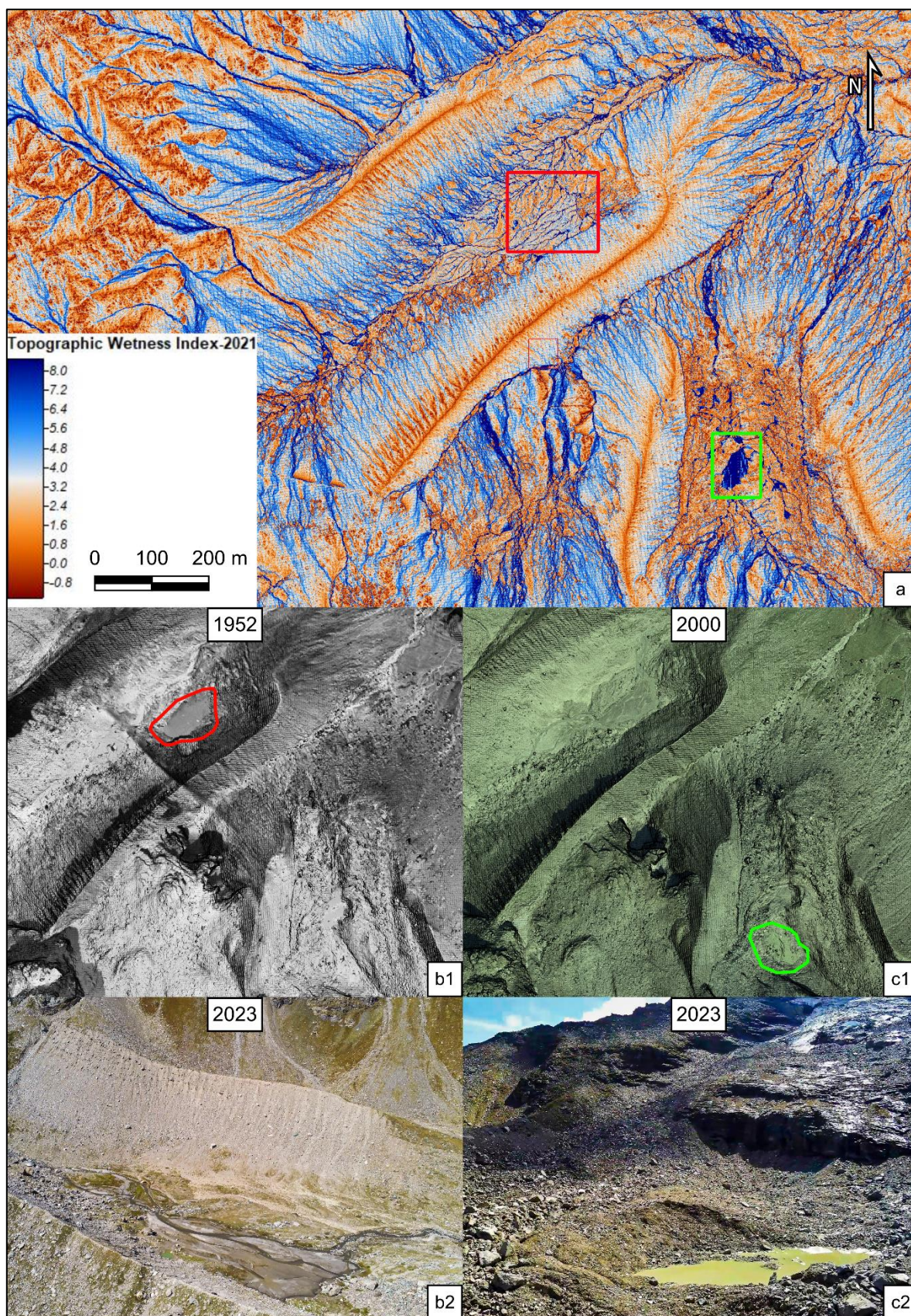


## Supplementary material



Sup. Fig. 1. The Topographic Wetness index (TWI) calculated on the 2000 DEM shows in blue the area of potential water accumulation (a); pictures b1-b2 and c1-c2 show, respectively, the evolution of the Aurona and Leone proglacial lakes through time.

