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Invited research article

The sediment sources availability index: Application of a new semi-quantitative index to assess the potential connectivity of sediment sources at the catchment scale☆

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ABSTRACT

The study introduces and applies the Sediment Sources Availability Index (SSAI), a new semi-quantitative method designed to assess the structural availability of sediment sources within mountain catchments. The method is applied to the Aurona creek catchment (Alpe Veglia, north-western Italian Alps), a paraglacial evolving basin strongly affected by glacier retreat. The research highlights the region's sediment cascade features, emphasising its structural connectivity characteristics. This catchment area is characterised by a complex interplay between various deposit types, influenced by ongoing climate change and permafrost degradation. Combining geomorphological mapping, field surveys, and high-resolution Digital Elevation Models, the SSAI integrates structural connectivity assessments and deposit characteristics to evaluate possible sediment sources and transport pathways. The framework combines the Index of Connectivity (*IC*) with the newly developed Erodibility index (*Ei*), which accounts for sediment granulometry and cohesion. Results highlight that sediment-source availability cannot be inferred from morphometric connectivity alone, highlighting the dual role of proglacial area landforms as sediment stores, barriers, and potential sediment sources. The SSAI provides a rapid first-order assessment of structural sediment availability, supporting sediment-cascade analysis, river management and geoconservation, while providing a robust basis for further functional sediment-connectivity investigations.

1. Introduction

Alpine environments, where glaciers strongly condition landscape evolution, are among the regions most affected by ongoing climate change (IPCC 2022). Glacier recession has profound implications for mountain ecosystems, influencing hydrological, geomorphological and ecological processes (Bollati et al. 2023). These environments typically evolve under paraglacial conditions (Ballantyne 2002), progressively transitioning towards a new equilibrium state of non-glacial conditions, characterised by decreasing glacier extent and volume, coupled with the widening of glacier forefields (D'Agata et al. 2020) and permafrost degradation (Bollati et al. 2023). Sediment fluxes respond to these changes (Stoffel et al. 2014), generally showing an initial increase associated with enhanced meltwater production, followed by progressive sediment exhaustion as catchments evolve from glacier-melt to rainfall-dominated regimes (Lane et al. 2017; Zhang et al. 2022).

The monitoring of suspended sediment fluxes provides fundamental information on sediment supply and, indirectly, on denudation rates within a catchment. However, suspended sediment monitoring alone could not explain the complexity of sediment transfer processes nor identify the relative contribution of the different sediment sources, stores, and transfer pathways composing the sediment cascade. Sediment connectivity (sensu Heckmann et al. 2018) has therefore become one of the key concepts for describing sediment behaviour and, consequently, the ongoing geomorphological evolution of mountain catchments. It can be defined as the degree to which landscape morphology facilitates the transfer of water and sediment through the coupling relationships between its components (Heckmann et al. 2018). The

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interaction between these components determines the continuity of sediment transfer from sources to sinks and ultimately controls the efficiency of the sediment cascade (Cavalli et al. 2019a).

Mountain catchments typically include a wide variety of depositional landforms characterised by contrasting sedimentological and geomorphological properties. Unstable glacial deposits, such as Little Ice Age (LIA) moraines, together with gravity-related deposits including debris cones and debris-flow fans, often represent important sediment sources (Ballantyne 2002). Furthermore, sediment transfer is not a static concept (Comiti et al. 2019). Its efficiency depends on time-varying forcing factors, including precipitation, temperature and geomorphological processes, whose magnitude changes seasonally and between individual events. Consequently, depositional landforms with similar sedimentological characteristics may exhibit different behaviours depending on the prevailing hydrogeomorphological conditions, alternately acting as sediment sources, temporary stores or buffer zones (e.g., Cossart and Fort 2008). This variability makes it difficult to determine the actual role of sediment deposits within the sediment cascade (Cavalli et al. 2019a; Buter et al. 2020; Buter et al. 2022).

Following Wainwright et al. (2011), structural connectivity describes the spatial configuration, the "anatomy", of a landscape, whereas functional connectivity represents the realised sediment transfer resulting from the interaction between structural conditions and time-dependent forcing factors (Heckmann et al. 2018).

Depositional landforms may therefore alternate between different roles within the sediment cascade. Scree slopes and scree cones may behave as sediment stores buffer zones (sensu Fryirs et al. 2007) or sediment sources depending on their degree of coupling with the drainage network. Similarly, debris flows may renew lateral connectivity, reconnecting previously isolated sediment stores to the active channel network (e.g., Cossart and Fort 2008). Frontal and lateral moraines generally act as barriers that locally interrupt sediment transfer (Cossart and Fort 2008; Heckmann and Schwanghart 2013). However, paraglacial processes progressively modify these landforms, potentially shifting their role from sediment barriers to sediment sources and occasionally generating large sediment-transfer events capable of producing significant downstream impacts (Chiarle et al. 2007; Bollati et al. 2019).

Lane et al. (2017) highlighted the effects of glacier retreat on sediment connectivity and supply, showing how negative feedbacks may progressively reduce sediment production despite increasing connectivity. Kociuba (2017) investigated the morphological evolution of a glacial valley by identifying the principal sediment sources, quantifying their spatio-temporal variability and evaluating their contribution to the sediment cascade. These studies highlighted the importance of glaciers, valley-floor deposits, channel sediments, hillslope processes and the active permafrost layer in controlling sediment transfer.

Due to their unconsolidated sediments, moraines, particularly those formed during the LIA, represent both important sediment stores and intermittent sediment sources (Carrivick et al. 2013). Likewise periglacial landforms such as rock glaciers may disconnect hillslopes from the drainage network or, owing to their roughness, reduce sediment transport by acting as sediment traps (Becht et al. 2015). Their role as sediment sources mainly depends on debris production along their margins, a process that may be enhanced by permafrost degradation through the progressive loss of ice cementation and the consequent reduction in sediment cohesion (Kummert et al. 2018; Kofler et al. 2022). Within proglacial areas, defined as the areas comprised between LIA glacier border and the current glacier front (sensu Schiefer and Gilbert 2007), paraglacial evolution commonly involves the formation of ephemeral proglacial lakes, which further contribute to sediment storage and local disconnection (Bollati et al. 2023).

A substantial body of literature has attempted to quantify the relationship between sediment sources and the sediment cascade through different approaches. Connectivity indexes (Heckmann et al. 2018) have been adopted to quantify structural connectivity both between hillslopes and channels (lateral connectivity) and along river networks (longitudinal connectivity). On the other hand, thematic maps, such as geological and geomorphological ones, provide valuable information for identifying sediment deposits and distinguishing the different morphogenetic processes influencing sediment transfer (Bollati et al. 2024).

Several studies have attempted to combine these approaches. Borselli et al. (2008) introduced the Index of Connectivity (*IC*) using the RUSLE C-Factor in agricultural catchments. Cavalli et al. (2013) subsequently adapted the *IC* to mountain catchments by introducing a roughness-based metric suitable for high-resolution Digital Elevation Models (DEM). Messenzehl et al. (2014) compared *IC*-derived connectivity patterns with geomorphological field mapping in a formerly glaciated valley. Tiranti et al. (2016, 2018) and Cavalli et al. (2017) investigated the relationship between *IC* and potential sediment sources identified through remote sensing and field observations, with particular emphasis on debris flows. Furthermore, Heckmann and Schwanghart (2013) and Buter et al. (2022) further explored sediment connectivity through graph theory, whereas Steger et al. (2022) and Pitscheider et al. (2024) integrated debris-flow susceptibility with structural connectivity.

Geomorphological mapping has also been increasingly used to infer sediment connectivity. Buter et al. (2020) derived connectivity characteristics directly from mapped geomorphological landforms, while Martini et al. (2022) demonstrated the effectiveness of the *IC* as a semi-quantitative indicator of structural connectivity, although highlighting limitations in predicting functional sediment connectivity.

Although these studies improved the understanding of sediment-source behaviour, they rarely provide a reproducible framework integrating geomorphological characteristics of sediment deposits with morphometric connectivity into a single spatial index capable of assessing sediment-source availability.

To address this gap, this study proposes the Sediment Sources Availability Index (SSAI), a semi-quantitative index providing a preliminary assessment of structural sediment-source availability. The SSAI integrates geomorphological information describing sediment properties through a newly developed Erodibility index (*Ei*) with morphometric structural connectivity derived from the Index of Connectivity (*IC*). In this way, the SSAI explicitly combines the intrinsic characteristics of sediment deposits with their structural connectivity, allowing sediment-source availability to be evaluated in addition to morphometric connectivity.

In this study, conducted in an alpine catchment undergoing deglaciation (Alpe Veglia, north-western Italian Alps), the SSAI is specifically designed to identify potential sources of suspended sediments under ordinary flow conditions. This choice reflects the monitoring evidence collected since 2021 along the Rio Aurona stream, draining the catchment, where suspended sediment load represents the dominant fraction of the total solid transport measured at the selected outlet.

2. Study area

2.1. Geographical and climate features

The Aurona creek catchment (Fig. 1a) is a high mountain watershed featuring 9.4 km^2. The Rio Aurona receives meltwater from the Leone and Aurona glaciers in the south-western sector of the catchment and joins the Rebbio stream, which drains the northern slopes before flowing first into the Cairasca, then into the Toce River, a tributary of Lake Maggiore. The catchment belongs to the Lepontine Alps (north-western Italian Alps) and has a mean elevation of approximately 2500 m a.s.l., ranging from the summit of Monte Leone (3553 m a.s.l.) to the outlet at 1740 m a.s.l. in the Alpe Veglia valley floor (site named *Ponte*). Mean annual precipitation averages about 1300 mm (ARPA 2022), with snowfall generally occurring between November and April. Precipitation is mainly concentrated during Spring and Autumn, although intense Summer storms may temporarily reactivate functional sediment

