Supplementary to “Multi-source remote sensing reveals the key role of hydro-geomorphological variables in mapping small alpine peatlands”

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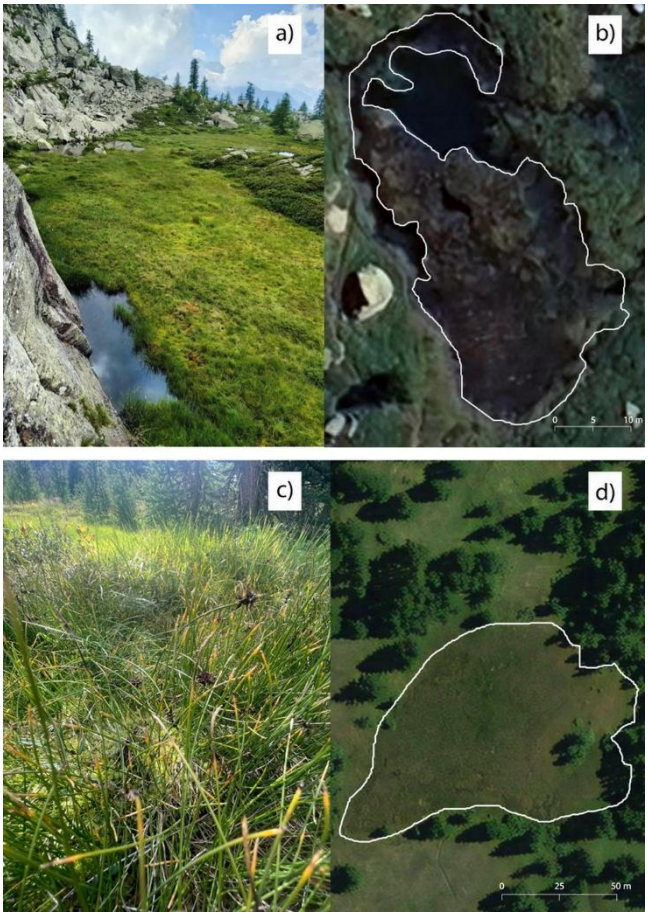


Figure S1. Examples of field observations used to support the visual interpretation and manual digitization of peatland polygons from satellite imagery. (a) An acid fen surveyed in July 2024 and (b) the corresponding peatland polygon manually digitized from Google satellite imagery. (c) A base-rich fen surveyed in July 2024 and (d) the corresponding manually digitized peatland polygon. Satellite imagery in panels (b) and (d): Map data © 2026 Google.

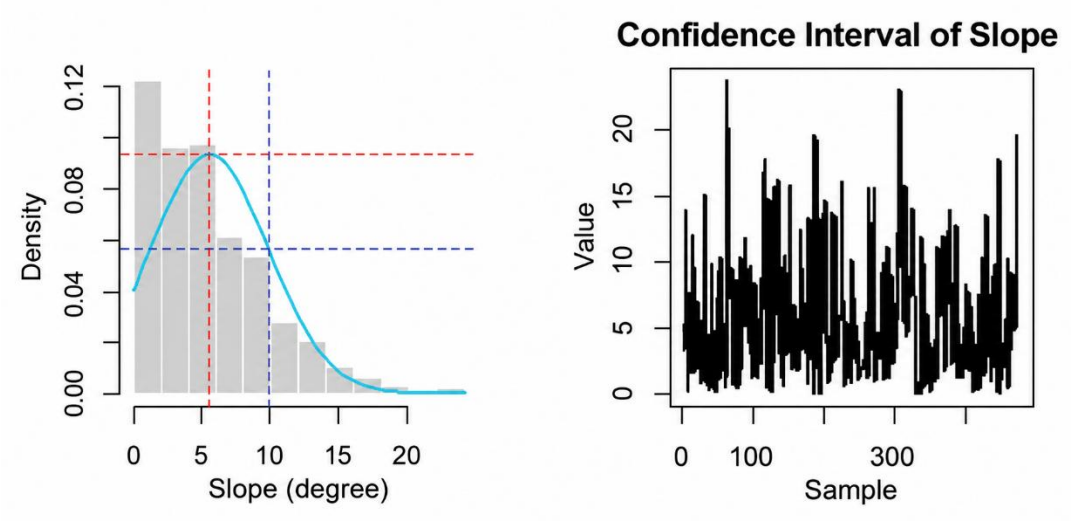


Figure S2. The slope value distribution of peatland sites in the Orco basin. The highest slope value is 23.81 degrees. Density values peak in the gentle slope range (approx. 0 – 5 degrees), with a rapid decline toward steeper slopes.