| Year | N° photo/Type of service | Type                       | Source                                                                                                                                             | Product type/Derived        | Nominal scale (m)    | Graphic error (m) | Pixel (p m <sup>-2</sup> ) | $\sigma_{xy}$ (m) | $\sigma_z$ (m) |
|------|--------------------------|----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|----------------------|-------------------|----------------------------|-------------------|----------------|
| 1872 | /                        | WMS Dufour map             | SwissTopo – knowing where (admin.ch)                                                                                                               | Topographic                 | 1:25000              | 5                 |                            | 150               |                |
| 1888 | /                        | WMS Siegfried map          | SwissTopo – knowing where (admin.ch)                                                                                                               | Topographic                 | 1:50000              | 19                |                            | 35                |                |
| 1925 | /                        | WMS Siegfried map          | SwissTopo – knowing where (admin.ch)                                                                                                               | Topographic                 | 1:50000              | 19                |                            | 35                |                |
| 1928 | 5                        | Perspective Photo          | SwissTopo – knowing where (admin.ch)                                                                                                               |                             |                      |                   |                            | -                 |                |
| 1946 | 1                        | “American Survey”          | SwissTopo – knowing where (admin.ch)                                                                                                               |                             | 1                    |                   |                            | 5-10              |                |
| 1952 | 18                       | Aerial b/w photographs     | IGM                                                                                                                                                | Orthomosaic                 |                      |                   | 0.75                       |                   |                |
| 1958 | 1                        | Aerial Orthophoto          | SwissTopo – knowing where (admin.ch)                                                                                                               | -                           |                      |                   | 0.5-1                      | 1                 |                |
| 1968 | 4                        | Aerial b/w photographs     | SwissTopo – knowing where (admin.ch)                                                                                                               | Orthomosaic                 |                      |                   | 0.5-1                      | 1                 |                |
| 1981 | 1                        | Aerial Orthophoto          | SwissTopo – knowing where (admin.ch)                                                                                                               | -                           |                      |                   | 0.5-1                      | 1                 |                |
| 1993 | 3                        | Aerial Orthophoto          | SwissTopo – knowing where (admin.ch)                                                                                                               | -                           |                      |                   | 0.5-1                      | 1                 |                |
| 2000 | 1                        | Aerial Orthophoto          | SwissTopo – knowing where (admin.ch)                                                                                                               | -                           |                      |                   | 0.5                        | 0.5               |                |
| 2000 | 6                        | Aerial RGB                 | Alluvione 2000-IRPI<br><a href="https://www.fototeca.to.irpi.cnr.it/fototeca/index.php">https://www.fototeca.to.irpi.cnr.it/fototeca/index.php</a> | Ortho..., DEM               | approximately 1:5000 | 0.26              |                            | 0.26              | 0.38           |
| 2010 |                          | Orthophoto, LiDAR der. DEM | Geoportale Piemonte                                                                                                                                | -                           | 5m                   |                   |                            | 0.4               | 0.3            |
| 2015 | /                        | WMS Orthophoto             | Agea                                                                                                                                               | -                           |                      |                   |                            |                   |                |
| 2018 | /                        | WMS Orthophoto             | Agea                                                                                                                                               | -                           |                      |                   |                            |                   |                |
| 2020 | 9                        | Orthophoto                 | SwissTopo – knowing where (admin.ch)                                                                                                               | -                           | 0.1                  |                   |                            | 0.15              |                |
| 2021 | /                        | WMS Orthophoto             | Agea                                                                                                                                               | -                           |                      |                   |                            |                   |                |
| 2021 |                          | LiDAR Point Cloud, DEM     | SwissTopo – knowing where (admin.ch)                                                                                                               | -                           | 0.2                  |                   | 17.5                       | 0.2               | 0.1            |
| 2023 | 2091                     | UAV nadir/inclined         | UAV July 2023 Aurona                                                                                                                               | Point Cloud, DEM, Ortho.... | 0.036                |                   |                            | 0.09              | 0.11           |

Sup. Tab. 1. General datasets used in the analysis, indicated the source and the spatial resolution

| Workflow steps         | Description                                                                 |
|------------------------|-----------------------------------------------------------------------------|
| New project            | Select the datum and input camera calibration features.                     |
| Data input             | Manually select GCPs and measure residual errors in x, y, and z dimensions. |
| DEM extraction         | Extract the DEM using a high-detail, low-smoothing filter.                  |
| Orthomosaic production | Tie point collecting and orthomosaics generation.                           |