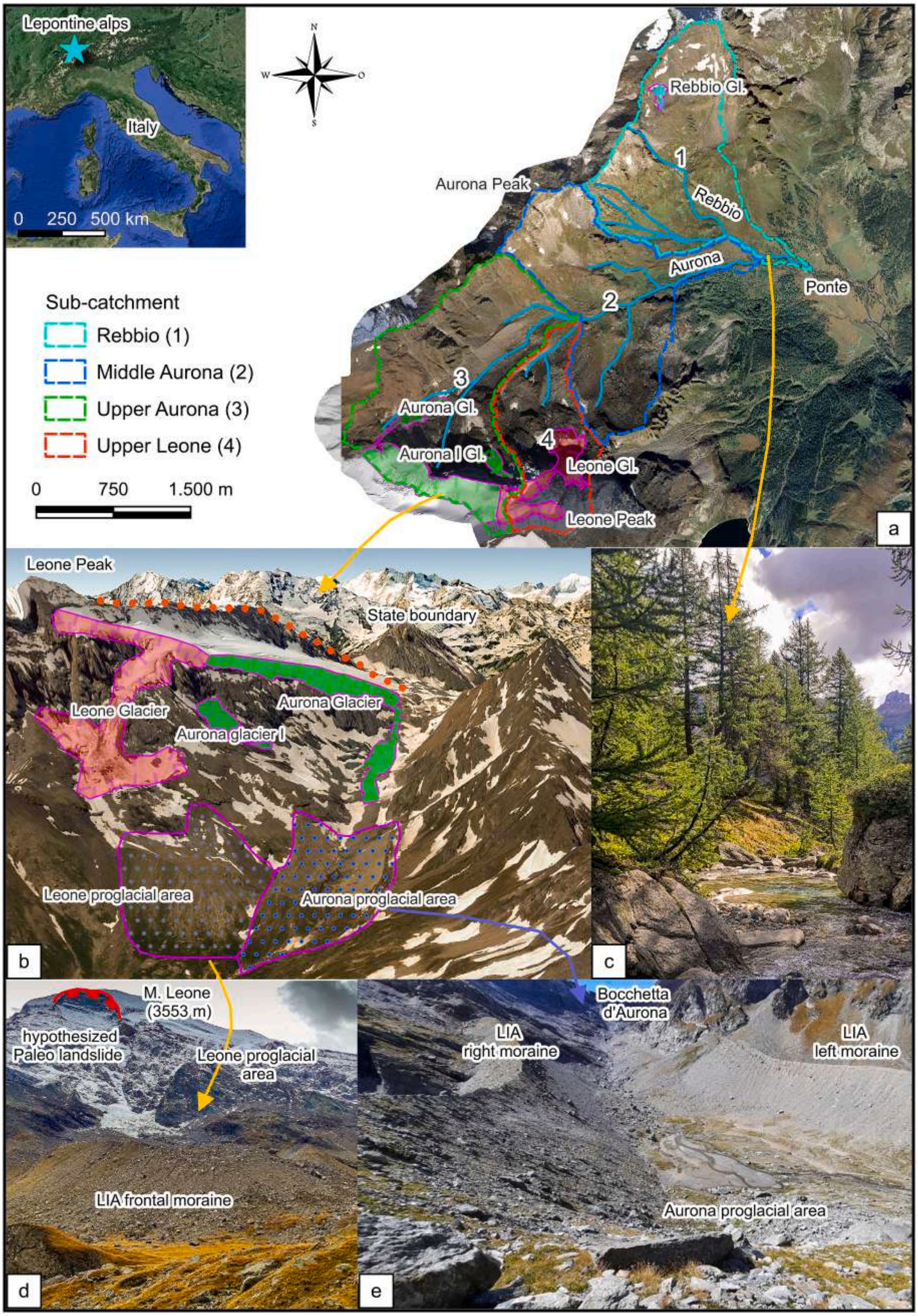

Fig. 1. Study area: nadiral view of the Aurona creek catchment and of the four sub-catchments (a). NE-SW perspective view on the Aurona and Leone proglacial areas (b). Representative view of the Rio Aurona course in proximity to the outlet point in Ponte locality (c). Focus on the Leone northern wall and proglacial plain from a N-S view (d). Focus on the Aurona proglacial plain from a NE-SW view (e).

connectivity.

The catchment currently hosts three glaciers located along the Italian-Swiss border, partially extending into Swiss territory (Smiraglia et al. 2015). The largest glacierized sector is located in the south-western part of the basin (Fig. 1b) and includes the Leone Glacier (0.31 km^2 3.3% of the catchment) and the Aurona Glacier, which is divided into two bodies: Aurona (0.35 km^2, 3.7%) and Aurona I (0.04 km^2, 0.4%). In the northern sector, the Rebbio Glacier (0.02 km^2, 0.2%) persists as a small hanging glacier.

The study site lies within the Alpe Veglia and Devero Natural Park, established in 1995.

The catchment forms part of the IAG-Denuchange long-term environmental observatory (GFL 2022), where hydrogeomorphological monitoring has been conducted since 2021 (Tronti 2025; Tronti et al. 2024; Tronti et al. 2026).

2.2. Geological and geomorphological setting

The study area (Fig. 1) features the outcrop of the Pennidic Units of the Western Alps, characterised by alternating basement and meta-sedimentary nappes arranged in overturned anticlines (Rigamonti and Uggeri 2016).

The main lithologies are represented by:

- Calcschist, which outcrops locally in the southwest and northeast of the Aurona catchment, as at the “Rossetto” residual spur.
- Paragneiss and ortogneiss belong to two different geological units: the Berisal unit and the Monte Leone unit. The first unit outcrops intercalated with the previous ones along the northern boundary of the catchment and in the northern Monte Leone area. The second unit outcrops in the centre of the Aurona catchment, in the proximity of the “Rossetto”.
- Prasinites outcrop locally in the southwestern area, in the surroundings of the “Bocchetta d'Aurona”, where the glacier is rapidly retreating.
- Quaternary deposits cover the remnant part of the area; they are mainly derived from ice-, water- and gravity-related processes acting on the slopes and covering the Veglia glacio-alluvial plain, which represents the local base level of this study.

According to Steck et al. (2013) and Piana et al. (2017), the Veglia Plain occupies a structural depression controlled by the Veglia Fault Zone, which guided glacier erosion and was subsequently occupied by a lacustrine basin before evolving into the present fluvial plain (Rigamonti and Uggeri 2016). Today, the plain represents the local base level of the Aurona catchment and includes a sequence of five fluvial terrace orders, with a maximum relative elevation of approximately 3 m in the Ponte sector (Fig. 1a).

From a geomorphological perspective, gravity-related processes dominate the steep valley sides, where talus slopes, debris cones and debris-flow deposits alternate with Pleistocene and Holocene glacial deposits. Among these, the LIA moraines of the Aurona, Leone and Rebbio glaciers constitute some of the most prominent depositional landforms within the catchment. Since glacier retreat, these landforms have been progressively reworked by gravitational, fluvial and periglacial processes associated with ongoing paraglacial adjustment, modifying both sediment availability and structural sediment connectivity. Extreme meteorological events may suddenly reactivate the sediment delivery, as recently occurred in 2000 and 2020 (e.g., Golzio et al. 2020).

Because the SSAI specifically targets potential sediment sources, depositional landforms constitute the principal geomorphological units investigated in this study.

3. Material and methods

3.1. Geomorphological survey and mapping

For the geomorphological mapping, we applied the Italian national guidelines (Campobasso et al. 2021). Accordingly, we classified the primary lithologies in a simplified classification based on the main response to the morphological processes, distinguishing three main groups: Carbonate and schistose metamorphic rocks (calcschist), massive metamorphic rocks (paragneiss and ortogneiss) and schistose metamorphic rocks (prasinite, micaschists).

Given the purposes of this study, which proposes a structural sediment assessment, different surveys were conducted to classify the main processes and landforms in the area. We coupled field surveys with photointerpretation of orthomosaics, perspective photos and drone surveys.

Both erosional and depositional landforms were mapped, with particular emphasis on depositional landforms, which were considered potential sediment stores that may act as sediment sources depending on their structural characteristics.

According to the Italian national guideline's classification (Campobasso et al. 2021), information about granulometric classes (boulders, cobbles, gravel, sands, silts and clays and combinations, Suppl. mat. 1. Tab. A) and degree of cohesion (loose vs cemented) were also recorded and used as proxies to assess the Erodibility index (par. 3.3.2).

We represented the landforms through polygonal vectors, using QGIS 3.43.3 Prizren (QGIS 2024), which were delineated as homogeneous areas at the survey scale of 1:10,000.

3.2. Descriptive analyses

To better distinguish among the main contributors in terms of sediment sources, we subdivided the Aurona catchment into four sub-catchments: Rebbio (1), Middle Aurona (2), Upper Aurona (3), Upper Leone (4). Each sub-catchment was defined in terms of surface (km^2) and relative surface with respect to the whole catchment (%), average slope (°), average elevation (m a.s.l.), lithotype cover (km^2, %) and prevalent geomorphic process (km^2, %), (Table 1).

3.3. Sediment sources availability index (SSAI) development

The Sediment Sources Availability Index (SSAI) is a semi-quantitative index that integrates morphometric connectivity with the geomorphological characteristics of sediment deposits within a Geographic Information System (GIS).

The workflow combines the Index of Connectivity (*IC*) with a newly developed Erodibility index (*Ei*) to assess the structural availability of potential sediment sources. Spatial analyses and data processing were carried out using ArcGIS Pro 3.2 (ESRI 2024), QGIS 3.43.3 Prizren (QGIS 2024), SAGA (Conrad et al. 2024) and GDAL processing tools.

Table 1
General features for each sub-catchment in the study area.

Catchment	Surface (km^2)	Relative surface (%)	Average elevation (m a.s.l.)	Average slope (°)
Rebbio (1)	2.4	25.5	2401.5	33.6
Middle Aurona (2)	2.5	27.1	2289.4	30.1
Upper Aurona (3)	3.1	32.8	2657.4	35.9
Upper Leone (4)	1.4	14.7	2709.9	35.7

3.3.1. Index of connectivity (IC)

SSAI considers lateral and longitudinal structural connectivity at catchment and sub-catchment scales (Wainwright et al. 2011; Heckmann et al. 2018). Sediment connectivity is here defined as the probability that sediment released from a given source reaches a selected outlet (Crema and Cavalli 2018). Among the different connectivity indices proposed in the literature (Heckmann et al. 2018) the Index of Connectivity (*IC*) developed by Cavalli et al. (2013) was selected because of its demonstrated performance in small mountain catchments (e.g., Bollati and Cavalli 2021) and its straightforward reproducibility. The *IC* quantifies structural connectivity using morphometric characteristics derived from a Digital Elevation Model (DEM) and is computed as the logarithm of the ratio between an upslope and a downslope component, expressing the potential connection between sediment sources and the selected outlet.

The *IC* map was derived from the 5 m resolution DEM provided by the Piedmont region (Regione Piemonte 2011) using the *SedinConnect* tool (Crema et al. 2015; Crema and Cavalli 2018). A 3 × 3 moving window was adopted to calculate surface roughness and the corresponding weighting factor. The resulting raster was subsequently resampled to a 20 m spatial resolution using the average method. This operation reduced local variability while producing connectivity polygons more consistent with the dimensions of the mapped depositional landforms and with the final representation scale (1:7000) of the SSAI map. The continuous *IC values* were then classified into five connectivity classes of increasing connectivity, using the quantile method (Class 1 - Very Low: $IC \leq -4.58$; Class 2 - Low: $-4.58 < IC \leq -4.36$; Class 3 - Medium: $-4.36 < IC \leq -4.13$; Class 4 - High: $-4.13 < IC \leq -3.87$; Class 5 - Very High: $IC > -3.87$.

Then, homogeneous vector polygons were generated from the classified raster using the GDAL “Contour Polygons” algorithm.

3.3.2. Erodibility index (Ei)

The classification of potential sediment-source areas was based on the geomorphological surveys and the resulting geomorphological map of the study area. The Erodibility index (*Ei*) was developed as a simple expert-based classification to distinguish the potential behaviour of depositional landforms according to their geomorphological characteristics. The adoption of an expert-based approach reflects the need to provide a reproducible preliminary assessment of sediment-source availability from geomorphological mapping.

