



Article

Alpine Catchments' Hazard Related to Subaerial Sediment Gravity Flows Estimated on Dominant Lithology and Outcropping Bedrock Percentage

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Abstract: Sediment gravity flows (SGFs) cause serious damage in the Alpine regions. In the literature, several methodologies have been elaborated to define the main features of these phenomena, mainly considering the rheological features of the flow processes by laboratory experiments or by flow simulation using 2D or 3D propagation models or considering a single aspect, such as the morphometric parameters of catchments in which SGFs occur. These very targeted approaches are primarily linked to the definition of SGFs' propagation behavior or to identify the predisposing role played by just one feature of catchments neglecting other complementary aspects regarding phenomena and the environment in which SGFs can occur. Although the research aimed at the quantification of some parameters that drive the behavior of SGFs provides good results in understanding the flow mechanisms, it does not provide an exhaustive understanding of the overall nature of these phenomena, including their trigger conditions and a complete view of predisposing factors that contribute to their generation. This paper presents a research work based on the collection and cross-analysis of lithological, geomechanical, geomorphological and morphometrical characteristics of Alpine catchments compared with sedimentological and morphological features of SGF deposits, also taking in to account the rainfall data correlation with historical SGF events. A multidisciplinary approach was implemented, aiming at quantifying SGF causes and characteristics starting from the catchments' features where the phenomena originate in a more exhaustive way. The study used 78 well-documented catchments of Susa Valley (Western Italian Alps), having 614 historical flow events reported, that present a great variability in geomorphological and geological features. As the main result, three catchment groups were recognized based on the dominant catchment bedrock's lithology characteristics that influence the SGFs' rheology, sedimentological and depositional features, triggering rainfall values, seasonality, occurrence frequency and alluvial fan architecture. The classification method was also compared with the catchments' morphometry classification, demonstrating that the fundamental role in determining the type of flow process that can most likely occur in a given catchment is played by the bedrock outcropping percentage, regardless of the results provided by the morphometric approach. The analysis of SGF events through the proposed method led to a relative estimate of the hazard degree of these phenomena distinguished by catchment type.

Keywords: debris flow; hyperconcentrated flow; alluvial fan; rainfall threshold; Western Italian Alps



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1. Introduction

Most of the SGF/SFF processes occurring in Alpine catchments affect human activities developed in alluvial fan areas, resulting in damage and victims that historically and frequently have been documented in all urbanized areas and infrastructure distributed along the Alpine valleys. Several studies on hazard evaluation associated with subaerial sediment gravity flows (SGFs) have been carried out, essentially focused on considering a single or a few factors for understanding these phenomena, such as through the quantification of the triggering causes identified mainly with rainfall [1–8], also considering the effects of climate

change on precipitation and the consequent variations in frequency and activity of SGFs with a view to designing defense works for risk mitigation [9]. Indeed, in recent decades, different approaches have been presented in order to define the most effective actions to mitigate the risk associated with such phenomena by research applied to the improvement of technologies for monitoring the phenomena and the development of new techniques for mitigating the effects through the design of more effective defense structures [10–13]. In this study, a new multidisciplinary approach able to characterize the subaerial SGFs that occur in small Alpine catchments (normally with an area $\leq 50 \text{ km}^2$), their causes (predisposing and triggering factors) and evolution is proposed, with the aim of providing an improved knowledge base that can facilitate and make more effective the planning of risk mitigation actions associated with these geomorphological processes. This methodology was developed by studying the catchments of Susa Valley (Western Italian Alps) which presents a great variability in terms of geomorphological and geological settings. The catchments were analyzed from different points of view to understand the SGF occurrence mechanisms and evolution [14–20] to determinate the propensity of a catchment to give such phenomena based on its characteristics. Agreeing with previous preliminary research works [14–20] to characterize an SGF process in a subaerial environment, an Alpine catchment susceptibility classification is proposed starting with the identification of the main predisposing factors characterizing the catchments that rule the flow processes determining their typology, rheology, depositional style, occurrence frequency and seasonality. According to the resulting susceptibility classification of catchments, triggering factors were identified starting from the analysis of historical reports on SGF/SFF events. The propensity that a catchment has in generating sediment flows (SGF, or a sediment fluid flow—SFF) is linked to the geomorphological settings [21–24], geological characteristics [25–29] and climate condition [30–34], also considering occasional factors, such as wildfires [35–38], glacial and periglacial processes [39–43] and earthquakes [44–46]. Even the morphometry of the catchments is considered a parameter determining the most likely flow process that can be generated in a given catchment. The understanding of predisposing and triggering factors, which in fact affect the initiation and behavior of flow phenomena that take place in small Alpine catchments, allows us to obtain an estimate of their relative hazard. The research in this paper introduces a classification system for catchment and related processes. The proposal is based on the study of 78 Alpine catchments in the Susa Valley (Western Italian Alps), which are characterized by active alluvial fans. The data include information on historical flow processes for a total of 614 events spanning from 1728 to 2023. All catchments were characterized considering bedrock lithology, geomechanical/structural conditions' distribution in which the catchment is modeled, the presence of surficial deposits such as landslides, the presence of deep-seated gravitational slope deformations (DSGSDs) affecting the bedrock, sedimentology and morphology of in-channel bed and alluvial fan deposits, the morphometry of the catchments and, finally, the triggering causes by the correlation of sediment flow historical events with rainfall data series from rain gauges and weather radars. The goal of this characterization focused on finding the relationship between flow process type and catchment features by means of statistical approaches.

Study Area

The studied catchments are located in the Susa Valley, one of the main valleys of the Western Italian Alps (Figure 1). The lithological units forming the Susa Valley belong to the so-called Penninic structural domain (Piemontese and Briançonnais Zones), characterized by continental margin, ophiolitic and oceanic units. The bedrock is formed by a metamorphic pre-Triassic crystalline basement covered by autochthonous Mesozoic metasediments and carbonate rocks with subordinate calc-schists; the ophiolitic and oceanic units consist mostly of calc-schists, marbles, quartzites and green stones [47] (Figure 1).

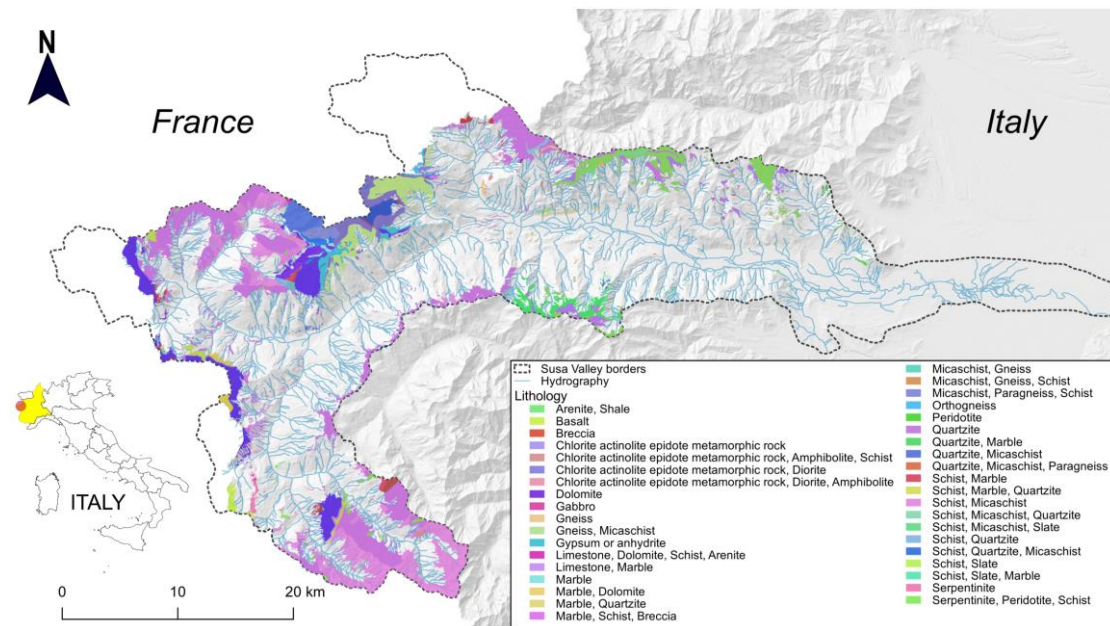


Figure 1. Lithological map of Susa Valley (modified from [48]) and the location of Susa Valley as a red dot in the geographic framing of Italy).