Sup. Tab. 2. Digital photogrammetry resumed workflow

| DATE                             | n° of photos                           | Aircraft Altitude a.s.l. [Zv] (m)   | Ground Elevation a.s.l. [Zt] (m) | Flight height a.g.l. [Z] (m) | Camera                               | Focal length on frame [c] (m) | Approximated scale [mb] | expected map scale [Δr]                  | graphic error [e] (m)               | Frame size [l] (m) |
|----------------------------------|----------------------------------------|-------------------------------------|----------------------------------|------------------------------|--------------------------------------|-------------------------------|-------------------------|------------------------------------------|-------------------------------------|--------------------|
|                                  |                                        |                                     |                                  | $z = Zv - Zt$                |                                      |                               | $mb = Z/c$              | $\Delta r = (mb/k) \wedge 2$             | $e = [\Delta r] * 0,2mm$            |                    |
| 2000                             | 6                                      | 4572                                | 2350                             | 2,222                        | Wild 15/4 UAG-S No 13204             | 0.152                         | 14618                   | 5342                                     | 1.068                               | 0.23               |
| Frame size on the ground [D] (m) | Distance between frame centres [b] (m) | Frame centers on the ground [B] (m) | Precision Coefficient [E]        | Precision coefficient [K]    | Acceptable error (half a pixel) (mm) | Necessary pixel size          | Minimum DPI scan        | $\sigma_{xy}$ (m)                        | $\sigma_z$ (m)                      | Scansion DPI       |
| $D = l * mb$                     |                                        | $B = mb * b$                        | $E = Z/B$                        | $K = B/Z$                    | $T = (m/2) * 10^3$                   | $P = (1/mb) * T$              | $25.4/P$                | $\sigma(xy) = [(mb * E) * (P/2)] / 10^3$ | $\sigma(z) = \sqrt{2} * \sigma(xy)$ |                    |
| 3362                             | 0.213                                  | 3120                                | 1.000                            | 0.639                        | 534.24559                            | 0.03655                       | 695.01350               | 0.26712                                  | 0.37752                             | 700                |

Sup. Tab. 3. Aerial photogrammetry features and error calculation.

| Workflow steps                              | Description                                                                                                                                  |
|---------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|
| Automated Mission Planning:                 | Using Pix4D Capture Pro (Pix4D SA, 2024) and conducting UAV surveys.                                                                         |
| Markers distribution and Coordinate Capture | Using a Leica CS-20 receiver in RTK mode for coordinates, with PPK post-correction where the RTK signal was unable.                          |
| Initial Alignment                           | Performed at the highest accuracy.                                                                                                           |
| Alignment                                   | Marker Placement and Camera Alignment Optimization.                                                                                          |
| Sparse Cloud Editing                        | Sparse Cloud Editing: Filtering tie points with a low image count ( $\leq 2$ ) and high reprojection error.                                  |
| Dense Cloud Creation                        | Dense Cloud Creation: Generated ultra-high quality with a medium-depth filter to remove outliers without losing significant information.     |
| Dense Cloud Filtering                       | Dense Cloud Filtering: Applied to remove values with confidence between 1-10 on a 1-100 scale, which could cause errors in subsequent steps. |