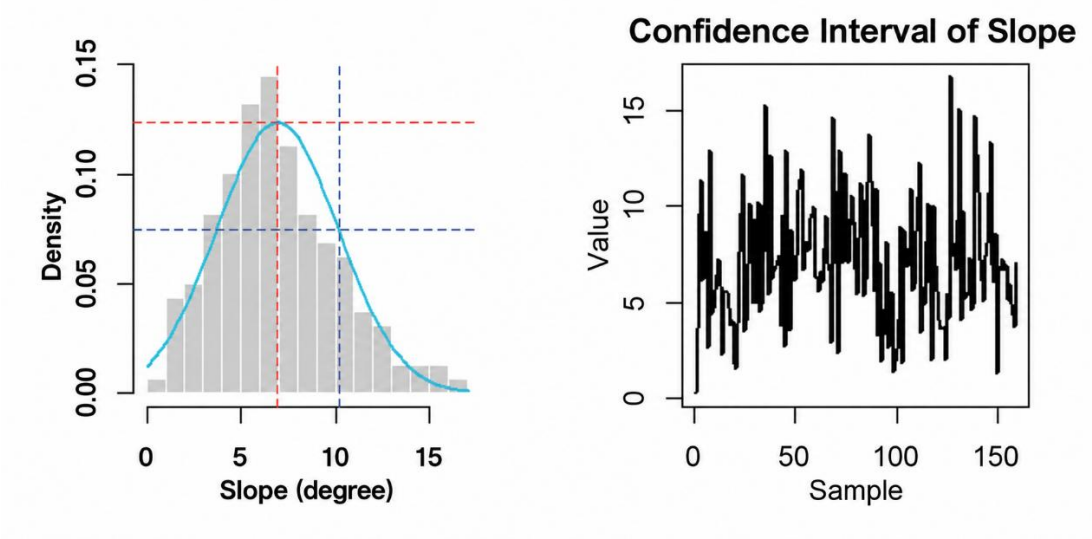


Figure S3. The slope distribution of peatland sites in the Avisio basin. The highest slope value is 16.81 degrees. The density value peaks in the gentle slope range (0 - 6.95 degrees).