Following the approach proposed by Buter et al. (2020), 134 non-overlapping polygons, representing 14 depositional landform types, were identified and classified (Suppl. mat. 1 Tab. B). Bedrock outcrops were excluded from the analysis because their contribution to sediment transfer depends on episodic rockfall and rock-slope failure processes, whose magnitude and frequency differ substantially from those governing unconsolidated sediment deposits. Although deglaciation (and related debuttressing) and the establishment of periglacial conditions may increase rockfall activity (Ballantyne 2002; Cossart et al. 2008), these stochastic processes were considered outside the scope of the present structural assessment.

The classification of landforms was derived from the combination of two binary qualitative indices: the Granulometric Index (*Gi;* Table 2) and the Cohesion Index (*Ci*; Table 3). A binary classification was deliberately adopted to maximise reproducibility among operators and minimise the subjectivity associated with assigning intermediate classes. Similarly to Tiranti et al. (2014) and Tiranti and Deangeli (2015), the fourteen depositional landforms were hence grouped into four *Ei* classes (A-D; Table 4) to simplify map interpretation while preserving the main differences in sediment behaviour.

Both indices were assigned through field observations and photointerpretation, considering the geomorphological characteristics of each depositional landform.

The Granulometric index (*Gi)* describes the expected abundance of fine sediments (clays, silts and sands) within each depositional landform (Table 2). The assumption is that, under the ordinary flow conditions considered in this study, fine sediments are more easily mobilised and transported over long distances than coarse material, requiring lower hydraulic energy to enter the sediment cascade. Conversely, coarse sediments (gravels, cobbles and boulders) generally require high-magnitude events to be mobilised and therefore tend to remain closer to their source areas.

Deposits enriched in fine sediments are therefore considered to have a greater probability of contributing to suspended sediment transport than coarse-grained deposits. This assumption is supported by the hydrogeomorphological monitoring programme initiated in 2021 in *Ponte* locality, which indicates that suspended sediments constitute the dominant component of the total solid load measured at the catchment outlet (Tronti et al. 2024).

Accordingly, two qualitative classes of *Gi* were defined from the granulometric information collected during the geomorphological

Table 2
Granulometric index-Gi categories.

Granulometric index (*Gi*)	Description	Granulometric classes (Campobasso et al. 2021; Table C)	Deposit examples in the study area
0	Low-moderate abundance of clays, silts and sands, coarse sediments with open-work or partially open-work texture	• boulders • cobbles • gravel • boulders and cobbles with little or no matrix • gravel with little or no fine-grained matrix	• scree slope • debris cone • avalanche cones • rockfall-toppling deposits • coarse debris in the riverbed • erratic block fields
1	Moderate-high abundance of clays, silts and sands, clast-matrix supported and unsorted	• sands • silts and clays • sands with a fine-grained matrix • low-plasticity silts and clays • high-plasticity silts and clays	• eluvial-colluvial cover • debris flow deposits • translational slide deposits • glacial deposits • fluvioglacial plains • kame deposits • rock glaciers

Table 3
Cohesion index-Ci categories.

Cohesion Index (*Ci*)	Description	Deposit examples in the study area
0	Consolidated, vegetated deposits; Stable permafrost	• consolidated glacial deposits • erratic block fields permafrost featured glacial deposits • rock glaciers • kame deposits • consolidated scree slope deposits • consolidated debris cone deposits
1	Loose deposits; Absent or degraded permafrost	• eluvial-colluvial cover • debris flow deposits • rockfall-toppling deposits translational slide deposits • loose glacial deposits, • talus deposits • scree slope deposits • debris cone deposits • fluvioglacial deposits • avalanche cone deposits • alluvial coarse debris

Table 4
Deposit erodibility classification.

Deposit class	*Gi* and *Ci*	*Ei*	Description	Deposit examples in the study area
A	1; 1	2	Unconsolidated deposits, absence of permafrost or presence of degraded permafrost, clast-matrix supported texture and unsorted texture, moderate to high abundance of clays, silts, and sands	Eluvial-colluvial cover, debris flow deposits, unconsolidated glacial deposits, transitional slide deposits, fluvioglacial deposits
B	0; 1	1	Unconsolidated deposits, characterised by the absence of permafrost or the presence of a degraded one, mainly consisting of coarse sediments with open-work or partially open-work texture	Talus deposits, scree slope, debris cone, avalanche cone, rockfall-toppling deposits, coarse debris in riverbed
C	1; 0	1	Consolidated deposits (dense, cemented, vegetated, or characterised by the stable presence of permafrost) characterised by sorted or unsorted clasts or matrix-supported, with a moderate to high abundance of clays, silts and sands	Overconsolidated/ permafrost featured glacial deposits, rock glaciers, kame deposits
D	0; 0	0	Consolidated deposits (dense, cemented, vegetated, or featured by the stable presence of permafrost) characterised by sorted or unsorted clasts or matrix-supported, with a moderate to low abundance of clays, silts and sands	Consolidated scree slope, consolidated debris cone, erratic block fields

surveys (Table 2; Suppl. mat. 1 Tab. A): *Gi* = *0:* low to moderate abundance of fine sediments (clays, silts and sands), dominated by coarse open-work or partially open-work sediments; *Gi* = *1:* moderate to high abundance of fine sediments characterised by matrix-supported and poorly sorted deposits.

The Cohesion index (*Ci)* describes the degree of deposit stabilisation by considering sediment consolidation (cemented or loose), compactness and vegetation cover, as an additional stabilising factor (Table 3). These characteristics provide an indirect proxy for the activity of the erosional processes responsible for production of debris and the consequent formation of deposits, which may represent potentially available sediment stores. In general, consolidated deposits are hardly remobilised, whereas unconsolidated deposits are more likely to be transported under current active processes.

The activity status of erosional processes potentially involving stored sediments, was also assessed based on data from Tronti et al. (2026), who, through multi-temporal monitoring focused on the Aurona and Leone proglacial areas, documented the relationship between sediment features and their evolution through time.

Permafrost conditions strongly influence the mechanical cohesion of unconsolidated sediments. Stable permafrost generally increases sediment cohesion through ice cementation, whereas permafrost degradation progressively reduces this effect, promoting sediment loosening and increasing the potential for sediment remobilisation. For this reason, permafrost occurrence was explicitly incorporated into the Cohesion Index.

Permafrost occurrence was assessed using the Alpine Permafrost Index (API), a statistical model developed within the *Permanet* project (Boeckli et al. 2012a, 2012b), following the approach proposed by Buter et al. (2022). The API was derived from multiple environmental variables, including rock glaciers, ground surface temperature, land cover and topographic characteristics, and distinguishes three probability classes of permafrost occurrence: I) Permafrost in all conditions; II) Permafrost in cold conditions; III) Permafrost only in very favourable conditions.

Considering both the spatial resolution of the API and its reference period (2012), the index was used as a qualitative indicator for permafrost occurrence. The API was therefore integrated with photo-interpretation and field surveys to verify current permafrost conditions, particularly within classes II and III (Table 3), where ongoing paraglacial evolution may have significantly modified permafrost distribution.

The Cohesion Index was then assigned by combining the geomorphological map with the API (Fig. 2), distinguishing two qualitative classes:

- *Ci* = *0:* consolidated deposits showing stable permafrost conditions (*API* classes I and II), where ice cementation contributes to maintaining sediment cohesion, and/or vegetation cover, generally associated with inactive or slowly evolving landforms.
- *Ci* = *1:* unconsolidated or loose deposits located within *API* class III showing absence of permafrost or evidence of permafrost degradation (e.g., ice cliffs and surface subsidence), generally associated with evolving or recently reworked landforms and therefore characterised by a greater potential contribution to sediment supply.

Finally, the Erodibility index (*Ei*) was obtained by combining the Granulometric Index (*Gi*) and the Cohesion Index (*Ci*):

$$Ei = Gi + Ci \tag{1}$$

Ei qualitatively evaluates the availability of fine sediments from different sediment sources by integrating morphogenetic processes, depositional landforms, sediment characteristics, and land cover.

From the combination of *Gi* and *Ci*, four deposit classes were derived as reported in Table 4 and Fig. 3.

3.3.3. Sediment sources availability index computation

Following the concept of Unique Conditions Units (UCUs, i.e., areal units defined by unique combination of the selected conditioning factors; Calcaterra et al. 2010; Tronti et al. 2023), commonly adopted in susceptibility analyses, the Sediment Sources Availability Index (*SSAI)* was derived by combining the Index of Connectivity (*IC*) and the Erodibility index (*Ei*). The overlay of the two thematic maps generated new polygons characterised by unique combinations of *IC* and *Ei* values:

$$SSAI = IC^{*}Ei \tag{2}$$

The resulting SSAI values were subsequently reclassified into five classes of increasing sediment source availability with respect to the selected outlet (Class 1 - Very Low: 0–1, Class 2 – Low: 1–2, Class 3 – Medium: 3–4, Class 4 – High: 5–6, Class 5: Very High: 8–10). The final SSAI map was produced at a scale of 1:7000.

4. Results

4.1. Geomorphological survey and mapping

From the geomorphological survey, maps of the lithologies (Fig. 4, Suppl. mat. 1, Tab. C), of the geomorphological processes (Fig. 5, Suppl. mat. 1. Tab. D), and of landforms distribution (Fig. 6) were produced.

Within the Rio Aurona catchment, depositional landforms constitute the dominant component (55.6%), mainly represented by Quaternary deposits, followed by massive metamorphic rocks (31.3%), carbonate