In the studied area, rock masses show a ductile deformation linked to four Alpine deformation events and a brittle deformation represented by three main sub-vertical fault systems, mainly normal, with strikes N60, N100/N140 and N-S. Morphotectonic evidence and slope deformations (e.g., trenches and fault scarps), variously oriented and involving bedrock and surficial deposits, are also intensely affecting this area. During the Quaternary Period, the studied area was modeled by the evolution of glaciers and landslides. Traces of two main glacier phases are recognizable by the presence of both shapes and deposits well preserved throughout the valley. The post-ice geomorphology is characterized by slope instability processes related to the tensional rebound caused by the deglaciation and the structural framework of the area (Figure 2).

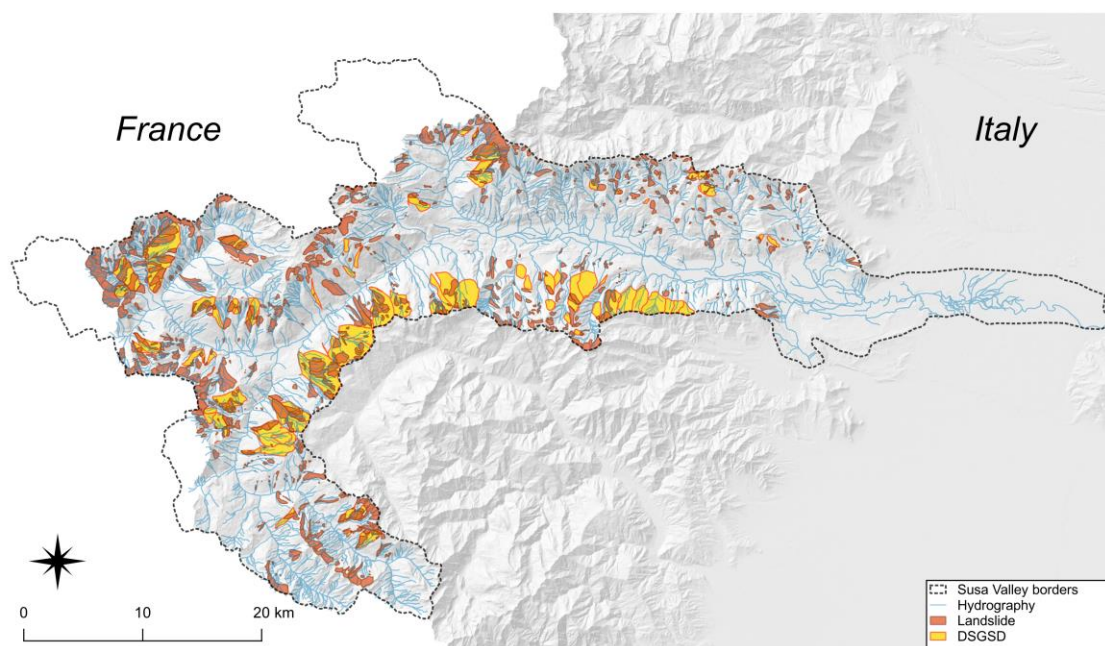


Figure 2. Landslide deposits and DSGSDs' distribution in Susa Valley.

The climate in Piemonte is prevalently controlled by the orography since the modest North-South extension in latitude ($2^{\circ}20'$) does not influence the climate. The annual rainfall distribution is bimodal, with two maxima during spring and fall and two minima during winter and summer. Four pluviometry regimes are recognized according to the seasonal main minimum, main maximum and secondary maximum of rainfall: three of them are of a continental type with a main minimum in winter, while the last one is of a Mediterranean type with a main minimum in summer. In particular, the Susa Valley is characterized by the Mediterranean-subcoastal regime (main minimum in summer, main maximum in fall and secondary maximum in spring) with lower fall precipitations and higher summer precipitations than the average values of the Alpine area [49]. The Western Alps are little influenced by oceanic and Mediterranean precipitations; consequently, they are more xeric than the rest of the Piemonte Alps, particularly in the axial part of Western Alpine valleys. In the Susa Valley, the mean annual precipitation is about 800 mm, where the annual average snowfall is about 144 cm during the winter season. The cumulative daily rainfall is also moderate, usually less than 20 mm/day.

2. Materials and Methods

2.1. Historical Recorded SGF and SFF Events

The Susa Valley's SGF and SFF events were identified and selected from the regional database of geo-hydrological events (<http://webgis.arpa.piemonte.it/bdgc/index.php>—accessed on 18 April 2024) and from the CNR-IRPI Italian national database of geo-hydrological events (<http://polaris.irpi.cnr.it/> and <https://avi.gndci.cnr.it>—accessed on 18 April 2024), obtaining a significant statistical sample capable of characterizing the SGF/SFF occurrence conditions in a comprehensive way. All the events are characterized by exhaustive and verified information about date of occurrence (including triggering hour in some cases), process type and, rarely, the magnitude. This dataset was used as input for statistical analysis to identify differences and correlations between the feeding catchments' characteristics, flow processes and associated deposits (along the channel network and alluvial fans). Moreover, the relationship between rainfall values and SGF/SFF occurrence was also analyzed using data from the regional rainfall database (<https://www.arpa.piemonte.it/dati-ambientali>—accessed on 18 April 2024) in which data from the regional rain gauge network (data from 1990 to 2024) and weather radar systems (data available from 2000 to 2024) are collected. Data from rain gauges start from 1990 because of the modernization and homogenization of regional weather station network. Rainfall data for SGF/SFF events that occurred before 1990 were not considered for the identification of rainfall-triggering thresholds. The historical SGF/SFF events were linked to rainfall values recorded during the occurrence day and in near period preceding the SGF/SFF occurrence in case of multi-day rainfall event durations.

2.2. Catchment and Process Classification Method

In this subsection, the methodologies adopted to address the various aspects related to the characterization of catchments and the processes occurring within them are described. The cross-analysis of all considered parameters aims to determine how they can drive the flow processes, considering the influence of individual factors and their relationships in statistical treatment.

2.2.1. Catchments' Classification by Morphometry

The Susa Valley catchments were classified starting from the quantitative geomorphological information, according to [50] who identified the most likely flow processes that a catchment can generate by analyzing a comprehensive set of morphometric parameters. The morphometric and quantitative geomorphological information, such as average catchment slope, length of main channel, average channel dip and catchment area, were processed from the regional DTM 10 m.