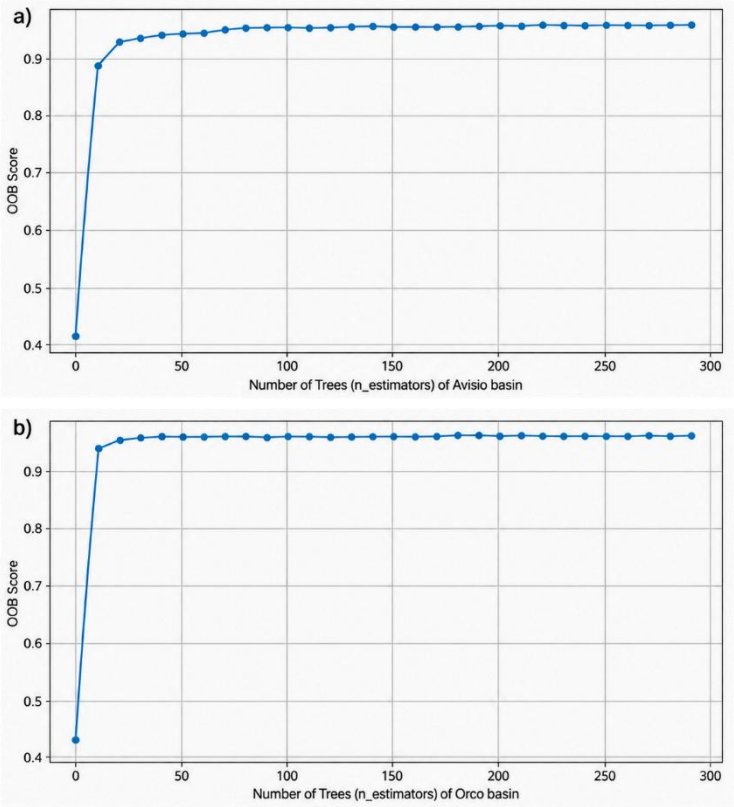


Figure S4. Out-of-Bag (OOB) score of Random Forest, a) in the Avisio basin and b) in the Orco basin. The OOB score is produced from a Random Forest classifier framework to test model performance. The validation accuracy is computed using validation samples from the Alpine peatland map to evaluate classification results.

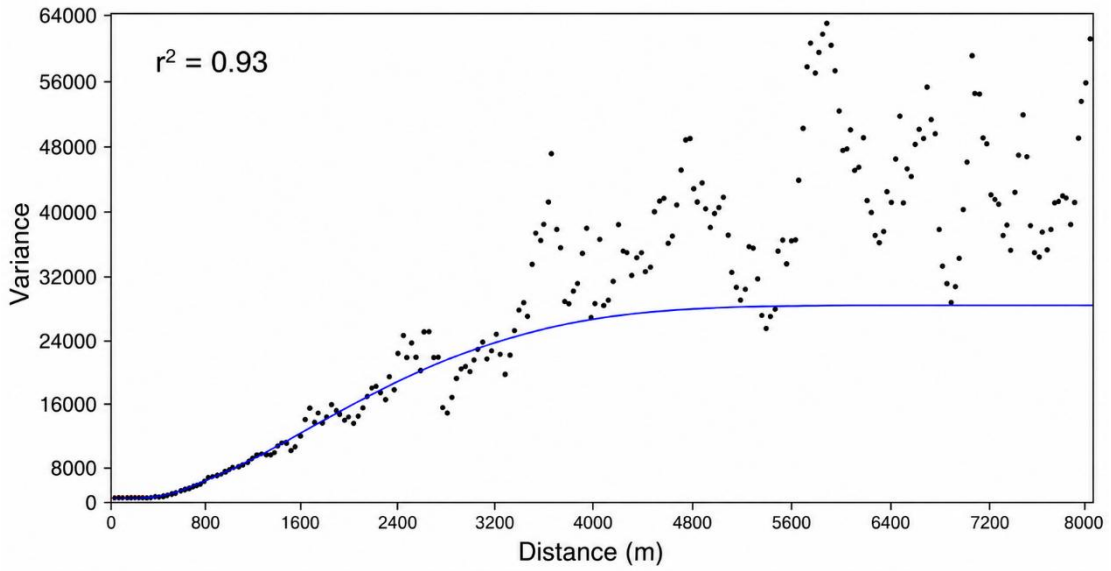


Figure S5. Variogram analysis based on the 30 m spatial resolution GLO-30 Digital Surface Model (DSM) for the Orco basin. The sill is 24,720.6, and the range is 2,217.74 m; spatial correlation becomes negligible beyond 4,000 m.