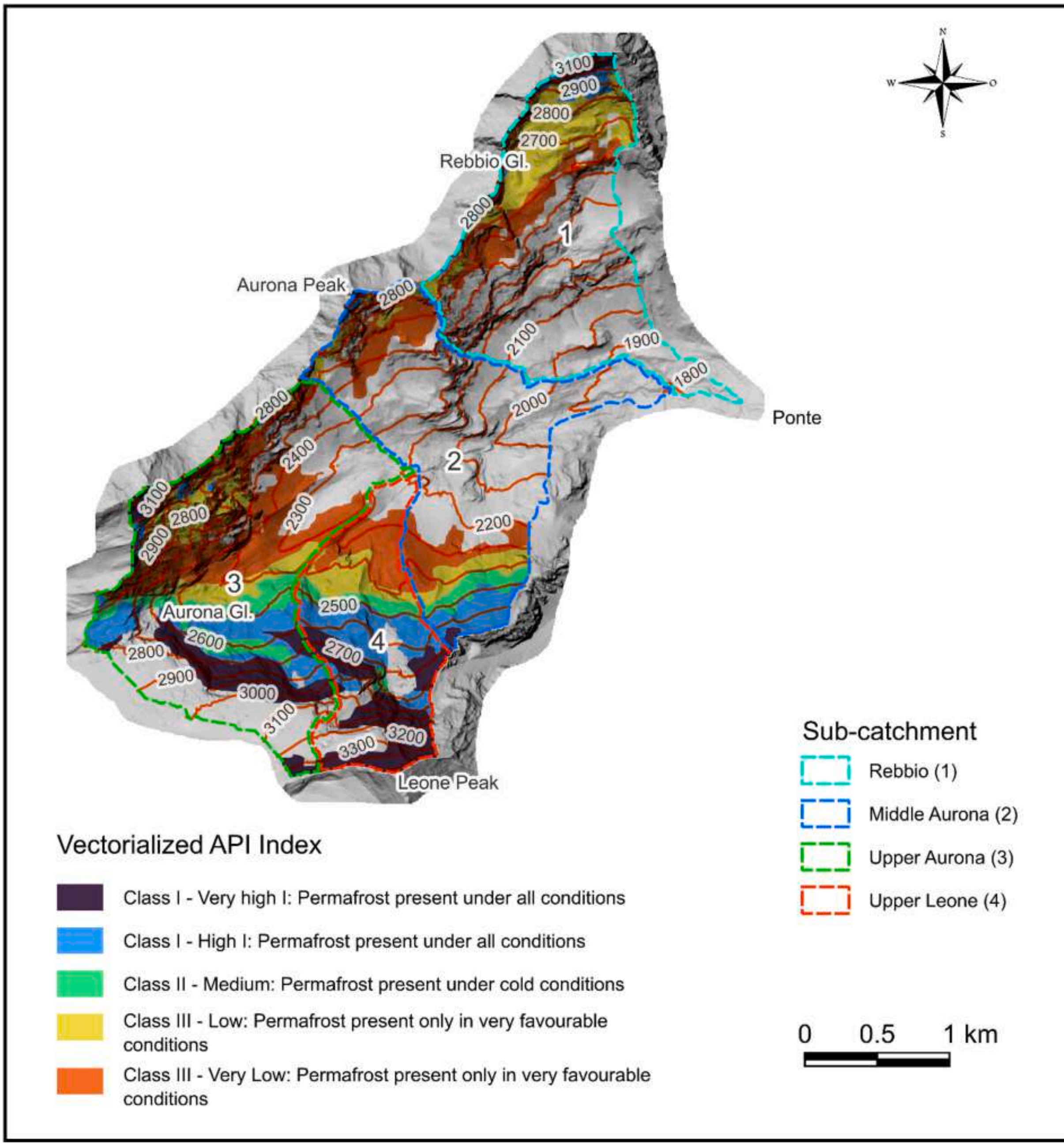

Fig. 2. Alpine Permafrost Index Map, Vector adaptation of the original raster map (Boeckli et al. 2012a, 2012b). Base layer hillshade derives from the 5 m resolution DTM of the Piedmont region (Regione Piemonte 2011).

schistose metamorphic rocks (4.8%) and schistose metamorphic rocks (0.1%).

This pattern is particularly evident in the Rebbio (1), and Middle Aurona (2) sub-catchments, where depositional landforms clearly prevail over bedrock outcrops. This is particularly true for the Middle Aurona, where the deposits cover up to 80% of the catchment. Conversely, bedrock outcrops dominate in Upper Aurona (3) and Upper Leone (4), particularly at the highest elevations.

The distribution of the geomorphological processes (Fig. 4) and landforms (Fig. 6) reflects the present and past glacial configuration of the catchments. Nivoglacial landforms are associated with the residual Rebbio, Aurona and Leone glaciers and include semi-permanent snowfields occupying favourable topographic settings at high elevations, together with glacial lakes located within the Rebbio foreland and, seasonally, within the Leone proglacial area.

Historical evidence indicates that a proglacial lake was also present within the Aurona foreland from at least 1952 (Tronti et al. 2026; Fig. 7d), during a phase of general glacier retreat. The former lake basin is currently infilled by extensive fluvioglacial deposits, and it remains only partially connected to the outlet.

Periglacial and nival landforms occupy a relatively small part of the catchment and are mainly concentrated in the Upper Leone sub-catchment (8%), where the proglacial area shows permafrost-related features and a morphology resembling that of a rock glacier. Snow avalanche cones are mainly distributed within the Rebbio (1) and Middle Aurona (2) sub-catchments.

Considering only the distribution of processes and landforms, glacial landforms dominate the Rebbio (~69%), Upper Aurona (~44%) and Upper Leone (~46%) sub-catchments. These are mainly represented by glacial deposits, but also include erratic boulder surfaces, kame terraces,

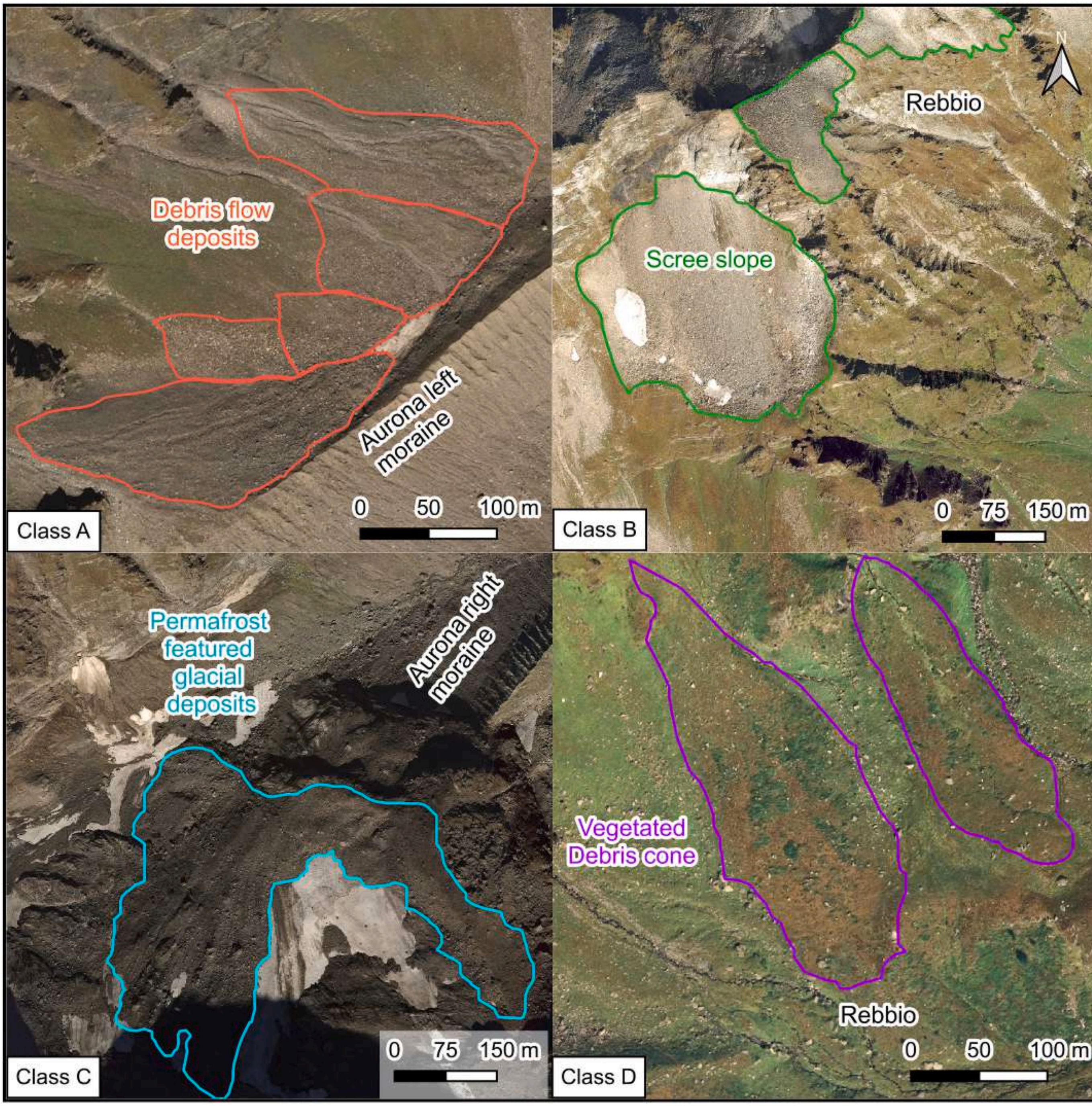

Fig. 3. Examples of depositional landforms classified through the Erodibility index. Debris flow deposits, representing the highest Ei (Ei = 2, Class A). Scree slope, representing an intermediate Ei deposit, with Gi = 0 and Ci = 1 (Ei = 1, Class B). Permafrost-featured glacial deposits, representing another intermediate Ei deposit, with Gi = 1 and Ci = 0 (Ei = 1, Class C). Vegetated/stabilised debris cone, representing the lowest Ei deposit, with Gi = 0 and Ci = 0 (Ei = 0, Class D).

and erosional landforms such as glacial striae and *roche moutonnées*. Glacier deposits remain abundant in the Middle Aurona sub-catchment (45%).

Gravity- and water-related processes account for approximately 30% across the catchment and are particularly widespread within the Middle Aurona sub-catchment (~48%). Earthflows, debris flows and water runoff erosion (Fig. 7a - c) are evident along the Aurona and Leone moraine slopes, locally producing colluvial fans between the valley sides and the proglacial plains. Finally, fluvial processes are mainly concentrated within the Middle Aurona sub-catchment (~4%), corresponding to the Aurona channel, whereas fluvio-glacial processes occur primarily within the Upper Aurona sub-catchment (6%), where they are associated with the braided channel network occupying the past lake area.

4.2. Sediment sources availability index (SSAI)

4.2.1. Index of connectivity (IC)

The *IC* (Fig. 8, Suppl. mat. 2 B) ranges from −6.8 to 2.9, with a mean of −4.2. The five connectivity classes are well distributed through the Rio Aurona catchment, with *IC* generally decreasing from the north-eastern to the south-western sector of the basin. The drainage network is characterised by the highest connectivity values, whereas lower values are mainly associated with the proglacial sectors and the surrounding depositional landforms.