The considered flow processes include the following [51–53]:

- Water flows (WFs) characterized by low sediment concentration (0.4–20%), transported via bedloading in a flow mixture displaying Newtonian behavior (SFF);
- Hyperconcentrated flows (HFs), represented by torrential mass-transport with moderate sediment concentration (>20–47%) in a flow mixture exhibiting either Newtonian or non-Newtonian behavior. An HF can therefore have the characteristics of either an SFF or an SGF depending on the concentration of the solid material being transported; typically, the transition from an SFF to an SGF occurs at a sediment concentration $\geq 30\%$;
- Debris flows (DFs), represented by SGF with high sediment concentration (>47–77%) in a flow mixture demonstrating non-Newtonian viscoplastic or collisional-frictional behavior related to the amount of fine sediment.

The propensity of a catchment to generate a specific flow phenomenon (SFF or SGF) is primarily driven by its morphometric characteristics, notably the Melton ratio [54] and the length of the watershed. Catchments with a Melton ratio < 0.3 and a watershed length > 8 km are predisposed to generate SFF, while hyperconcentrated flows predominantly affect catchments with a Melton ratio > 0.3 and watershed length values ranging between 3 and 8 km. DFs are typical of catchments with a Melton ratio > 0.6 and a watershed length < 3 km (Figure 3).

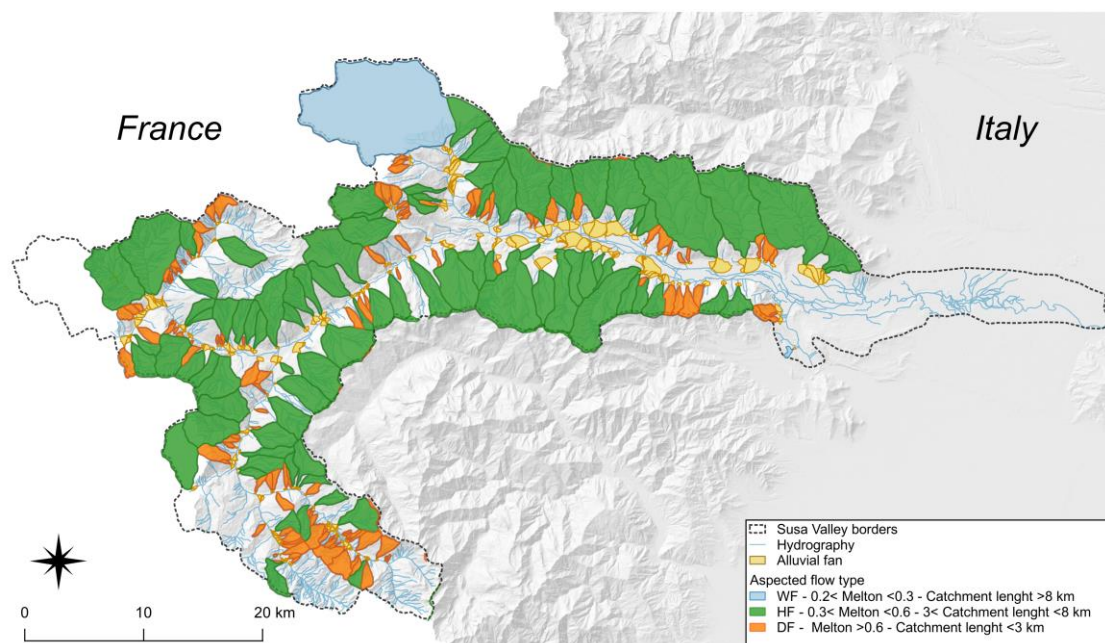


Figure 3. Morphological classification of Susa Valley's catchments defining the likely expected flow process.

2.2.2. Determination of Catchments' Dominant Bedrock's Lithology

The first step consists of the evaluation of bedrock outcropping percentage to identify the catchments' area percentage covered by outcropping and sub-outcropping rocks instead of vegetation and surficial deposits. For this purpose, a bedrock outcropping map at 1:10,000 scale derived from the processing of the Regional Technical Cartography of Piemonte (https://www.geoportale.piemonte.it/geonetwork/srv/api/records/r_piemonte:ea9ea426-cf4d-41d0-81d4-e0a642f30aa3#gn-tab-raster—accessed on 18 April 2024) and the Regional Territorial Forestry Plans of Piemonte (<http://www.sistemapiemonte.it/popalfa/indaginiPFT/indexCartaForAGG2016.do?sessionId=7x6SmgbybbnCQDvpt4prdsmh4GJLpnJZKLDW4l2nHg9yYvJzHv47L!128788123!-933934292>—accessed on 18 April 2024) was implemented for the Susa Valley. As result, a bedrock outcropping map was obtained (Figure 4) and used as processing mask for other thematic layers in GIS environment.

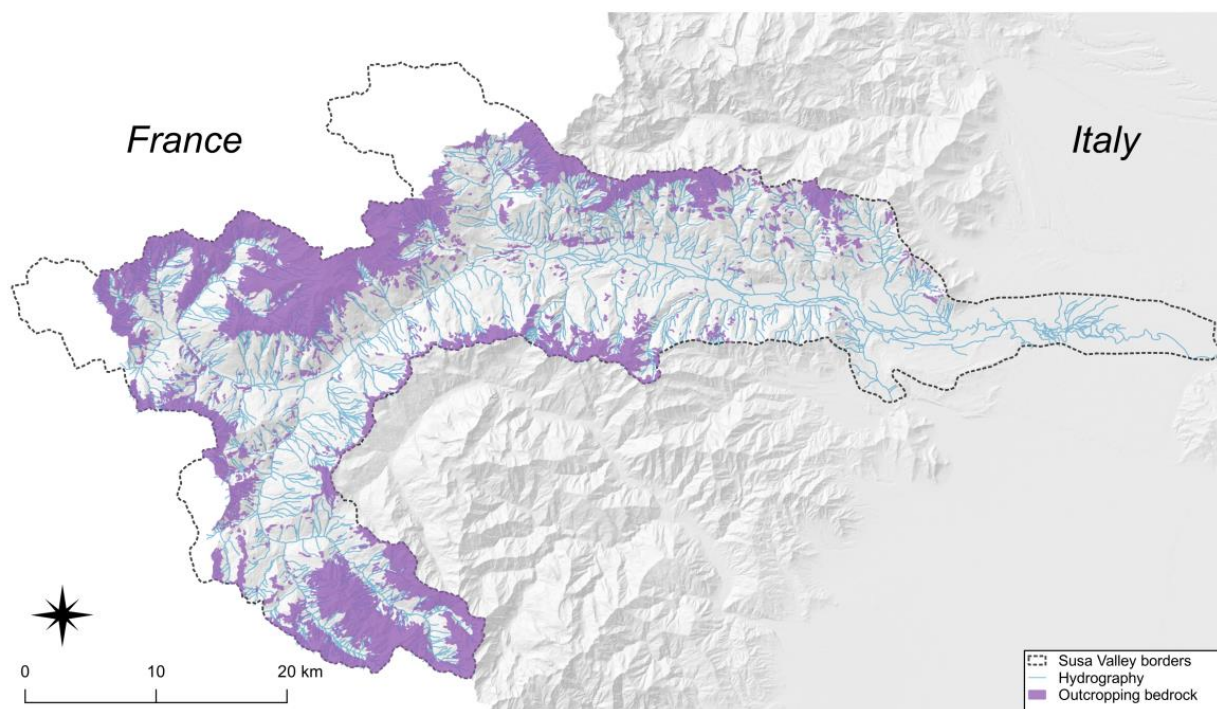


Figure 4. Bedrock outcropping map of Susa Valley.