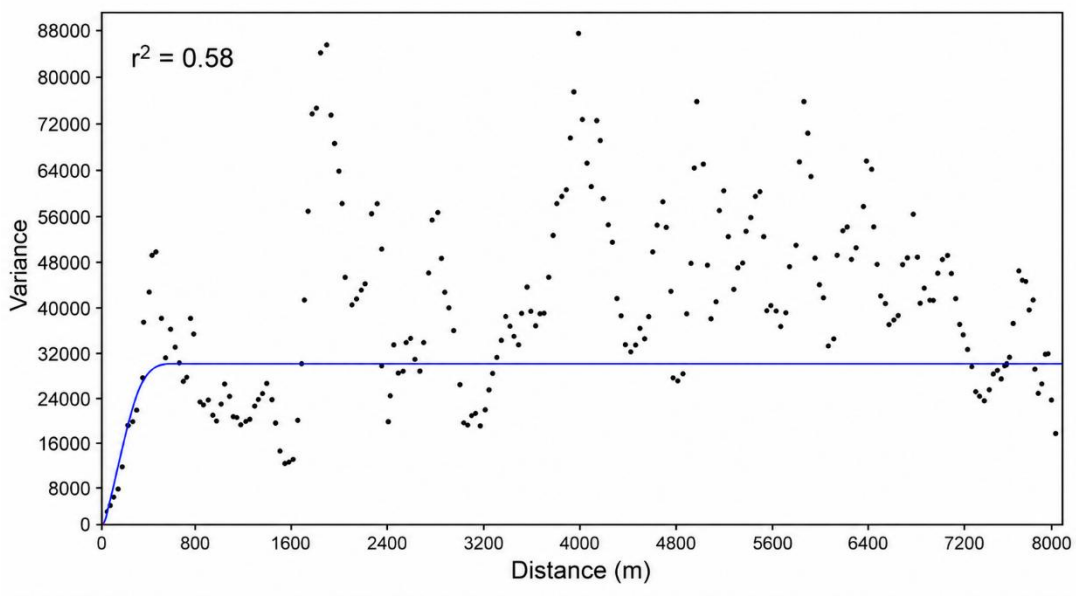


Figure S6. Variogram analysis of the Avisio basin based on the 30 m GLO-30 Digital Surface Model (DSM). The sill is 27,659.7, and the range is 265.89 m; spatial correlation becomes negligible beyond 1,000 m.

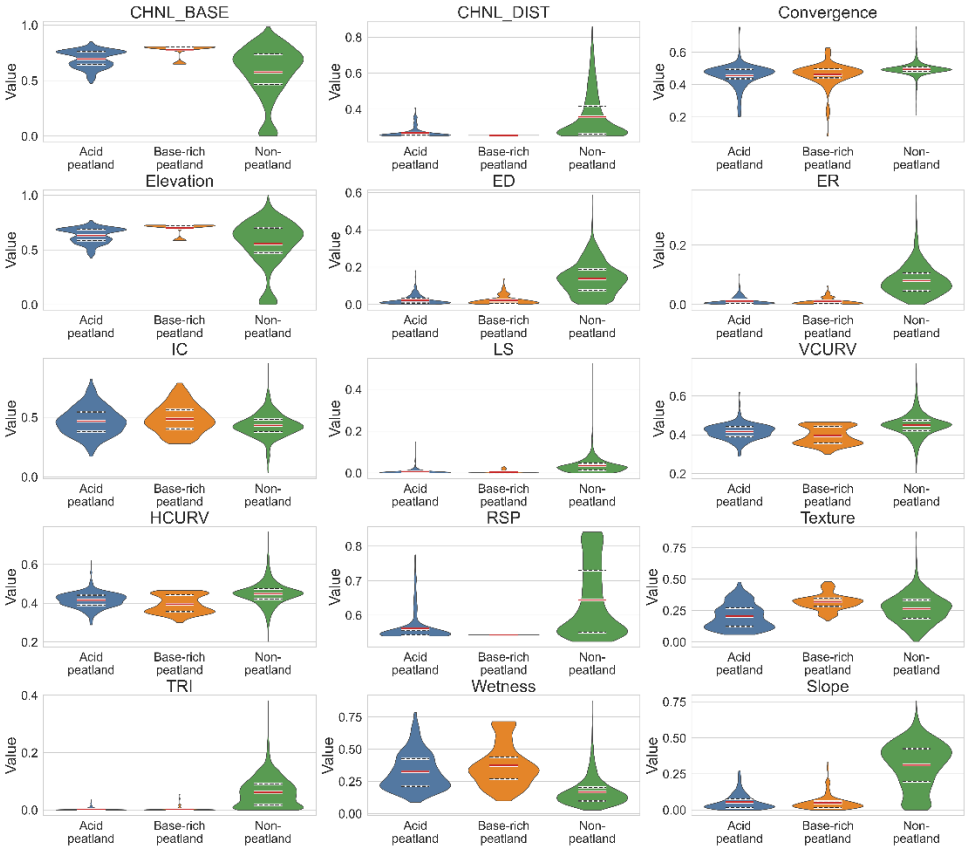


Figure S7. Distribution of topographic and terrain-related variables across acid peatland, base-rich peatland, and non-peatland samples in the Orco datasets. Violin widths represent probability density; red solid lines indicate means, and black dashed lines indicate the first and third quartiles