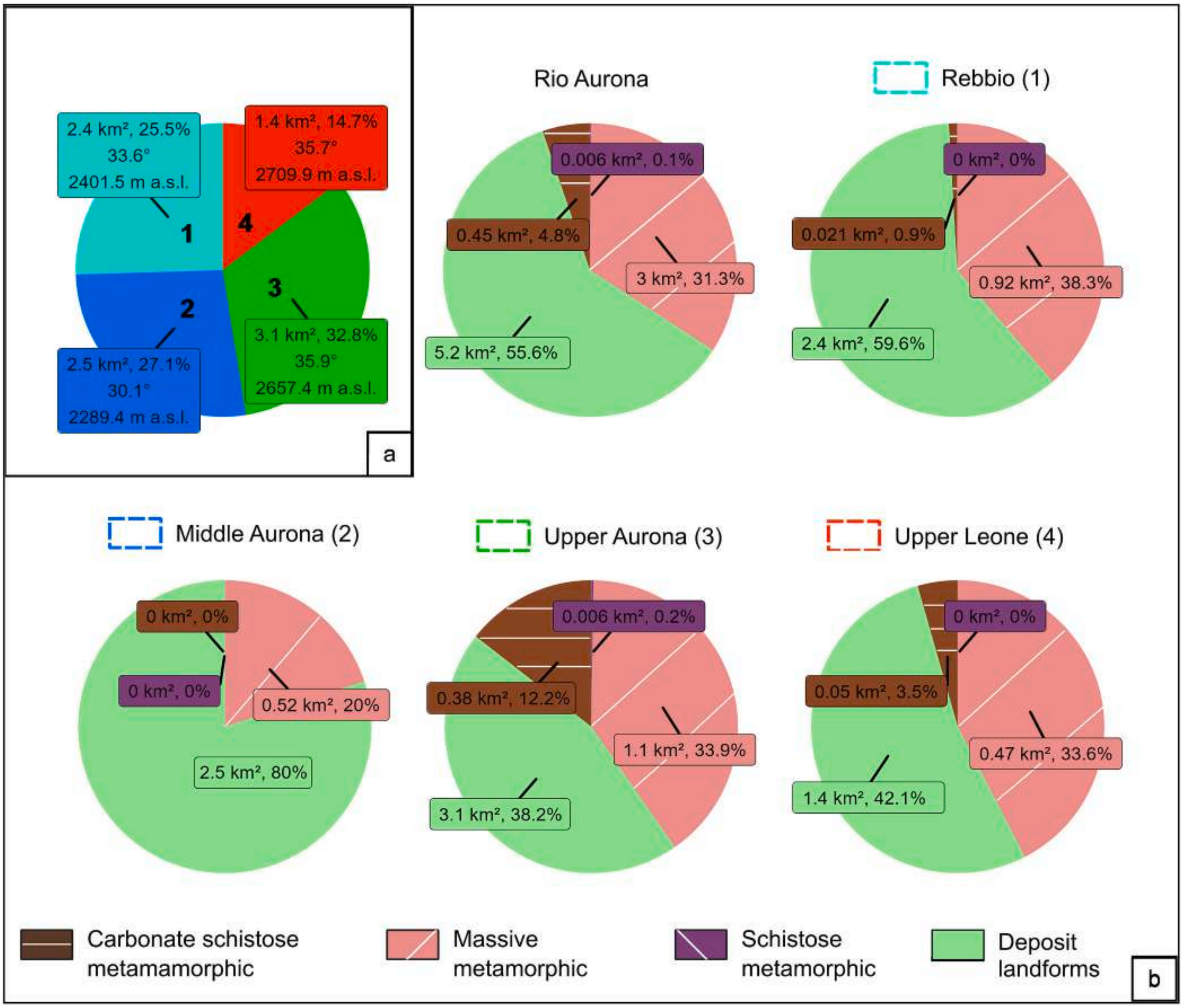

Fig. 4. Spatial features and lithological cover of the Rio Aurona and its sub-catchments: areal extension in square kilometres and percentage, mean slope, mean elevation (a). Rio Aurona and sub-catchments outcrop cover in absolute and relative terms (b). Data in Suppl. mat. 1, Tab. C.

The spatial distribution of the *IC* differs among the four sub-catchments (Fig. 8):

- Rebbio (1) - This sub-catchment shows the highest connectivity, with Class 4 (High) and 5 (Very high) accounting for approximately 80% of the area. High-connectivity classes are widespread, whereas lower-connectivity areas are mainly associated with the LIA moraines.
- Middle Aurona (2) - Class 3 (Medium) is the dominant connectivity class, covering approximately 52% of the sub-catchment. The distribution of connectivity classes is relatively homogeneous, with local areas of lower connectivity corresponding to glacial and landslide deposits.
- Upper Aurona (3) - Class 1 (Very low) and 2 (Low) account for approximately 83% of the sub-catchment. Higher connectivity values are mainly confined to the debris flow channels crossing the slopes towards the fluvioglacial plain, whereas the fluvioglacial plain itself acts as a low-IC area (Fig. 7b, Suppl. mat. 2B).
- Upper Leone (4) - As in the Upper Aurona sub-catchment, Class 1 (Very low) and 2 (Low) are the dominant connectivity classes, accounting for approximately 71% of the area. Local increases in *IC* are associated with the glacial and bedrock scarps, or moraine breaches, whereas lower-connectivity areas correspond to the fluvioglacial plain and the surrounding glacial deposits.

4.2.2. Erodibility index (Ei)

The Erodibility index (Fig. 9, Table 4) highlights the spatial variability of the potential sediment-source characteristics across the Rio Aurona catchment. The four *Ei* classes are well distributed throughout the basin. Class A, corresponding to the highest erodibility, is mainly concentrated in the northern and southern sectors of the catchment, where unconsolidated LIA glacial deposits and debris-flow deposits are widespread. Classes C and D are predominantly associated with consolidated or vegetated deposits and with areas affected by permafrost.

The spatial distribution of the *Ei* classes differs among the four sub-catchments:

- Rebbio (1) - Bedrock covers approximately 40% of the sub-catchment. Among depositional landforms, Class C is the most widespread (~43%), mainly corresponding to consolidated or partially vegetated glacial deposits. Class A deposits represent

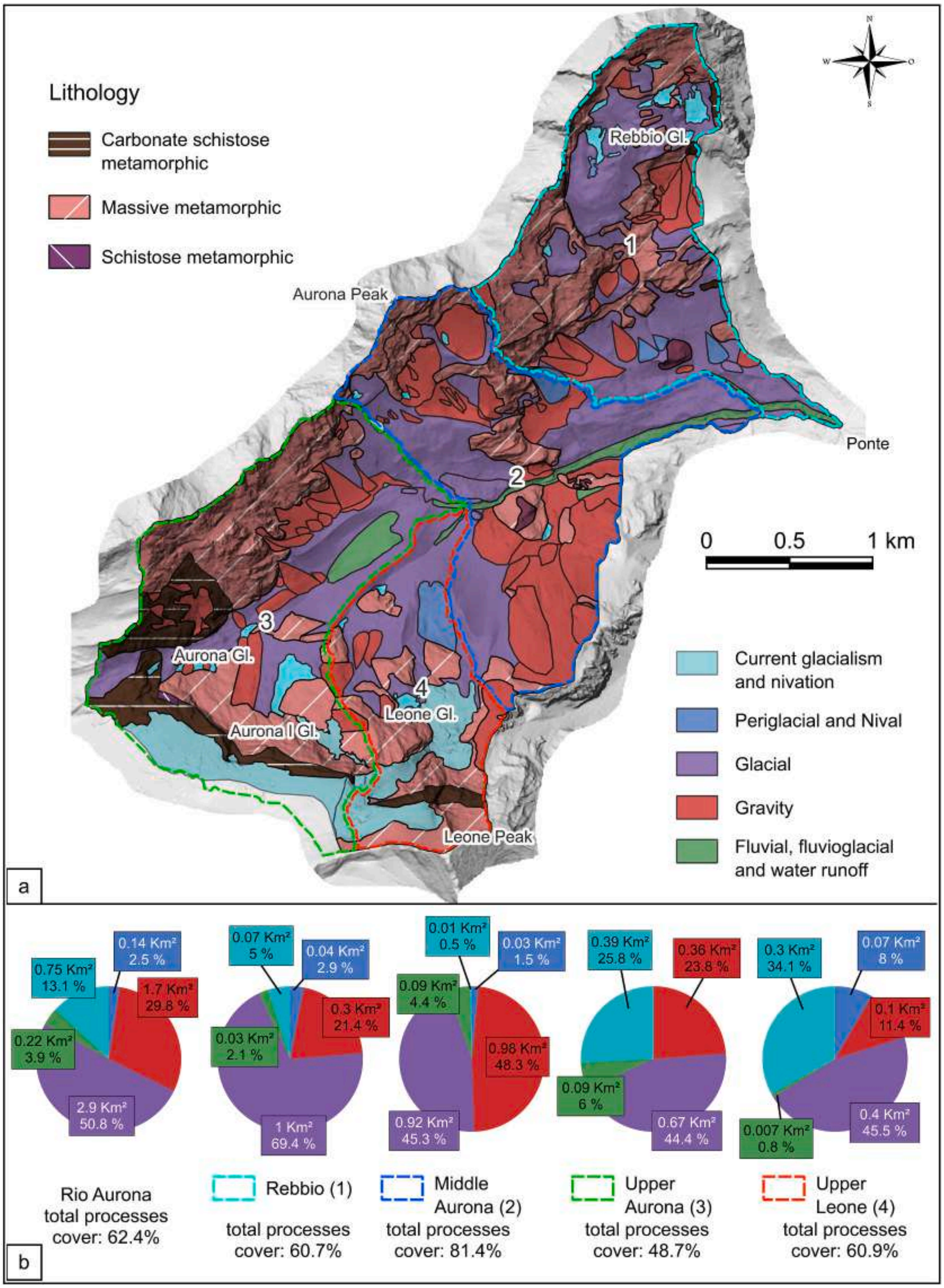

Fig. 5. Distribution of the main geomorphological processes in the study area (a). The pie charts in b show the distribution of area coverages by processes in square kilometres and percentages with respect to the Rio Aurona and the four sub-catchments (outcrop areas were excluded). Base layer hillshade derives from the 5 m resolution DTM of the Piedmont region (Regione Piemonte 2011). Data in Suppl. mat. 1, Tab. D.

approximately 36%, mostly glacial deposits, featured by the absence or the presence of degraded permafrost. Class B accounts for approximately 14% and mainly includes scree slopes, landslide deposits and riverbed deposits, whereas Class D represents approximately 7%, largely corresponding to partially consolidated/vegetated debris cones and scree slopes).

- Middle Aurona (2) - Bedrock covers approximately 20% of the sub-catchment. Class B is the dominant *Ei* class (~35%), mainly represented by scree slope, landslide, and riverbed deposits. Class C deposits cover approximately 30% of the depositional landforms, mainly with stabilised, or permafrost cemented glacial deposits. Class D accounts for approximately 20%, with stabilised/partially vegetated scree slopes, debris cones, and permafrost-featured landslide deposits. Class A is the least represented (~15%) and is mainly associated with the Leone right moraine, which drains into this sub-catchment, and debris-flow deposits