To characterize the catchments from a lithological point of view, the Susa Valley's outcropping rocks map was intersected with the regional geological map of Piemonte (north-western Italy) (<https://webgis.arpa.piemonte.it/agportal/apps/webappviewer/index.html?id=6ea1e38603d6469298333c2efbc76c72>—accessed on 18 April 2024) to obtain the relative percentage of the different lithologies forming the bedrock. Then, the lithologies were grouped by macro-classes based on composition (mineralogical association/paragenesis), structure, texture and grain-size features to operate a first homogenization considering the scale of investigation (Figure 5). The homogenization identifies three main bedrock lithological classes as follows:

1. Bedrock formed mainly by fine-grained schistose metamorphic rocks (FMBR), such as calc-schists, shales, slates, green schists, phyllites, etc.
2. Bedrock formed mainly by massive or coarsely stratified carbonate rocks (MCBR), such as limestone, dolostones, marbles, cemented carbonate breccias and conglomerates, etc.
3. Bedrock formed mainly by coarse-grained or massive crystalline rocks (CCBR), such as granitoids, gneiss, quartzites, eclogites, migmatites, peridotites, etc.

Moreover, a quick assessment of the geomechanical state of rock masses has been addressed using comparative tables to define the Geological Strength Index (GSI) [55] by field survey and from the analysis of the rocks' descriptions in the regional geological map legends. The GSI is a very qualitative approach compared to other methodologies for the evaluation of geomechanical conditions of rock masses [56] but easier to apply over large areas (Figure 6).

Subsequently, the polygons representing the watersheds of the Susa Valley's catchments were related to the previously described maps to obtain the relative and absolute percentages of outcropping bedrock and its prevailing lithology in which catchments are modeled.

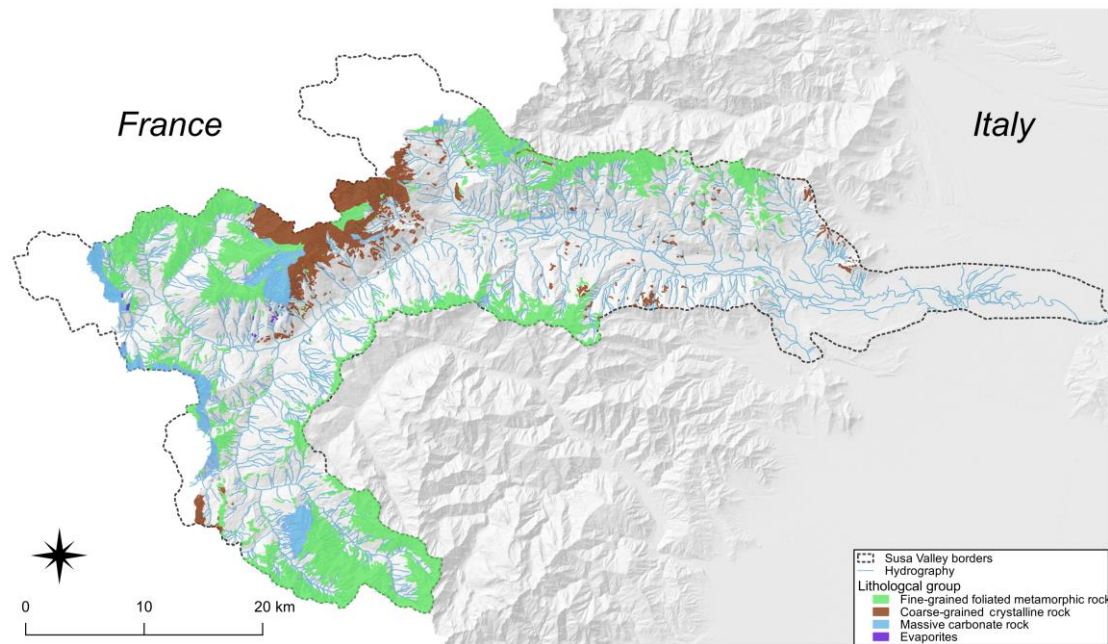


Figure 5. Lithological group obtained by the merging of lithology having similar characteristics (derived from Figure 1).

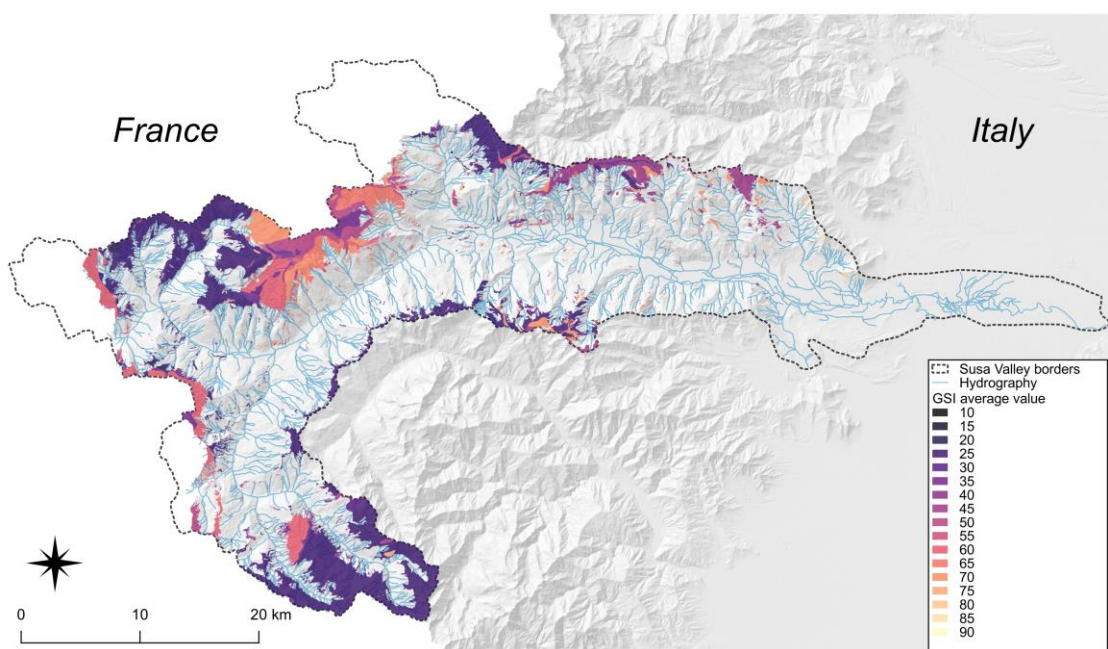


Figure 6. Distribution of GSI values characterizing the rock masses of Susa Valley.

2.2.3. Characterization of Alluvial Fans

The analysis takes also into account the alluvial fan bodies (<https://geoportale.arpa.piemonte.it/app/public/?pg=mappa&ids=5554d33c511140e0acc77ff46fcac86c>—accessed on 12 April 2024) to characterize the sedimentary accretional processes [57]. Each alluvial fan feature was linked to the characteristics of feeding catchment. It's important to highlight that the consideration of alluvial fan characteristics (size, shape, sedimentology and architecture) was not influenced by secondary morphogenetic factors different from catchment flow processes (such as tectonic tilting, fluvial processes of main valley, rock fall phenomena, glacial lake outburst flood—GLOF, landslides, etc.). As described in subsequent paragraphs, the accretional processes of alluvial fans are uniquely driven by SGF

and SFF (primary processes). All the alluvial fans related to their feeding catchments were analyzed considering three main parameters:

- Shape and area, determined by the identification of alluvial fans' boundary by photogrammetric analysis in GIS environment and verified by field survey.
- Morphometry, obtaining the slope (mean and local distribution) of the alluvial fan depositional upper surface by processing the regional DTM 10 m.
- Sedimentological characteristics such as clast-size distribution, deposits' structure and texture, matrix abundance and grain size acquired by field surveys and laboratory analyses.