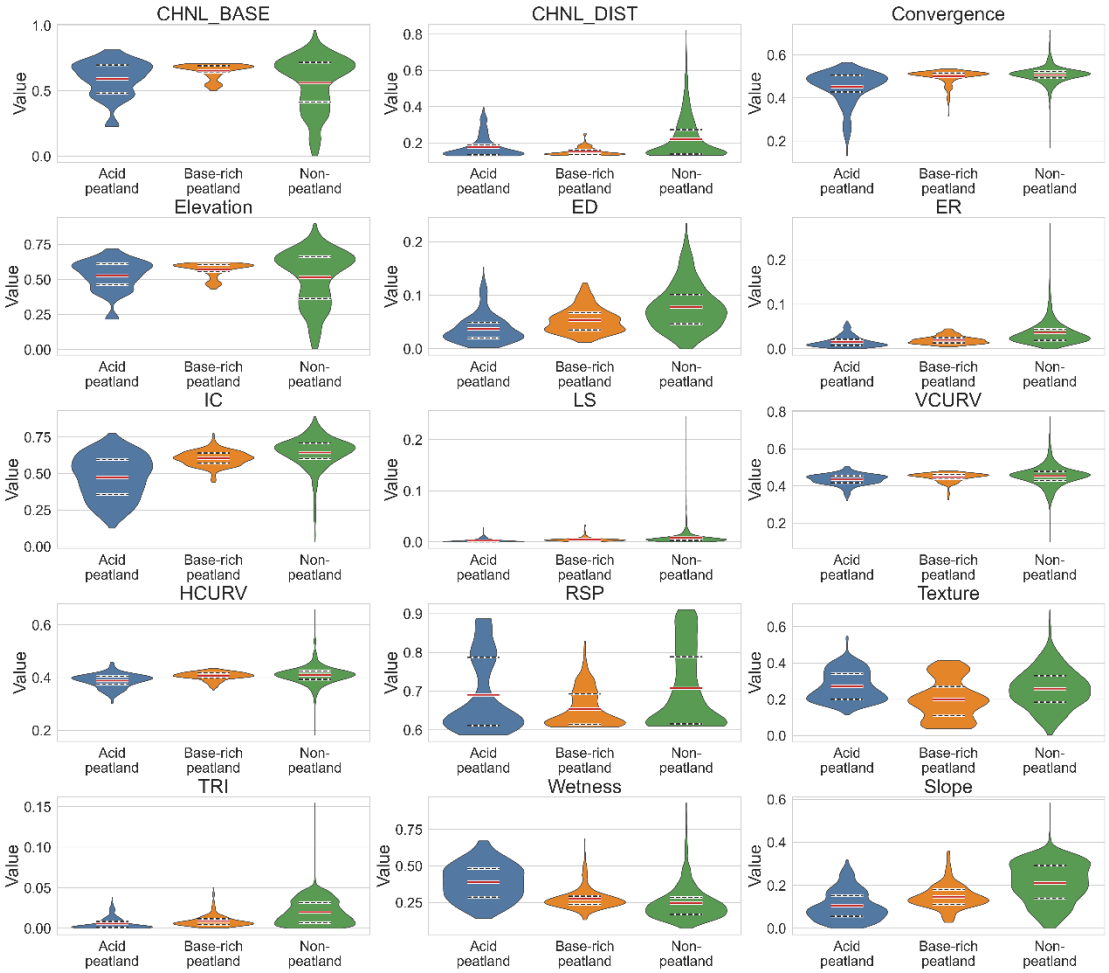


Figure S8. Distribution of topographic and terrain-related variables across acid peatland, base-rich peatland, and non-peatland samples in the Avisio datasets. Violin widths represent probability density; red solid lines indicate means, and black dashed lines indicate the first and third quartiles

Table S1. Comparison of the characteristics of the two study sites. Soil pH and climate data are expressed as mean (min, max).