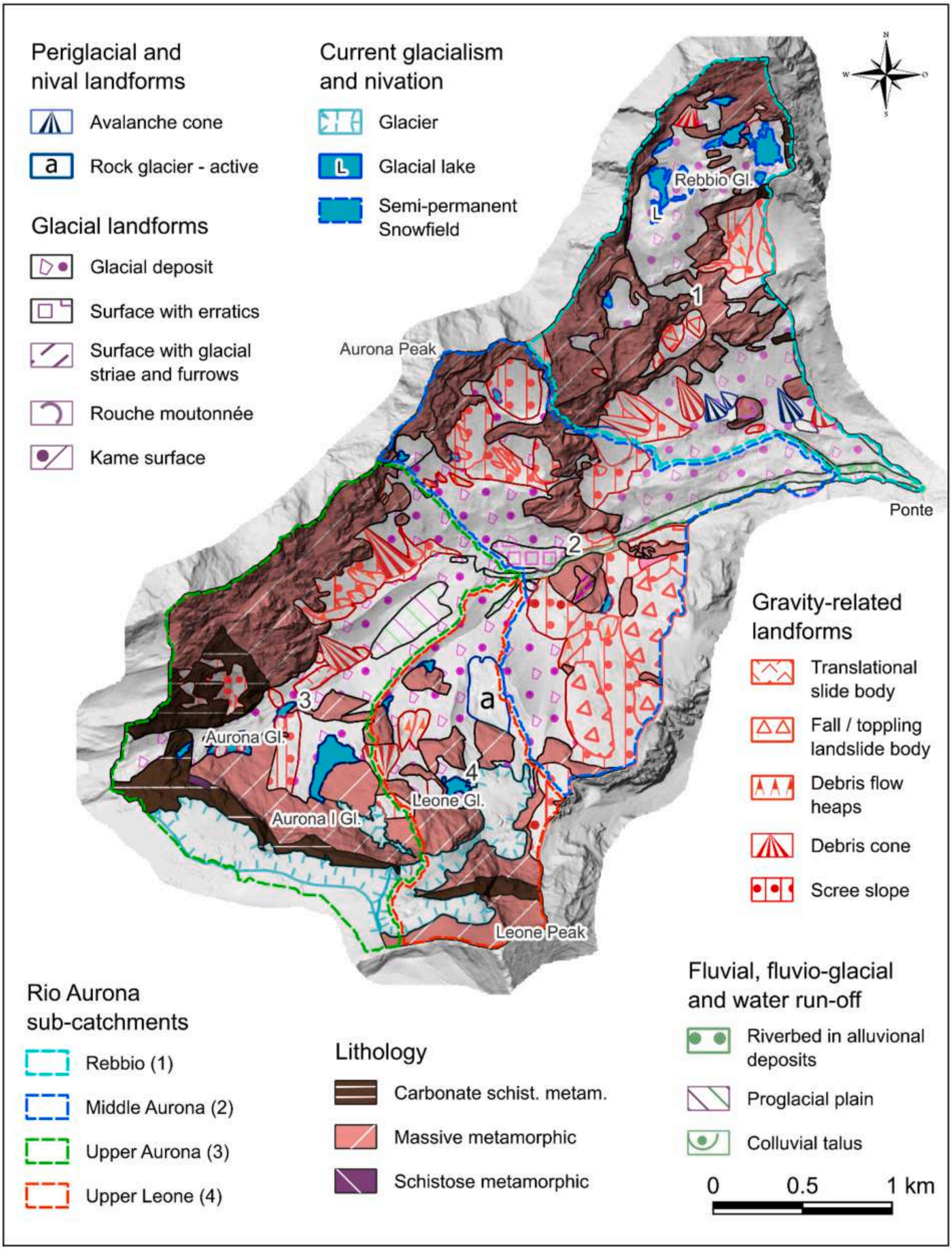

Fig. 6. Geomorphological sketch of landforms distribution. Base layer hillshade derives from the 5 m resolution DTM of the Piedmont region (Regione Piemonte 2011).

- Upper Aurona (3) - Bedrock covers approximately 63% of the sub-catchment. Among depositional landforms Class A is dominant (~50%) mainly corresponding to the Aurona LIA moraines and debris flow deposits. Class C accounts for approximately 25%, mainly featured by glacial and debris flow deposits cemented by the presence of permafrost. Class B follows with approximately 17%, mostly represented by scree slope deposits in the hydrographic left slopes. Class D deposits are poorly represented (~8%), mainly with permafrost-featured scree slope and debris cone deposits.

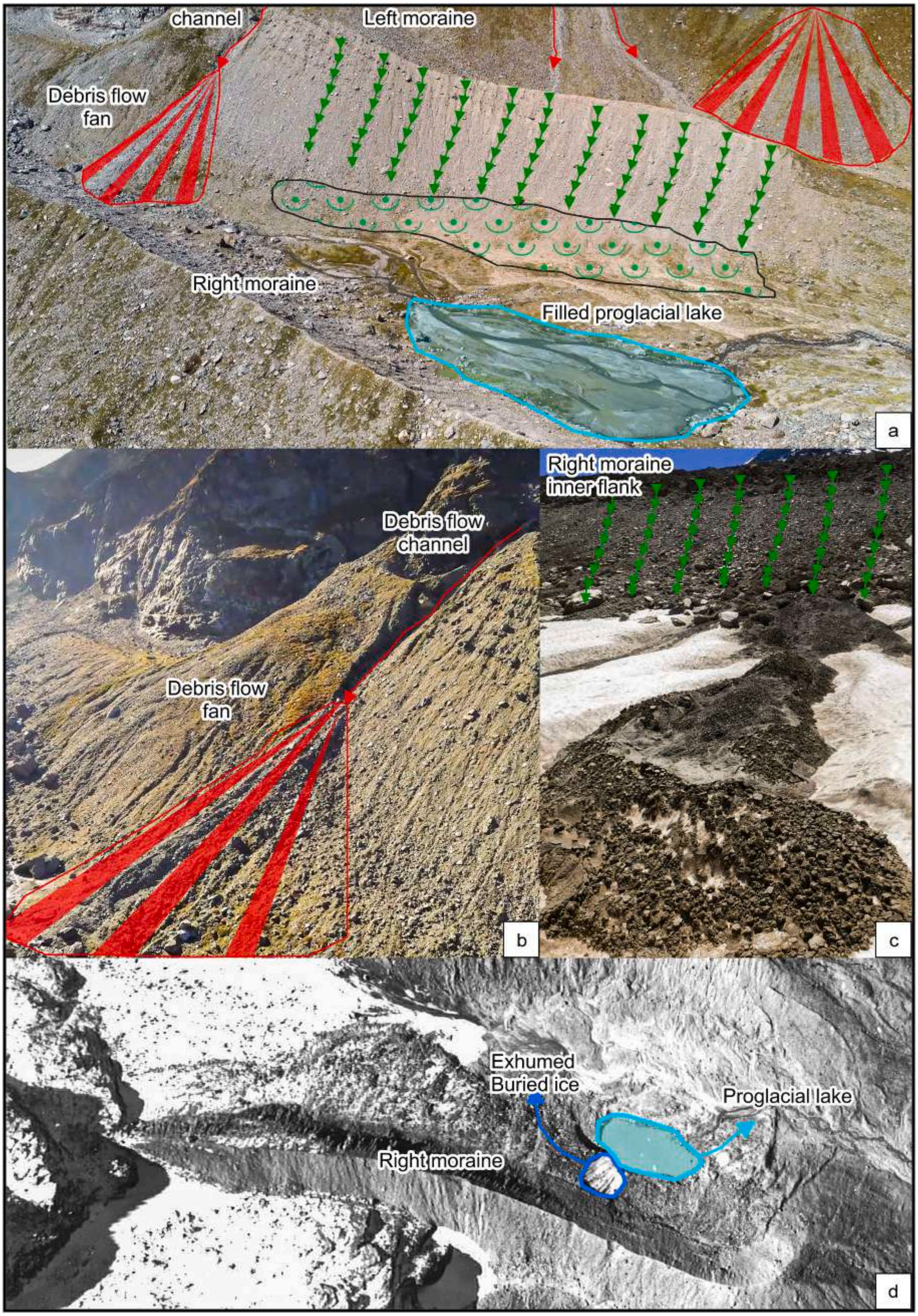

Fig. 7. Aurona proglacial area, UAV view from east (a); Debris flow detail on the left moraine (b); runoff and gully erosion, earthflows and falls from the right moraine create debris accumulation, and feed colluvial fans (c); 1952 Aerial photo of the Aurona proglacial area, note the glacier front inside the LIA moraines, the buried ice, partially covered by debris, and the evident proglacial lake *(d)* ©IGM credits.

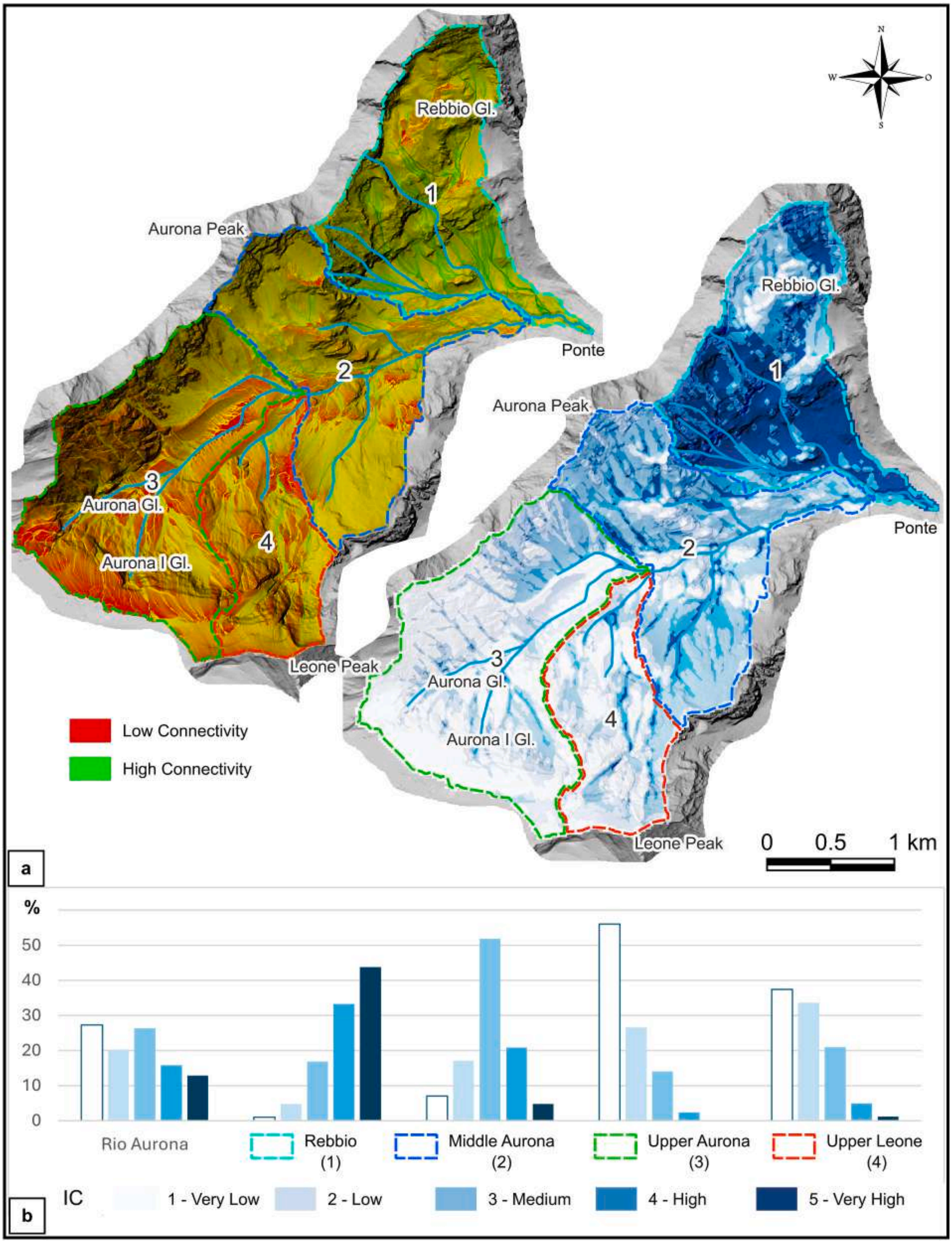

Fig. 8. From left to right, index of Connectivity scores and reclassified map (a). Frequency distribution of each connectivity class for the Rio Aurona catchment and each sub-catchment (b). Base layer hillshade derives from the 5 m resolution DTM of the Piedmont region (Regione Piemonte 2011).