2.2.4. Characterization of SGF Deposits

Deposits in the proximity of or in channel bed and in alluvial fan area were analyzed from a sedimentological and morphological point of view by direct observation from catchments' head to alluvial fan's toe. During the surveys, morphological measurements of SGF deposits were made, their shape, longitudinal and cross sections were described and documented, sediment samples were taken to perform grain-size laboratory analysis on 2 sediment samples per catchment (from deposits in channel bed and in alluvial fan) from undisturbed deposit (from the core of levees to avoid the underestimation of grain-size distribution of fine sediments due to secondary surficial winnowing processes). Photographs were taken and subsequently used for analysis of grain-size distribution and clasts' orientation, structure and texture. All the parameters presented in Section 2 were subsequently related to the historical events of SGF/SFF that occurred in Susa Valley and related rainfall data, characterized by information with a low degree of uncertainty (SGF/SFF events from 1990 to 2023).

3. Results

3.1. Historical SGF/SFF Event Behavior

Although according to the morphological classification shown in Figure 4, all the catchments of the Susa Valley are considered capable of generating SGFs/SFFs, the analysis of historical documentation reveals that out of 208 catchments in the Susa Valley, only 78 have documented events from 1728 to 2023 resulting from database queries (Figure 7).

Notably, there is a gap in information for the period 1943–1945 coinciding with World War II and during the COVID-19 pandemic from 2020 to 2021. The frequency of documented reports peaks in the 20th century, with scarce valid reports recorded before 1800. It is relevant to note that information preceding 1978 may carry a lower degree of reliability, necessitating interpretation to classify the flow phenomena according to modern scientific terminology [58]. The older periods (1728–1989) are characterized by lower quality of information, while there is a greater reliability of data in more recent times (1990–2023). This heterogeneity in the temporal distribution of information in terms of flow events and associated rainfall data is common to all the studied catchments and can be considered as normalized for the investigated area. The difference in data quality can be attributed to an increasing freshness of events' observations, the technological improvement of rain gauges and their growing distribution after 1990 and the installation of a weather radar in 2000. This phenomenon is also partly due to data loss resulting from the inevitable fading of historical memory passed down from archive to archive and partly due to missed reports due to force majeure, as evidenced by the inevitable shadow zones around the main wartime and pandemic periods. There are also cases where even in more recent periods, there are interruptions in the historical series on the activity of a catchment; in these cases, the lack of data is often due to the efficiency of mitigation structures, which after their construction have decreased the propagation of phenomena reducing the perception of the event's severity from citizens. As already mentioned, an SGF/SFF that does not cause damage or generate alarm does not attract interest and consequently is not reported by any source. As a consequence, the collected data do not have the same informative value; indeed, some of them, especially the older ones, lack precise information regarding the date of occurrence and phenomena classification. In some cases, there is no indication

of the day or even the month of the event; in other cases, descriptions regarding the referenced process are missing or are difficult to understand because they are expressed in non-conventional terms or sensationalistic or arbitrary language. However, efforts to reduce uncertainty through cross-analysis of various sources after verifying their reliability minimized information loss. Only about 10% of data was discarded due to being deemed completely unreliable. The 614 SGF/SFF events resulting from the first selection (Figure 8) were treated differently based on the completeness of their information content.

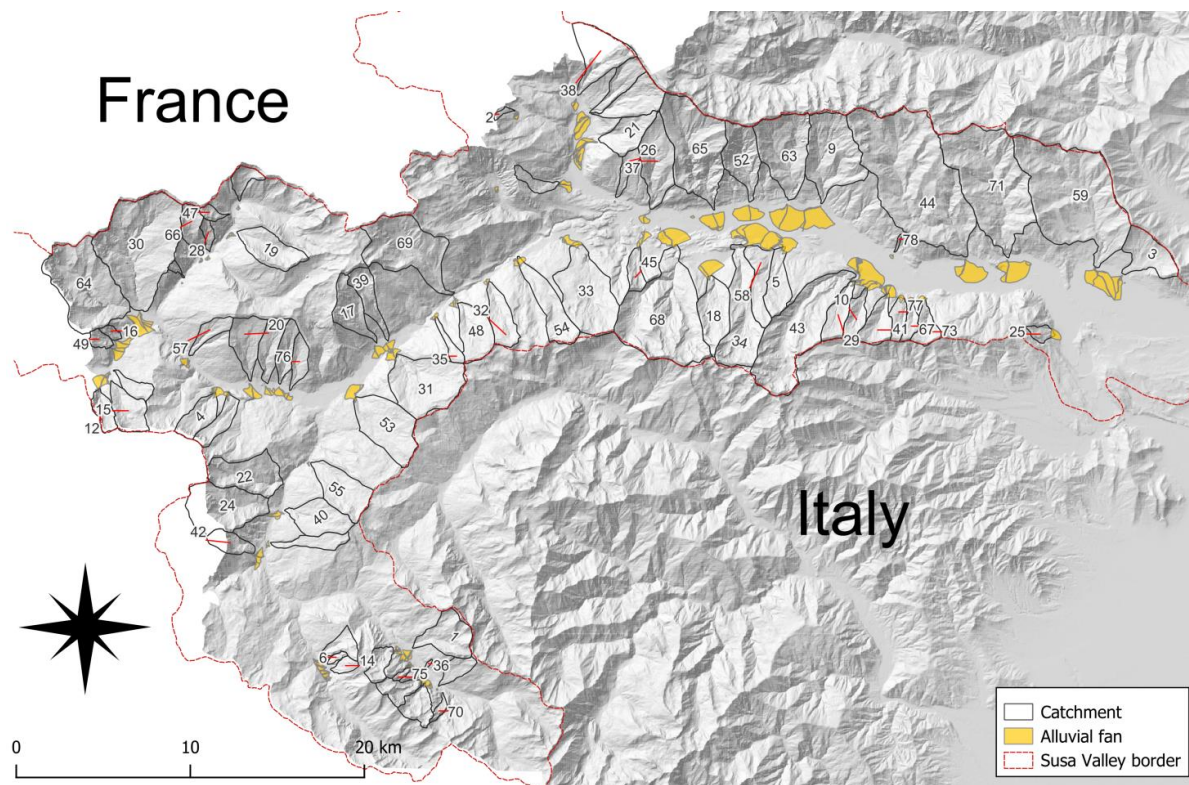


Figure 7. A total of 78 catchments having recorded SGF/SFF historical events with assigned ID number.