	Orco basin	**Avisio basin**
Central point Longitude and Latitude	45°43′N, 7°53′E	46°31′N, 11°55′E
Extent (ha)	68,386	88,883
Habitat Directive peatland codes	7110*, 7140, 7150, 7220*, 7230, 7240*	7110*, 7140, 7150, 7210, 7220*, 7230, 7240*, 91D0*
Lithology	Bedrock is predominantly composed of metamorphic rocks, dominated by schist and gneiss with widespread eclogite; limestone, peridotite, granite, dacite and other minor lithologies occur only locally	Bedrock is predominantly composed of igneous and sedimentary rocks, dominated by dacite, dolomite, and limestone; anorthosite, monzonite, and other minor lithologies occur only locally
Soil pH	7.2 (6.5, 8.4)	7.0 (6.2, 8.1)
Annual mean temperature (℃)	3.9 (–5.3, 11.6)	4.3 (-1.5, 11.6)
Mean Temperature of the Wettest Quarter (℃)	3.2 (-11.3, 14.9)	12.4 (5.7, 21.4)
Mean Temperature of the Driest Quarter (℃)	6.9 (-0.7, 14.7)	-3.0 (-7.8, 4.2)
Annual mean precipitation (mm)	1080 (524 - 1514)	763 (463 - 1119)
Precipitation in Warmest Quarter (mm)	235 (107, 283)	293 (181 - 419)
Precipitation in Coldest Quarter (mm)	255 (121, 412)	95 (49, 203)

Note. In this table, the Habitat Directive codes correspond to active raised bogs (7110*), transition peatlands and quaking bogs (7140), Depressions on peat substrates of the Rhynchosporion (7150), calcareous fens with Cladium mariscus and species of the Caricion davallianae (7210), petrifying springs with tufa formation (Cratoneurion) (7220*), alkaline fens (7230), alpine pioneer formations of the Caricion bicoloris–atrofuscae (7240*), and bog woodland (91D0*).

Table S2. Sources of the Orco basin inventory

Inventories	Classification	Data creator/ Holder of rights	Format	Link
Banca Dati Zone Umide	Peatlands or Natura 2000 Code where available	Arpa Piemonte	Polygons	https://webgis.arpa.piemonte.it/secure_apps/Viewer/?config=zone_umide.json https://webgis.arpa.piemonte.it/w-metadoc/Download/zone_umide.zip
Carta degli Habitat del Parco Nazionale Gran Paradiso	Acid peatlands, base-rich peatlands, transition mires	Parco Nazionale Gran Paradiso	Polygons	
Database of the paper *"Ecology of some mire and bog plant communities in the Western Italian Alps"*	Mires classified in sintaxon	Dr. Luca Miserere	Points	https://doi.org/10.4081/jlimnol.2003.88 + Unpublished data

Table S3. Sources of the Avisio basin inventory

Inventories	Classification	Data creator/ Holder of rights	Format	Link
Natura 2000 Habitat	6410/7110/7140/ 7150/7230/91D0	Italian Ministry of Environment	Polygons	http://wms.pcn.minambiente.it/ogc?map=/ms_ogc/wfs/SIC_ZSC_ZPS.map
Riserve Naturali provinciali	swamp, peatland	Provincia autonoma di Trento - Servizio Sviluppo sostenibile e aree protette	Polygons	https://siatservices.provincia.tn.it/idt/vector/p_TN_ef4cc49b-83e0-44e8-95f6-44c8ad3ff271.zip
Biotopi di interesse provinciale	peatland, peatlands	Provincia autonoma di Trento - Servizio Sviluppo sostenibile e aree protette	Polygons	https://siat.provincia.tn.it/geonetwork/srv/eng/catalog.search#/metadata/p_TN:416a8c4d-74e4-42bf-835b-7608820c1071
Riserve locali (puntuali)	swamp, peatland, peatlands	Provincia autonoma di Trento - Servizio Sviluppo sostenibile e aree protette	Points	https://siatservices.provincia.tn.it/idt/vector/p_TN_d1b2bdc5-f900-4b7c-98b5-ff9b05876214.zip
Riserve locali (poligonali)	palu, torba, torbiera	Provincia autonoma di Trento - Servizio Sviluppo sostenibile e aree protette	Polygons	https://siatservices.provincia.tn.it/idt/vector/p_TN_39151199-82fb-4f2d-988d-dc55986e22a7.zip

