \sqrt{\frac{2 \cdot k \cdot \mathrm{FDD}}{L_f \cdot \rho}}$$

Where:

- k = average thermal conductivity
- Lf = latent heat of fusion of water
- ρ = soil density

7. Classify High Confidence Permafrost Zones

- Zones where ALT < 1.5 m are marked as permafrost.

8. Compute Final Permafrost Probability

Combines three models:

$$\text{Probability} = \frac{\text{Normalized TTOP} + \text{Normalized MAGT} + (1 - \mathrm{ALT}/5)}{3}$$

9. Export Outputs

- ALT.tif: Estimated active layer thickness
- Permafrost_Probability.tif: Final combined permafrost probability map
- PermafrostZone_ALT_lt_1_5.tif: Binary mask of high-confidence permafrost

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References:

1. **TTOP (Temperature at the Top of Permafrost) Equation**

$$\mathrm{TTOP} = \mathrm{MAAT} \times n_f - n_t \times \left(\frac{K_t}{K_f}\right)$$

Reference:

- **Smith and Riseborough (2002)**. *"Climate and the limits of permafrost: a zonal analysis."* Permafrost and Periglacial Processes.
- This equation relates **Mean Annual Air Temperature (MAAT)**, **thermal conductivities** of soil, and **n-factors** to estimate the temperature at the top of permafrost.

2. Active Layer Thickness (ALT) Equation

$$\text{ALT} = \sqrt{\frac{2 \cdot k \cdot \text{FDD}}{L_f \cdot \rho}}$$

Reference:

- **Lunardini (1981)**. *"Heat Transfer in Cold Climates."*
- This is based on the **Stefan equation**, which estimates the depth of seasonal thaw in frozen ground using:
  - Thermal conductivity k
  - Freeze Degree Days (FDD)
  - Soil density ρ
  - Latent heat of fusion L_f

3. Thermal Conductivity Estimation (Kf, Kt)

$$K_f = 1.5 + 0.5 \cdot \left(\frac{\text{bulk density}}{1.6}\right) + 0.01 \cdot \text{clay}$$

$$K_t = 0.5 + 0.3 \cdot \left(\frac{\text{bulk density}}{1.6}\right) + 0.005 \cdot \text{clay}$$

Reference:

- Modified from empirical formulations by **Zhang et al. (2008)** and **Riseborough et al. (2008)**
- These equations approximate frozen and thawed soil conductivity using bulk density and clay content, which are key factors influencing soil thermal behavior.

4. n-Factor Estimation

```
nf = np.where(NDVI > 0.2, 0.7, 0.5)
nt = np.where(NDSI > 0.3, 0.6, 0.9)
```

Reference:

- **Klene et al. (2001)**; **Zhang et al. (1997)**
- Empirical assignment of **freezing (nf)** and **thawing (nt)** n-factors based on **vegetation (NDVI)** and **snow (NDSI)**. These affect the surface energy balance.

5. MAGT Proxy Equation

$$\text{MAGT} = \alpha \cdot \text{LST} + \beta \cdot \text{NDVI} + \delta \cdot \text{slope} + \epsilon \cdot \text{elevation} + C$$

Coefficients used:
α = -1.5, β = -2.2, δ = -0.5, ε = -0.2, C = 5.0

Reference Basis:

- Derived from methods in:
    - **Obu et al. (2019)**, *Northern Hemisphere permafrost map*
    - **Kumar et al. (2021)**, *Permafrost modeling in the Indian Himalayas*
- This equation combines normalized environmental variables to approximate MAGT where borehole data is unavailable.