- Upper Leone (4) - Bedrock covers approximately 58% of the sub-catchment. Class A represents approximately 50% of the depositional landforms and is mainly associated with the Leone frontal and lateral moraines. Class C accounts for approximately 33%, mainly represented by permafrost cemented glacial deposits and by the rock glacier-like deposits of the Leone proglacial area. Class D deposits represent approximately 17% and are constituted by permafrost

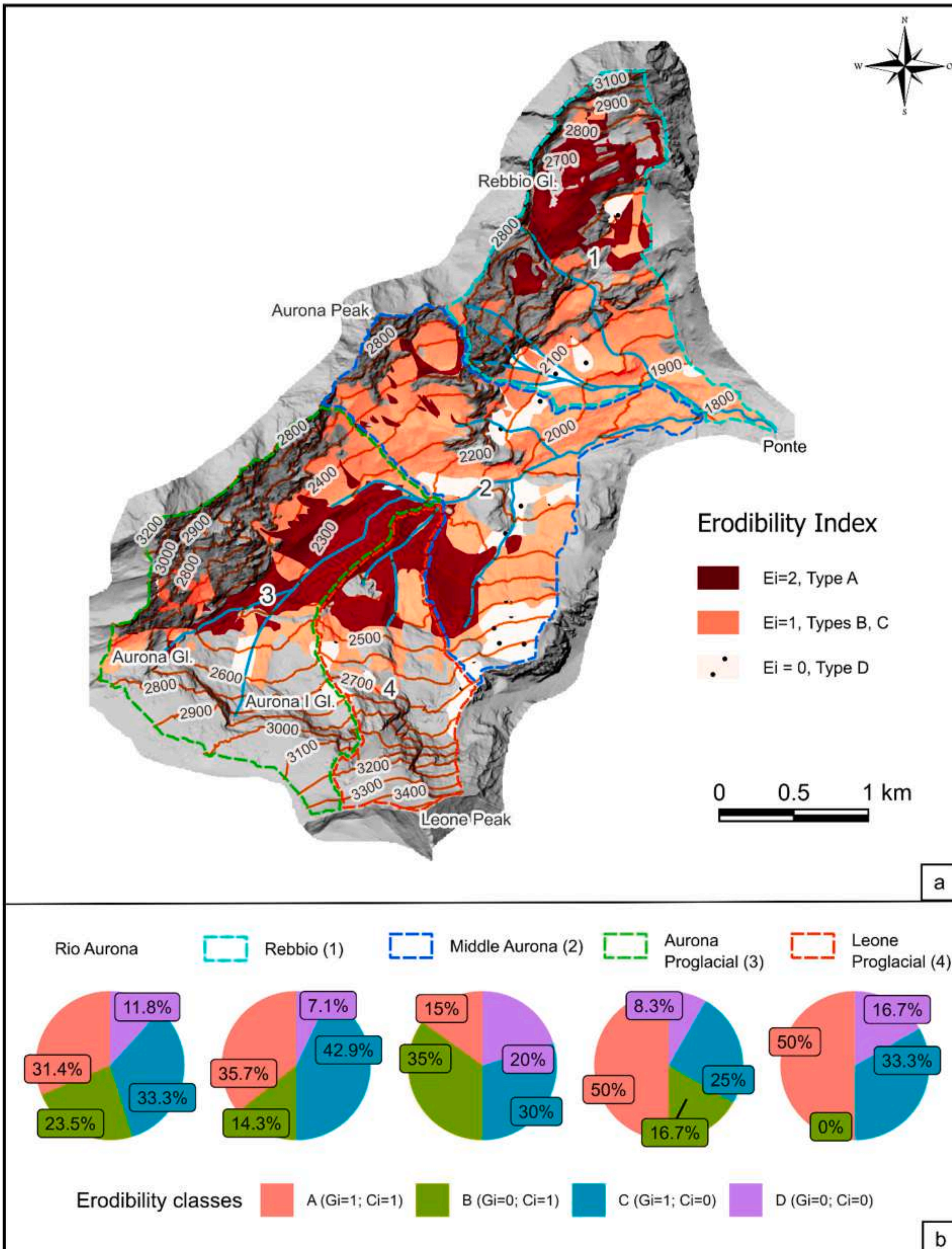

Fig. 9. Erodibility index map (a). The pie charts represent the abundance of each Erodibility index class in percentage (b). Base layer hillshade derives from the 5 m resolution DTM of the Piedmont region (Regione Piemonte 2011). Data in Suppl. mat. 1, Tab. E.

cemented scree slope and debris cone deposits derived from the Monte Leone northern wall. Class B deposits are almost absent.

4.2.3. Sediment sources availability index (SSAI)

The Sediment Sources Availability Index (SSAI) map (Suppl. mat. 2 A) highlights the spatial variability of the potential availability of sediment sources across the Rio Aurona catchment. The highest SSAI values are mainly associated with depositional landforms combining high structural connectivity and high erodibility, particularly unconsolidated LIA moraines and debris-flow deposits. Conversely, the lowest SSAI values are generally associated with depositional landforms characterised by low connectivity and/or high sediment cohesion or greater deposit size.

The distribution of the SSAI classes differs among the four sub-catchments (Fig. 10):

- Rebbio (1) - This sub-catchment is characterised by the highest SSAI values within the catchment. High and Very High SSAI classes are widespread and mainly associated with unconsolidated glacial deposits connected to the drainage network.
- Middle Aurona (2) - Low and Medium SSAI classes are the most abundant. High SSAI values are mainly confined to the Leone right lateral moraine and to debris-flow deposits, whereas lower classes prevail within the extensive glacial deposits occupying the middle sector of the basin.
- Upper Aurona (3) - Very Low and Low SSAI classes dominate the sub-catchment. Higher SSAI values are restricted to the debris-flow deposits located along the hydrographic left slope and to fluvioglacial area portions, where depositional landforms are present conferring higher connectivity.
- Upper Leone (4) - The SSAI pattern is comparable to that of the Upper Aurona sub-catchment, with a predominance of Very Low and Low classes. Higher SSAI values are mainly associated with the frontal moraine breaches and with depositional landforms directly connected to the main drainage network.

5. Discussion

5.1. SSAI application in the Aurona catchment and sediment cascade features

The SSAI highlights that sediment-source availability is primarily controlled by the interaction between structural connectivity and the intrinsic characteristics of sediment deposits. Consequently, sub-catchments showing similar morphometric connectivity may exhibit contrasting sediment-source potential depending on landform type, sediment cohesion and their ongoing geomorphological evolution. This finding supports previous observations that sediment transfer depends on the interaction between connectivity and sediment-source properties rather than on morphometric connectivity alone (Heckmann et al. 2018).

The SSAI was intentionally designed to identify potential sources of fine sediments contributing to suspended sediment transport under ordinary flow conditions. This choice reflects both the lower transport energy required for suspended sediments and the monitoring evidence collected since 2021, indicating that suspended load represents the dominant fraction of the solid transport at the selected catchment outlet (Tronti et al. 2024).

The comparison between the Rebbio (1) and Middle Aurona (2) sub-catchments illustrates how similar structural connectivity conditions may produce markedly different sediment-source availability. Rebbio is characterised by highly connected, weakly consolidated deposits that favour sediment delivery. The limited occurrence of permafrost further reduces sediment cohesion, enhancing the availability of unconsolidated glacial deposits. In contrast, the Middle Aurona sub-catchment is dominated by older and partially stabilised glacial deposits, which locally behave as structural barriers despite their large sediment storage capacity. Moreover, the predominance of scree slopes and rockfall deposits, characterised by coarser granulometry, further reduces their potential contribution to suspended sediment transport.

Within the upper Aurona sub-catchment (3), sediment-source availability is strongly influenced by the interaction between structural connectivity and the geomorphological configuration of the proglacial area. Although overall connectivity is reduced because of the greater distance to the outlet and the presence of several disconnectivity elements, the SSAI highlights the contrasting roles played by different depositional landforms. The extensive glacial and fluvioglacial deposits of the Aurona foreland interrupt longitudinal sediment transfer (Cavalli et al. 2019b), whereas the colluvial fans developed along the inner moraine slopes act both as local sediment sources and as buffer zones between the hillslopes and the proglacial plain.

This behaviour confirms that glacial deposits should not be regarded solely as sediment sources but also as geomorphological elements capable of locally interrupting sediment pathways, thereby confining hillslope-derived material (Cossart and Fort 2008). A representative example is provided by the debris-flow deposit located along the hydrographic left side of the Aurona foreland, which was partially

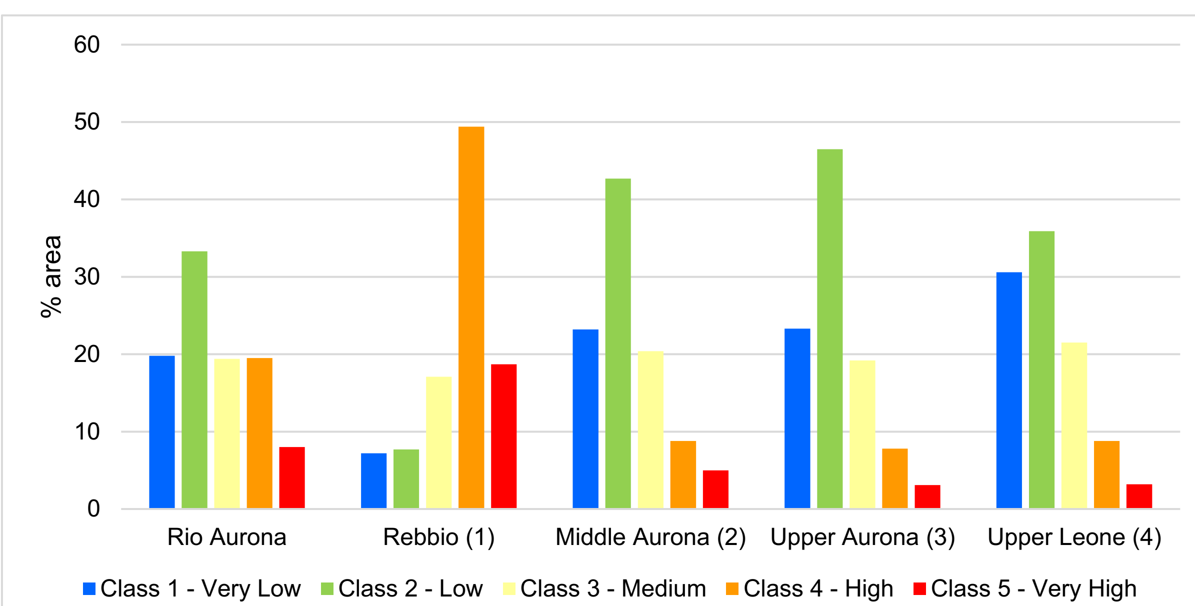

Fig. 10. SSAI classes coverage of the entire Rio Aurona catchment and each sub-catchment, considering only the depositional landforms (i.e., excluding bedrock outcrops).

impounded by the left LIA moraine. At the same time, debris flows represent one of the most effective mechanisms for restoring sediment connectivity. Besides supplying abundant fine sediments, they reconnect previously isolated hillslopes to the active drainage network, as also observed by Cavalli et al. (2013) and Bollati et al. (2024). The debris flow crossing the left moraine of the Aurona proglacial area provides a clear example of this process, reconnecting the slope to both the proglacial plain and the main Aurona channel.