Table S4. The list of Satellite scenes used in the research

Basin	Sentinel-2 (Tiles: T32TPS and T32TQS)	Sentinel-1 (Ascending and Descending)
Avisio	20230625	20230603, 20230604, 20230604, 20230608, 20230611, 20230615, 20230616, 20230620, 20230623, 20230627, 20230628
	20230707	20230702, 20230705, 20230709, 20230710, 20230714, 20230717, 20230721, 20230722, 20230726, 20230729
	20230811, 20230816, 20230819, 20230821, 20230824	20230802, 20230803, 20230807, 20230810, 20230814, 20230815, 20230819, 20230822, 20230826, 20230827, 20230831
	20230908, 20230910, 20230925, 20230928, 20230930	20230903, 20230907, 20230908, 20230912, 20230915, 20230919, 20230920, 20230924
	20231124, 20231129	20231001, 20231002, 20231006, 20231009, 20231013, 20231014, 20231018, 20231021, 20231025, 20231030
	20231214, 20231217, 20231219	
	Sentinel-2 (Tiles: T32TLR and T32TMR)	**Sentinel-1 (Ascending and Descending)**
Orco	20230623, 20230625	20230601, 20230602, 20230606, 20230613, 20230614, 20230618, 20230625, 20230626, 20230630
	20230710, 20230720, 20230730	20230707, 20230708, 20230712, 20230719, 20230720, 20230724, 20230731
	20230807, 20230822, 20230824	20230801, 20230805, 20230812, 20230813, 20230817, 20230824, 20230825, 20230829
	20230906, 20230911, 20230926	20230905, 20230906, 20230910, 20230917, 20230918, 20230922, 20230929, 20230930
	20231001, 20231006, 20231008, 20231011	20230905, 20230906, 20230910, 20230917, 20230918, 20230922, 20230929, 20230930

Table S5. The optical indices used in this classification approach

Indices	Definition
Normalized Difference Vegetation Index (NDVI)	(NIR - Red) / (NIR + Red)
Enhanced Vegetation Index (EVI)	2.5 × (NIR - Red) / (NIR+ 6 ×Red - 7.5 ×Blue +1)
Normalized Difference Moisture Index (NDMI)	(NIR - SWIR2) / (NIR + SWIR2)
Shortwave infrared transformed reflectance (STR)	(Green-SWIR1) / (Green+SWIR1)
Normalized Difference Snow Index (NDSI)	(1-SWIR2) ^ 2 / (2×SWIR2)

Table S6. Hydro-geomorphological variables used in this study

Variables	Definition
Elevation	Elevation is derived from Copernicus 30 m Global Digital Surface Model (GLO-30 DSM).
Slope	$$p = \frac{z_E - z_W}{2r}, q = \frac{z_N - z_S}{2r}$$ $$slope = arctan\left(\sqrt{p^2 + q^2}\right) \times \frac{180}{\pi}$$ where $z_{E,W,N,S}$represent the elevation values of the four neighboring pixels to the east, west, north, and south of the center pixel, respectively. r is the input raster pixel resolution.
Elevation Difference (ED)	$$ED = max(z_i \in N) - min(z_i \in N)$$ where N is the neighborhood. z_i represents the elevation of each neighboring cell. Elevation Difference (ED) was calculated to quantify local terrain variation.
Elevation Ratio (ER)	$$ER = \frac{z_0 - min(z_i \in N)}{max(z_i \in N) - min(z_i \in N)}$$ where N is the neighborhood. z_0 represents the elevation of the central cell, and $z_i$represents the elevation of each neighboring cell. Elevation Ratio (ER) was calculated to quantify the relative height of each grid cell within its local neighborhood.
Topographic Roughness Index (TRI)	$$TRI = \frac{1}{cos\ cos\ (rad)}$$ $$rad = \frac{slope \times \pi}{180}$$ Where $slope$ is extracted from elevation dataset using 4 neighborhood size. TRI is a measure of variability in

the landscape surface.