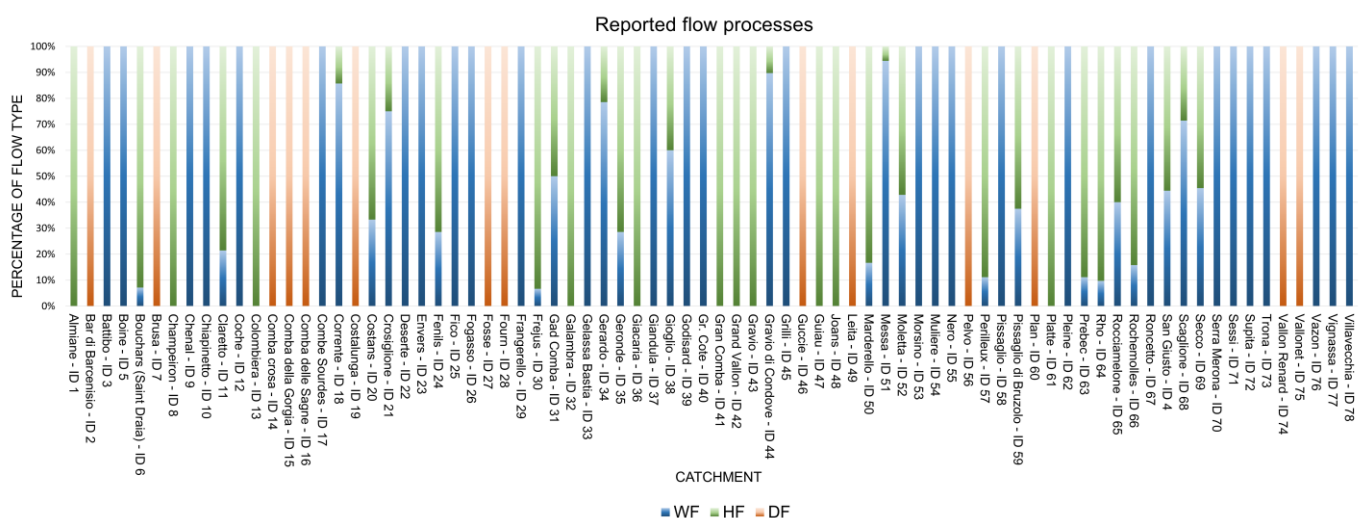


Figure 8. A total of 614 flow processes within 78 catchments distinguished by flow type (water flow (WF), hyperconcentrated flow (HF), debris flow (DF)) observed in the Susa Valley.

The SGF/SFF event occurrence dates were weighted and used according to their degree of uncertainty. Dates lacking day information were valuable for determining the occurrence seasonality, while dates consisting only of the year information were used to provide more robust estimates of the occurrence frequency and flow typology distribution. Events with complete dates were used for analyses aimed at quantifying triggering causes (critical rainfall values) with greater accuracy achieved where hourly data were available. From the reasoned statistical analysis of the collected historical data, despite the evident lack of temporal continuity in recording events, it was possible to obtain indications for each catchment regarding the characteristics of SGF/SFF initiation, especially concerning their temporal distribution. It was possible to characterize the seasonality (Figure 9) and the frequency of occurrence (Figure 10) of flow events.

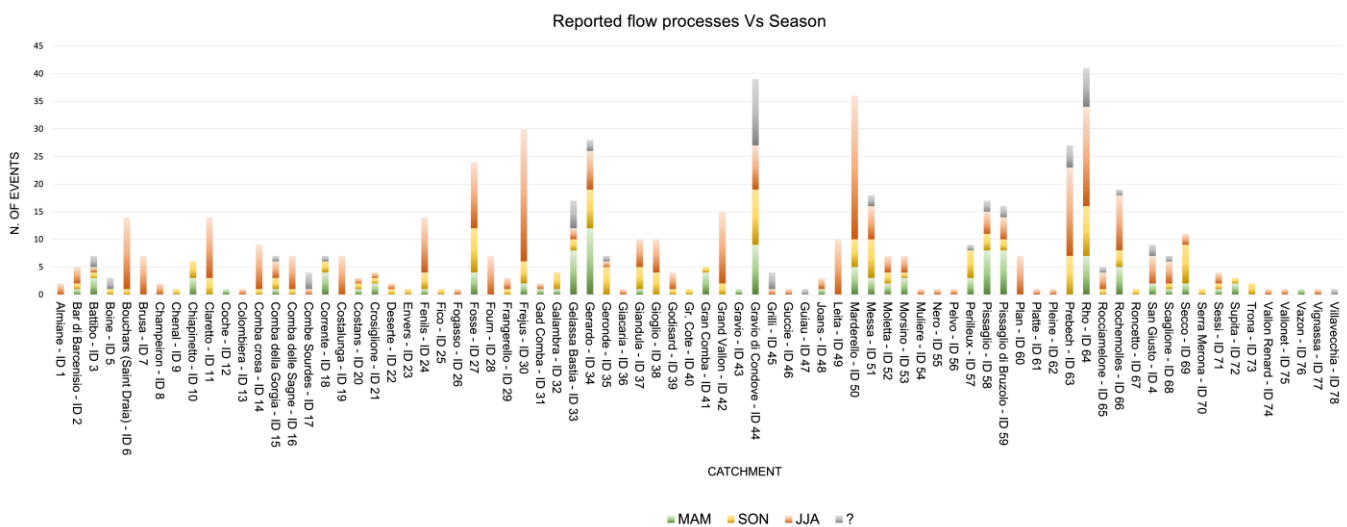


Figure 9. Seasonal distribution of SGF/SFF events.

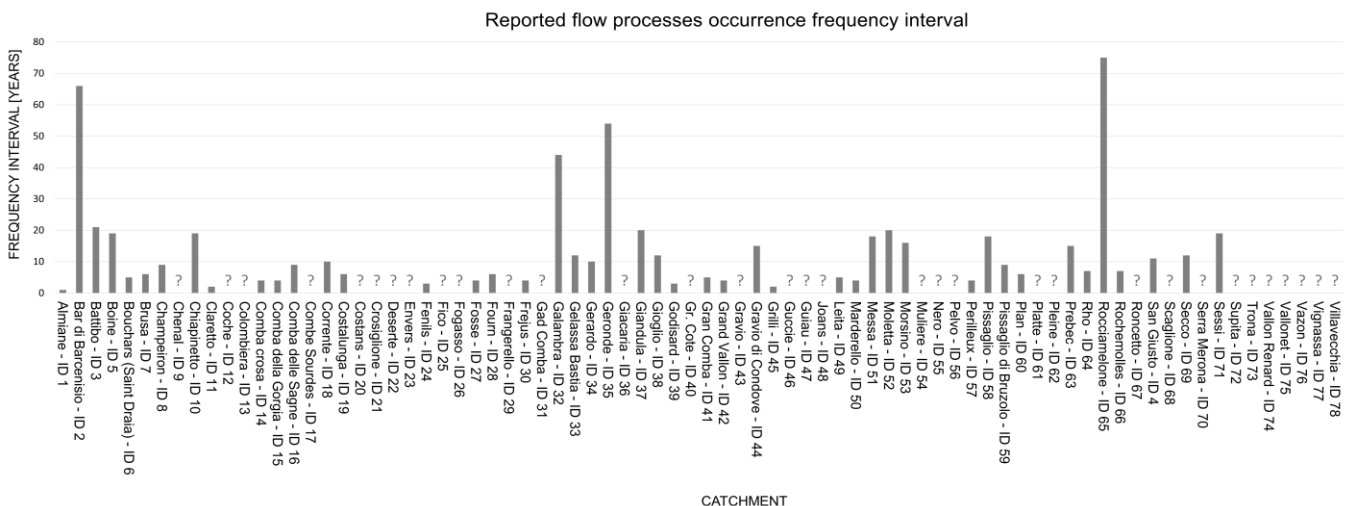


Figure 10. Interval of occurrence of SGF/SFF events for catchments with sufficient historical information. The question marks refer to the impossibility of deriving an occurrence interval due to the absence of recurring historical events.