The historical evidence of the Aurona proglacial lake, documented since 1952 and now completely infilled by fluvioglacial deposits, further supports the interpretation of the Aurona foreland as a long-term sediment sink. The present geomorphological configuration probably results from the combined influence of the barrier effect exerted by the LIA moraines, a buried structural threshold (to be confirmed through further geophysical analyses) and the continuous interaction of gravitational and fluvial processes (Tronti 2025; Tronti et al. 2026). Consequently, the Aurona proglacial plain presently behaves predominantly as a sediment store/sink, becoming an effective sediment source only when local geomorphological conditions temporarily restore structural connectivity.

Although occupying a relatively limited proportion of the catchment area, depositional landforms within the Aurona and Leone proglacial sectors represent key potential sediment sources because of their low cohesion, fine-sediment content and proximity to the active drainage network. Furthermore, LIA moraines, despite their limited areal extent, store considerable sediment volumes owing to their large vertical thickness, thus representing an important component of sediment availability.

Tronti et al. (2026) demonstrated that the Aurona proglacial area experienced substantial geomorphological changes during the last two decades while maintaining an overall near-equilibrium balance between erosion and deposition. The authors' observations indicate that buried-ice degradation constitutes one of the main drivers of geomorphological evolution, progressively reducing sediment cohesion and potentially enhancing sediment availability.

Given this consideration, it is worth noting that, in the study case, the API was used as a proxy of the permafrost presence, but it is referred to the 2010 conditions (Boeckli et al. 2012a, 2012b). Therefore, the permafrost presence should be continuously re-evaluated. Indeed, if intact permafrost can act as a cohesion factor, degrading permafrost, now spreading in mountain environments, can act oppositely, favouring instabilities, as observed in the Aurona and Leone proglacial areas.

A similar evolution characterises the Upper Leone sub-catchment (4), although with a different geomorphological expression. Here, buried-ice degradation has promoted the formation of seasonal ephemeral lakes and the progressive degradation of ice-cored moraines and rock glacier-like landforms. Stable permafrost currently contributes to maintaining sediment cohesion through ice cementation, whereas its degradation progressively reduces this effect, favouring sediment remobilisation and modifying sediment connectivity. The ephemeral lakes and related topographic hollows presently behave as sediment traps, while the breached frontal moraine locally reconnects the proglacial plain to the downstream sediment cascade. These observations explain the predominance of low SSAI classes despite the large amount of unconsolidated sediment stored within the Leone foreland.

The comparison between the Aurona and Leone proglacial systems clearly illustrates how similar glacial landforms may exhibit contrasting sediment-source behaviour depending on their stage of paraglacial evolution. The rock periglacial deposits of Monte Leone are currently classified as very low SSAI, mainly because of the barrier effect exerted by the frontal LIA moraine. Nevertheless, Tronti et al. (2026) documented active water and sediment transfer through breaches in the frontal moraine (confirmed by SSAI), locally reconnecting sediment stores with the downstream sediment cascade. Although this contribution appears to have decreased in recent years because of buried-ice degradation and the formation of ephemeral sediment-trapping lakes, the Leone proglacial area still contains abundant unconsolidated sediments generated by the combined action of glacial and gravitational processes. This interpretation is consistent with the sporadic monitoring data, which generally indicate higher suspended sediment concentrations in the Leone sector than in the Aurona proglacial area (Tronti et al. 2024).

From a broader paraglacial perspective, the two proglacial systems appear to represent different stages of the evolutionary model proposed by Cossart and Fort (2008). The Aurona foreland can be interpreted as an advanced Stage II system, where sediment disconnection produces a relative sediment deficit and the proglacial area approaches geomorphological equilibrium. Conversely, the Leone foreland still resembles an earlier Stage II, where breaches in the frontal moraines efficiently connect the large sediment stores accumulated within the proglacial area.

Overall, these findings not only confirm the high geomorphological significance of the Aurona and Leone proglacial systems (Coratza et al. 2021; Tronti et al. 2026) but also demonstrate how integrating structural connectivity with geomorphological characteristics of sediment deposits allows the SSAI to identify potential sediment sources more realistically than morphometric connectivity alone.

5.2. Advantages and limits of SSAI approach

The principal strength of the SSAI lies in its ability to synthesise morphometric connectivity with geomorphological information describing sediment-source characteristics. While the Index of Connectivity (*IC*) effectively identifies structurally connected and disconnected areas, the Erodibility index (*Ei*) complements this information by accounting for sediment texture, cohesion and geomorphological characteristics derived from geomorphological mapping, allowing a distinction between sediment stores and potential sediment sources. Consequently, low SSAI values identify structurally disconnected deposits acting predominantly as sediment stores, whereas high SSAI values indicate structurally connected deposits with a greater potential to contribute sediment to the drainage network. Intermediate SSAI classes identify deposits whose behaviour may shift between sediment storage and sediment supply according to local environmental conditions and stochastic events (e.g., extreme meteorological events), representing potentially functional sediment sources.

The SSAI was intentionally conceived as a first-order structural assessment of sediment-source availability. Rather than predicting the actual sediment transfer during specific hydrological events, the method identifies those landforms that are potentially capable of supplying sediments under ordinary flow conditions. In this respect, the SSAI represents a screening tool that helps identify priority areas where detailed monitoring and management efforts should be concentrated.

The main limitation of the approach is the availability and quality of the input datasets. High-resolution geomorphological maps, Digital Elevation Models and updated information on permafrost distribution are required to provide reliable predictions. In addition, the *Ei* classification is based on geomorphological interpretation and therefore inherits the intrinsic degree of subjectivity typical of expert-based approaches (Dramis et al. 2011). Within the present study these uncertainties were reduced by combining multiple data sources, repeated field surveys and detailed photointerpretation. Nevertheless, future applications would benefit from quantitative validation through permanent erosion plots, sediment-yield measurements and sediment tracing techniques, allowing calibration of the *Ei*, *IC*, and the SSAI classes.

A further limitation concerns the spatial representation of depositional landforms. Because the *Ei* is derived from polygon-based geomorphological mapping, small depositional features represented as point or polyline elements cannot be directly incorporated into the analysis. However, this simplification is partially compensated by their limited areal extent relative to the mapping scale (1:5000) and final representation (1:7000). Similarly, the planimetric representation of deposits does not account for their vertical dimension, and hence volumes. This may underestimate the contribution of relatively small but volumetrically important deposits, particularly within the Aurona and Leone proglacial sectors where LIA moraines and recently deglaciated deposits locally store considerable sediment volumes. Future developments integrating deposit thickness and volumetric changes derived from repeated high-resolution topographic surveys (e.g., Altmann et al. 2024; Betz-Nutz et al. 2023; Tronti et al. 2026) would further improve the representation of sediment availability.

Compared with existing approaches, the SSAI should be considered complementary rather than alternative. Multi-temporal investigations based on repeated orthophotos (Marden et al. 2005), DEM differencing (Scorpio et al. 2022) or high-resolution 3D monitoring (Tronti et al. 2026) directly quantify geomorphological evolution and the temporal variability of sediment connectivity. These methods provide detailed information on sediment mobilisation and landscape evolution but require repeated surveys, long-term monitoring programmes and considerable economic and logistical resources. Conversely, the SSAI provides a rapid structural assessment using information that is commonly available for many alpine catchments, such as geomorphological maps and Digital Elevation Models. Its main advantage therefore lies in identifying potential sediment sources to direct more demanding investigation activities to specific areas.

Several studies identified landscape structure as one of the principal controls on sediment connectivity (Cossart and Fressard 2017; Cossart et al. 2018; Cucchiaro et al. 2019; Llena et al. 2019; Scorpio et al. 2022), whereas others emphasise the dominant influence of functional connectivity under specific hydrological conditions (Baartman et al. 2020). The SSAI deliberately focuses on the structural component of sediment connectivity. However, seasonal snow accumulation, glacier melt, rainfall intensity, stochastic events such as debris flows or landslides, and permafrost degradation may substantially modify sediment availability without changing the underlying structural configuration. For example, ongoing permafrost or dead-ice degradation may reduce sediment cohesion and enhance sediment mobilisation (Kummert et al. 2018; Tronti et al. 2026), while debris flows may either reconnect previously isolated sediment stores or create new barriers within the sediment cascade (Korup 2005). These examples demonstrate that structural and functional connectivity should not be regarded as competing concepts but rather as complementary components of sediment-cascade analyses.

Consequently, the SSAI is not intended to replace process-based or multi-temporal approaches but to provide the structural framework upon which functional information can subsequently be incorporated. Depending on the available datasets, the method can be integrated with orthophoto interpretation, repeated topographic surveys or field monitoring to evaluate different scenarios of sediment-source activation. Likewise, periodic updates of the SSAI following major geomorphological changes or extreme events would also provide an effective tool for monitoring temporal variations in sediment-source availability.

6. Conclusions

- Sediment-source availability in mountain catchments is controlled by the interaction between morphometric connectivity and the intrinsic characteristics of sediment deposits, including granulometry and cohesion. The SSAI framework provides a practical tool to explore the relative contribution of these structural factors governing the potential behaviour of sediment deposits.

- The SSAI provides a rapid first-order assessment of structural sediment connectivity and can be adapted to different types of input data, such as geomorphological maps or superficial-deposit maps, as well as to catchments characterised by different suspended-load and bedload regimes through appropriate calibration of the *Ei* scores. Its simplicity, flexibility and limited data requirements make it suitable for repeated applications and long-term monitoring of sediment-source availability under paraglacial evolution.

- The SSAI method also provides a practical tool for stakeholders, including civil protection authorities and hydroelectric infrastructure managers, to identify potential sediment sources involved in geomorphological processes, representing putative hazards for people and infrastructure. In addition, SSAI may support geoconservation by providing indications of the potential evolution of significant geoheritage elements, such as Little Ice Age moraines.
- Future developments should focus on validating the *Ei* through long-term monitoring, sediment tracing and repeated topographic surveys, as well as integrating volumetric changes in sediment stores to improve the predictive capability of the SSAI framework.

CRediT authorship contribution statement

G. Tronti: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Pelfini:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **M. Cavalli:** Writing – review & editing, Validation, Software. **F. Comiti:** Writing – review & editing, Validation, Supervision. **L. Mao:** Writing – review & editing, Visualization, Validation, Supervision. **E. Scognamiglio:** Data curation. **I.M. Bollati:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Irene Maria Bollati reports financial support was provided by Italian Ministry for Universities and Research. Irene Maria Bollati reports financial support was provided by University of Milan, Piano di Sostegno alla Ricerca Projects 2019, 2020, 2021, and 2022. Irene Maria Bollati reports financial support was provided by PRIN project GEOTres G53D23001330006 - 2022NYS98X_001. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2026.110505.

Data availability

Data will be made available on request.

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