Sup. Tab. 4. Structure from motion resumed workflow

| Year | Glacier Area (Km <sup>2</sup> ) | Glaciers Reduction (%) | Aurona proglacial area (m <sup>2</sup> 10 <sup>4</sup> ) | Aurona Widening ± RMSE (m <sup>2</sup> 10 <sup>4</sup> ) | Aurona Widening Rate (m <sup>2</sup> y <sup>-1</sup> 10 <sup>4</sup> ) | Leone proglacial area (m <sup>2</sup> 10 <sup>4</sup> ) | Leone Widening ± RMSE (m <sup>2</sup> 10 <sup>4</sup> ) | Leone Widening Rate (m <sup>2</sup> y <sup>-1</sup> 10 <sup>4</sup> ) |
|------|---------------------------------|------------------------|----------------------------------------------------------|----------------------------------------------------------|------------------------------------------------------------------------|---------------------------------------------------------|---------------------------------------------------------|-----------------------------------------------------------------------|
| 1872 | 3.8 ± 1.48                      | -                      | -                                                        | -                                                        | -                                                                      | -                                                       | -                                                       | -                                                                     |
| 1888 | 3.0 ± 0.51                      | -21.1                  | -                                                        | -                                                        | -                                                                      | -                                                       | -                                                       | -                                                                     |
| 1928 | 2.8 ± 0.51                      | -26.3                  | 8.96 ± 12.21                                             | + 8.96 ± 12.21                                           | + 0.22                                                                 | -                                                       | -                                                       | -                                                                     |
| 1958 | 1.5 ± 0.01                      | -60.5                  | 30.75 ± 0.32                                             | + 21.79 ± 12.21                                          | + 0.73                                                                 | 19.07 ± 0.28                                            | + 19.07 ± 0.28                                          | + 0.64                                                                |
| 1981 | 1.5 ± 0.02                      | -60.5                  | 35.42 ± 0.43                                             | + 4.67 ± 0.54                                            | + 0.20                                                                 | 16.31 ± 0.28                                            | -2.76 ± 0.40                                            | - 0.12                                                                |
| 2000 | 1.1 ± 0.01                      | -70                    | 36.98 ± 0.19                                             | +1.57 ± 0.47                                             | + 0.083                                                                | 25.24 ± 0.14                                            | +8.93 ± 0.32                                            | + 0.47                                                                |
| 2010 | 0.9 ± 0.00                      | -76.3                  | 52.15 ± 0.19                                             | +15.17 ± 0.27                                            | +1.52                                                                  | 26.56 ± 0.14                                            | + 1.32 ± 0.20                                           | + 0.13                                                                |
| 2020 | 0.8 ± 0.00                      | -78.9                  | 52.15 ± 0.07                                             | + 0 ± 0.21                                               | + 0                                                                    | 27.37 ± 0.424                                           | + 0.81 ± 0.15                                           | + 0.08                                                                |

Sup. Tab. 5. Data selected for the glaciers and proglacial areas cover (Km2) monitoring.

| Area   | Sub-areas (moraine) | Monitoring years | Maximum displacement (m) | Mean displacement (m) |
|--------|---------------------|------------------|--------------------------|-----------------------|
| Aurona | Left (a1)           | 1958-1981        | 7                        | 1.3                   |
|        |                     | 1981-2000        | 8                        | 1.6                   |
|        |                     | 2000-2020        | 4.6                      | 0.7                   |
|        | Right (a2)          | 1958-1981        | 3.7                      | 1.2                   |
|        |                     | 1981-2000        | 4                        | 1.1                   |
|        |                     | 2000-2020        | 5.7                      | 1.8                   |
| Leone  | Left (a3)           | 1958-1981        | 6.7                      | 1.5                   |
|        |                     | 1981-2000        | 1.9                      | 0.5                   |
|        |                     | 2000-2020        | 3.4                      | 0.8                   |

Sup. Tab. 6. Results of the monitoring of the Aurona and Leone moraines ridge regressive displacement.

| Monitoring period | N° monitored boulders | Lower velocity (m y <sup>-1</sup> ) | Higher velocity (m y <sup>-1</sup> ) | Mean velocity (m y <sup>-1</sup> ) | Mean Azimuth direction (°) |
|-------------------|-----------------------|-------------------------------------|--------------------------------------|------------------------------------|----------------------------|
| 1958-1968         | 11                    | 3.6                                 | 9.8                                  | 5.8                                | 316.8                      |
| 1968-1981         | 13                    | 0.8                                 | 4.8                                  | 3.4                                | 299.5                      |
| 1981-1993         | 19                    | 0.4                                 | 3.6                                  | 2.1                                | 240.5                      |
| 1993-2000         | 61                    | 0.3                                 | 5.6                                  | 1.4                                | 238.9                      |
| 2000-2010         | 66                    | 6.8                                 | 0.2                                  | 1.2                                | 235.5                      |
| 2010-2015         | 57                    | 0.1                                 | 7.1                                  | 1.1                                | 242.4                      |
| 2015-2020         | 106                   | 0.1                                 | 2.5                                  | 0.7                                | 223.9                      |

Sup. Tab. 7. Boulders monitoring on the Leone proglacial area.