From the histogram in Figure 9, seasonal differences in the occurrence of SGFs/SFFs for the considered catchments are highlighted, where in many cases, the predominance of events in the summer period (JJA) is markedly pronounced. It is also evident from the analysis in Figure 10 that there is appreciable variability in the frequency of occurrence of SGFs/SFFs, ranging from 1–2 years for some catchments to periods of quiescence exceeding

70 years for others. Regarding considerations on the intensity of historical events, unfortunately, the data proved to be unreliable as the estimation of magnitude has often been deduced from partial volumes of mobilized material. Indeed, the volumetric quantifications found in the analyzed documents refer to the accumulation of sediments in deposition areas exclusively in the lower sections of the catchments or to volumes of sediments retained upstream of mitigation structures, or alternatively, to volumes related only to sediments deposited in the alluvial fan area. As an obvious consequence, the reported volumes tend to systematically underestimate (to a variable and unquantifiable extent in each case) the likely actual magnitude of the SGF/SFF events reported. For this reason, the values related to the volume of sediments mobilized by SGFs/SFFs were not considered a reliable parameter for rigorous statistical processing. Indeed, damage ratios (from light to severe) can be helpful in estimating the probable magnitude. For the same catchment, it can be assumed that an SGF/SFF causing severe damage is characterized by a higher magnitude compared to one responsible for moderate or light damage. Following this criterion, it was possible to estimate, although with a non-negligible level of uncertainty, the likely magnitude of the SGF events documented in the historical archives. Damage severity classes associated with the Susa Valley's catchments are published at <https://geoportale.arpa.piemonte.it/app/public/?pg=mappa&ids=5554d33c511140e0acc77ff46fcac86c> (accessed on 12 April 2024).

Rainfall-Triggering Thresholds

The historical SGF/SFF events with a complete date of occurrence were therefore correlated with the rainfall values recorded on the day of SGF/SFF initiation and for the day before in case of multi-day rainfall event duration. At the considered latitude, rainfall is between two extremes of a wide range of intermediate phenomenological cases: short-duration (hours) convective precipitations, typically scattered (isolated rainstorms, laterally discontinuous), and long-duration (days) advective rainfall, typically widespread (rainfall with uniform lateral continuity at the synoptical scale). The sizes of these rainfall typologies vary horizontally, from 1 km for convective storm cells to a scale of 100–400 km for advective rainfall front systems, and vertically, respectively, from a few kilometers up to 15 km of cloud thickness. The duration also varies significantly, from an average of one hour for convective rainfall to several days for advective ones. Between these two extremes, intermediate types of rainfall can occur. Rainfall also varies depending on the maximum cumulative amount reached. In fact, in the observed cases, for convective rainfall, a value of 70 mm is reached for durations of about 1 h, for extended advective rainfall, cumulative values of 270 mm are reached for durations of 25 h, while for intermediate or mixed rainfall (advective system with convective component), rainfall values up to 87 mm for 29 h are recorded. As emerged from this study, the occurrence of SGFs/SFFs is essentially linked to rainfall with a neglectable contribution of antecedent precipitation, which is the most common triggering cause in the Alps, excluding high elevations [59] where snow melting and glacial-periglacial processes can be the main triggering causes. From the comparison of rainfall values recorded by neighboring rain gauges, located at comparable distances and elevation with the catchment, a high variability in the recording of rainfall heights was noted at the scale of a single event. The spatial distribution of rainfall is extremely variable, except of course in cases where it is associated with extensive advective systems, making it difficult to attribute a critical rainfall value based solely on the spot measurement performed by rain gauges. Even attempts to spatialize rainfall values using various commonly used interpolation methods, such as kriging [60], have not proven useful in obtaining reliable calculated values when compared with real rainfall distribution provided by weather radar estimation. The obvious consequence of using data recorded by a rain gauge is the underestimation, even significant, of the rainfall intensity responsible for SGF/SFF initiation. The underestimation progressively decreases, until it disappears, going toward extended advective rainfall, where the rainfall data recorded by rain gauges are more uniform due to the lack of significant discontinuities in the lateral distribution of precipitation fields at the scale considered. In summary, the spatial variability of rainfall

fields for convective rainfall hinders the correct attribution of critical rainfall values, also in terms of duration, if relying only on rain gauge recordings, as it is very rare to have a rain gauge directly under the rainstorm shower's center. Therefore, the rain gauge network is more reliable in estimating critical rainfall values for advective rainfall. Since 2000, with the installation of the C-band weather radar on the Torino Hill 84 km east of the head of the Susa Valley, it has been possible to identify with high spatiotemporal resolution the storm showers' centers and peaks of advective rainfall events [61]. Thanks to the data acquired from the weather radar, it has been possible to determine that the triggering of SGFs is mainly associated with intense peaks, typically of short duration (ranging from a few minutes to a few hours). In Figure 11, critical rainfall values expressed in mm/h, derived from weather radar observations corrected with the recording of rain gauges, identified for the initiation of SGFs/SFFs are reported for catchments with a comprehensive set of information on the initiation timing (complete dates with probable initiation hour) and an adequate consistence and quality of rainfall data.

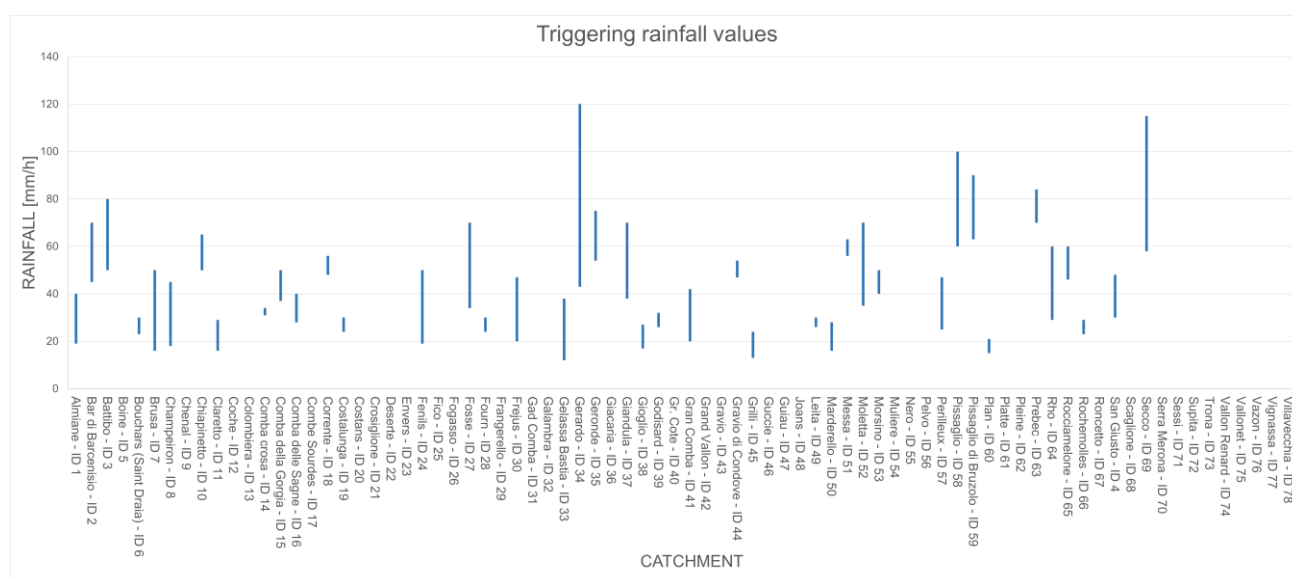


Figure 11. Rainfall values (mm/h) recorded during SGF/SFF events by weather radar and rain gauges.

From the data shown in Figure 11, some differences in the distribution of critical rainfall values within the selected catchments are evident. Considering the averages of the minimum rainfall values responsible for the occurrence of SGFs/SFFs and the seasonal recurrence of events (Figure 9), two distinct catchment profiles emerge:

1. Catchments where SGFs/SFFs are caused by rainfall every rainy season with higher incidence in summer (JJA) because of the higher frequency of rainstorms with intensity from moderate to very high, defining a minimum critical rainfall value from 20 to 30 mm/h (resulting from weather radar observations);
2. Catchments where SGFs/SFFs are caused mainly by very high intensity rainfall peaks during extreme rainfall events that occur every rainy season with values ≥ 50 mm/h (resulting from weather radar observations).