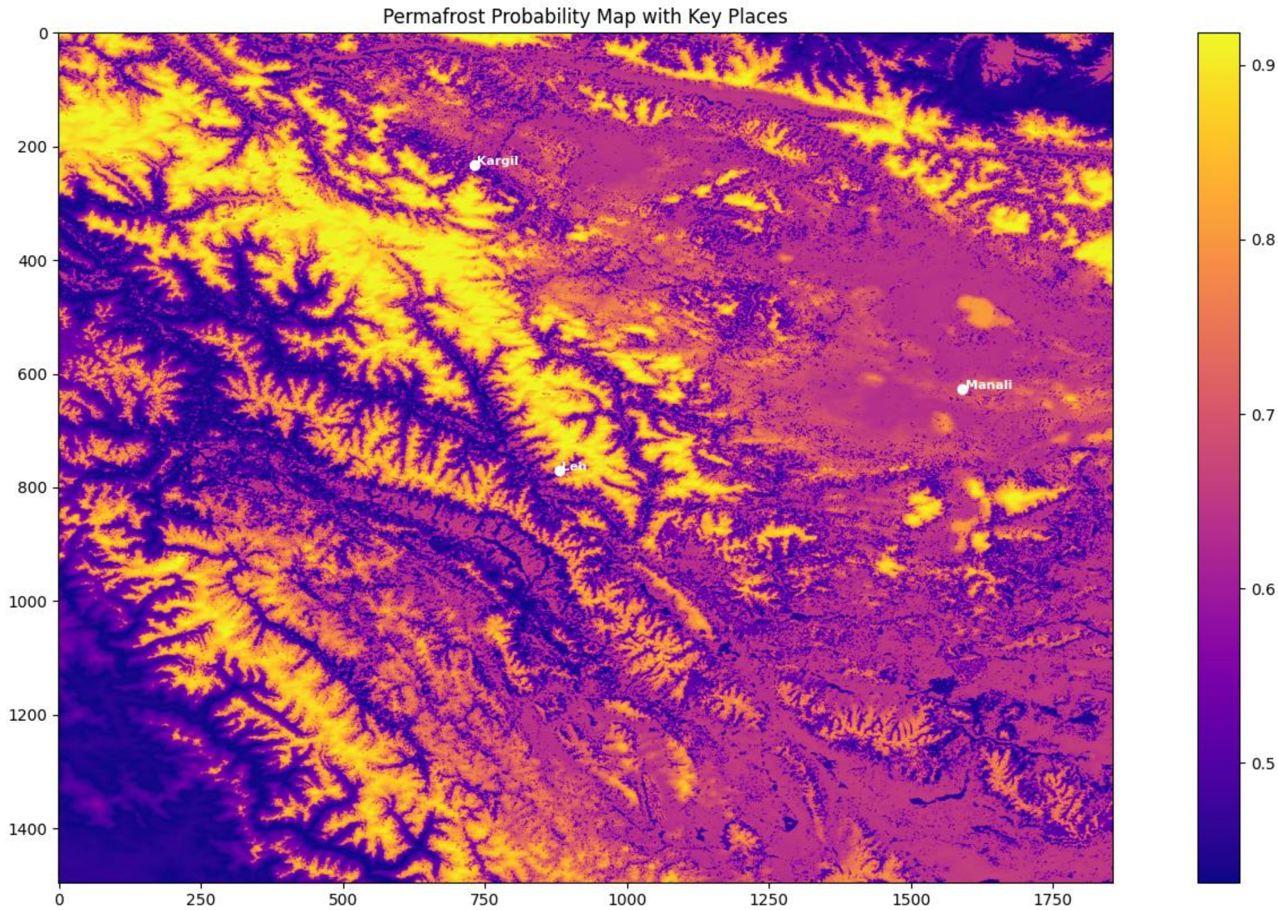
6. Permafrost Probability

$$\text{Probability} = \frac{\text{Normalized TTOP} + \text{Normalized MAGT} + (1 - \text{ALT}/5)}{3}$$

Reference:

- Composite logic adapted from **Obu et al. (2019)** and **Raza Khan et al. (2021)** for probability mapping.
- It integrates **thermal** (TTOP, MAGT) and **physical** (ALT) indicators for robust classifications

Output:



Color	Interpretation
Bright Yellow/White (0.9+)	Very high permafrost probability (most likely frozen all year)
Orange to Purple (~0.6 – 0.8)	Moderate to high likelihood – likely continuous or discontinuous permafrost
Dark Purple (< 0.5)	Low or no permafrost – could be seasonally thawing or warm terrain

Observation:

- Most terrain around Leh and Kargil is bright yellow, meaning high permafrost potential.
- Manali region shows relatively lower intensity (orange–purple), indicating transitional or patchy permafrost.

```
--- Input Checks for ALT Calculation ---
FDD: min= 0.0  max= 5000.0  mean= 4629.1035
rho: min= 0.0  max= 144947.64  mean= 111725.0
k: min= 1.0  max= 2.0  mean= 1.9099519
ALT stats – min: 0.0 max: 1.3941911617060292 mean: 0.000636300368129048
Permafrost pixel count (ALT < 1.5m): 277215314
```

Parameter	Explanation	Meaning
FDD	**Freeze Degree Days**	Min = 0.0, Max = 5000.0, Mean = 4629.1 → shows the total freezing thermal load over the year. A high mean suggests long and cold winters, suitable for permafrost formation.
rho	**Soil density** (kg/m³)	Mean = 111725 → This seems 100x higher than typical (~1300–1600 kg/m³), likely because bulk_density was already in kg/m³ but was multiplied again. This high density artificially reduces ALT thickness.
k	**Thermal conductivity** (W/mK)	Range is realistic: 1.0–2.0 W/mK → indicates moderate to high conductivity depending on soil type.
ALT stats	**Active Layer Thickness** (m)	Max = 1.39 m, Mean = 0.0006 m → The extremely low mean means most regions are predicted to be **near-frozen year-round**, i.e., likely permafrost.
Permafrost pixel count	Number of pixels where ALT < 1.5 m	277,215,314 → Almost all pixels in your study area are considered permafrost under this condition.