Hydrological Connectivity Index (IC)

$$IC = \frac{D_{up}}{D_{dn}}$$

$$D_{up} = \underline{WS}\sqrt{A}$$

$$D_{dn} = \sum_{i} \frac{d_i}{W_i S_i}$$

where D_{up} and D_{dn} are the upslope and downslope components of connectivity, respectively. $\underline{W}$ is the average weighting factor of the upslope contributing area, $\underline{S}$ is the average slope gradient of the upslope contributing area (m/m) and A is the upslope contributing area $(m)^2$. d_i is the length of the flow path along the i^{th} cell according to the steepest downslope direction (m), W_i and S_i are the weighting factor and the slope gradient of the i^{th} cell, respectively. IC represents the potential sediment connectivity characteristics within a small alpine catchment.

Channel Network Baselevel (CHNL_BASE)

$$B = (E(x))$$

where B is the base level. $E(x)$ is the elevation profile function of the river along its course x. The Channel Network Baselevel represents the minimum elevations of a channel network.

Channel Network Distance (CHNL_DIST)

$$D = \sum_{i=1}^{n} L_i$$

where L_i is the length of each channel segment within the network, n is the total number of channel segments. The Channel Network Distance represents the distance along the channel network from each cell to the nearest channel network cell.

Terrain Surface Texture (TEXTURE)

$$T = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (h_i - \underline{h})^2}$$

where N is the total number of height measurements or sample points, h_i is the height of the terrain at the i-th sample point. $\underline{h}$ is the mean height of the terrain surface. Terrain Surface Texture measures the variation and roughness of the ground surface.

LS-Factor (LS)

$$LS = \left(\frac{m}{22.1}\right)^{0.4} \left(\frac{s}{0.0896}\right)^{1.3}$$

where m is the slope length in meters, S is the slope steepness or gradient in percent (rise over run, expressed as a percentage). The LS represents the combined effect of slope length and slope steepness on soil erosion.

Relative Slope Position (RSP)

$$RSP = \frac{h - h_{min}}{h_{max} - h_{min}} \times 100$$

where h is the elevation or height of the point of interest. h_{min} is the minimum elevation in the neighborhood around the point. h_{max} is the maximum elevation in the same neighborhood. Relative Slope Position is a crucial topographic aspect in peatland studies, influencing factors like erosion, and sediment transport.

Wetness Index (WETNESS)

$$WETNESS = ln\ ln\ \left(\frac{A}{tan\ tan\ \beta}\right)$$

where A is the contributing area, which represents the upslope contributing area to a point on the terrain surface. It is often calculated using algorithms that simulate surface water flow accumulation. β is the slope gradient. The WETNESS is a significant parameter used in hydrological analysis to assess the tendency of an area to accumulate water.

Profile Curvature (VCURV)

$$C_p = -\frac{d^2z}{dx^2}\left(1+\left(\frac{dz}{dx}\right)^2\right)^{-\frac{3}{2}}$$

where z is the elevation of the terrain surface. x is the horizontal distance along the profile. $\frac{dz}{dx}$ represents the slope gradient (first derivative of elevation with respect to distance). $\frac{d^2z}{dx^2}$ represents the second derivative of elevation with respect to distance, which describes the curvature of the profile. Profile Curvature quantifies the topographic influence on hydrological processes by considering both slope and the upstream contributing area per unit width orthogonal to the flow direction.

Plan Curvature ($HCURV$)

$$C_{pl} = -\frac{d^2z}{dy^2}\left(1+\left(\frac{dz}{dx}\right)^2\right)^{-\frac{3}{2}}$$

where z is the elevation of the terrain surface. x and y are the horizontal and vertical coordinates, respectively. $\frac{dz}{dx}$ and $\frac{d^2z}{dy^2}$ represent the first and second derivatives of elevation with respect to x and y, respectively. Plan Curvature reflects the rate of change in aspect along a contour line and is crucial for understanding flow convergence or divergence within a landscape.

Convergence

$$Convergence = -tan\,tan\,(\alpha) \cdot \frac{W}{A}$$

where α is the slope angle. W is the contour length perpendicular to the flow direction. A is the upslope contributing area. Convergence typically occurs in valleys or depressions where water from surrounding areas converges towards a central point, which is critical information in understanding hydrological

processes, especially in relation to water flow.