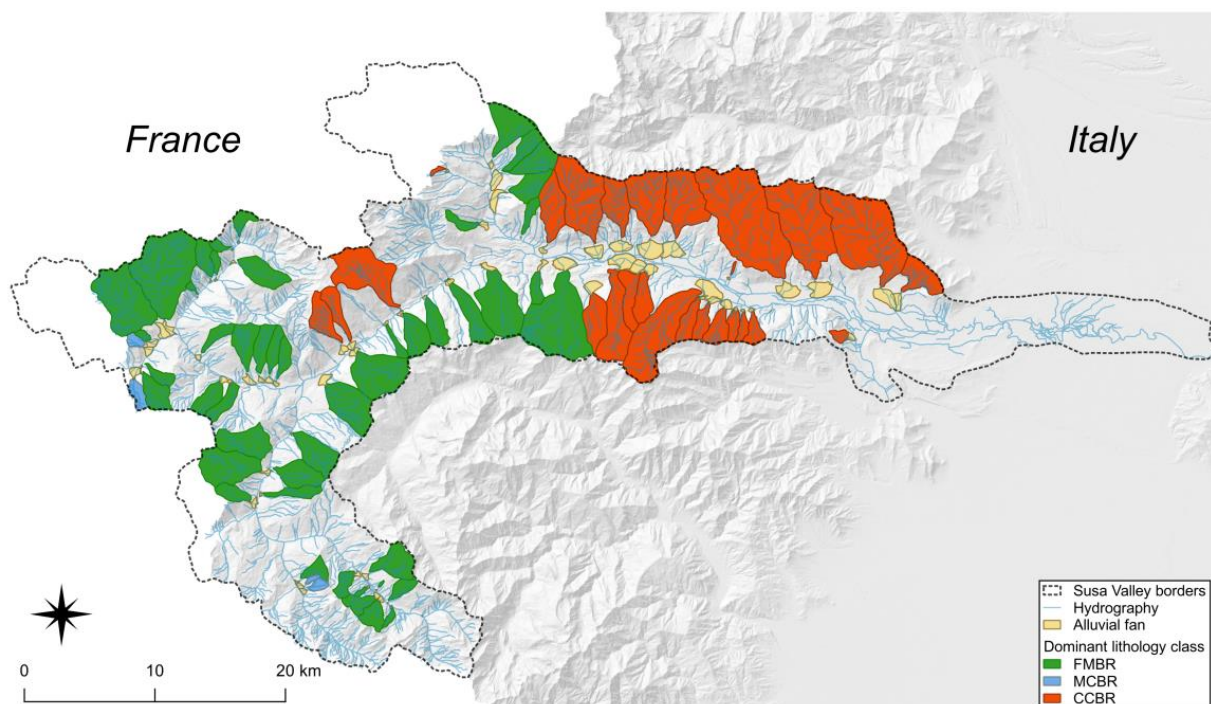
Considering the return period for the above rainfall values in Susa Valley derived from the Atlas of Intense Rainfall of Piemonte (<https://webgis.arpa.piemonte.it/agportal/apps/webappviewer/index.html?id=378e0fcb7ddd4565ba836c07dd1c4c9b>—accessed on 24 April 2024), there appears to be a certain consistency with the intervals of occurrence of SGF/SFF events illustrated in Figure 10 (Table 1).

Table 1. Return period for minimum rainfall triggering values linked to SGF/SFF initiation.

Area	Rainfall Value (mm/h)	Reference Return Period (years)
Susá Valley (Cottian Alps)	20	5
	30	20
	50	100

3.2. Catchments' Lithological Characterization

The lithological groups of the Susa Valley catchments, as defined in Section 2.2.2, were classified starting from the Clay Weathering Index (CWI) classification proposed by [16]. This index assesses the propensity of rock masses to produce varying quantities of clay-sized fine sediment from weathering processes. Clay percentage in fine sediments can influence the SGF rheology, depositional style and some features of alluvial fans. Clay in fine sediment under 5% generates non-cohesive SGFs; for values > 5%, the SGFs are characterized by a cohesive behavior [17,20]. The updated classification here proposed also takes into account the coarse sediment characteristics deriving from parent rocks considering their geomechanical conditions. Given the significant influence of the structural characteristics and physical properties of rock masses on loose material production, each rock mass was classified not only from a strictly lithological point of view but also from a geomechanical perspective. To this end, the method proposed by [55] for fractured rock masses was employed. In summary, the characterization of the rock mass is expressed through a numerical index called the Geological Strength Index (GSI), assigned by combining the assessment of the fracturing and/or deformation state observable in the field and the evaluation of the weathering conditions found on the surfaces (outcropping surface and fractures' surfaces) characterizing the rock masses. The characterization of rocks proved useful for identifying and evaluating the potential rate of loose material type and generating rate from source areas (parent rocks). Catchments classified by lithological groups and GSI are shown in Figure 12.

**Figure 12.** Lithological classification of Susa Valley's catchments having historical SGF/SFF events reported.

What was highlighted is a varying production, both in terms of abundance and type, of loose material depending on the dominant lithological group of considered catchments. What results from the distribution of GSI values assigned to all the lithologies forming the catchments' bedrocks by comparing the associated loose material is the following:

1. Catchments having bedrock mainly formed by thin foliated metamorphic rocks (FMBR) characterized by poor geomechanical properties, producing abundant loose material with a high clay component (Figure 13) and being more predisposed to the accumulation of gravitational deposits (very susceptible to frequent small rock falls). The production of loose material resulting from the weathering of rock masses is constant and abundant, given the poor geomechanical characteristics of rocks. The coarse fraction of loose material is represented by the following:
 - Rare boulder of 1–2 m³ with sphericity from prismoidal to sub-prismoidal and rarely spherical and roundness from angular to very angular;
 - Common blocks of 0.50–0.70 m³ with sphericity from prismoidal to sub-discoidal and roundness from angular to very angular;
 - Abundant cobbles/pebbles with sphericity from prismoidal to discoidal and roundness from angular to very angular;
 - Very abundant gravels with sphericity from prismoidal to discoidal and roundness very angular.
2. Catchments having bedrock mainly formed by massive carbonate rocks (MCBR) characterized by good geomechanical properties, producing moderate amounts of loose material (Figure 14) and non-negligible quantities of clayey sediment (clayey silt as insoluble fraction in carbonate rocks). The production of loose material resulting from the weathering of rock masses is quite constant and moderately abundant, given the good geomechanical characteristics of rocks. The coarse fraction of loose material is represented by the following:
 - Common boulders of 1–3 m³ with sphericity from spherical to sub-discoidal and rarely sub-prismoidal and roundness from sub-angular to angular;
 - Abundant blocks of 0.50–0.80 m³ with sphericity from spherical to sub-discoidal and rarely sub-prismoidal and roundness from angular to very angular;
 - Very abundant cobbles/pebbles with sphericity from spherical to discoidal and roundness from angular to sub-angular;
 - Very abundant gravels with sphericity from sub-prismoidal to discoidal and roundness angular.
3. Catchments having bedrock mainly formed by coarse-grained crystalline rocks (CCBR) characterized by excellent geomechanical properties, producing smaller quantities of material in a comparable time period related to the other two types, in the form of loose material with abundant blocks and large boulders (Figure 15). Additionally, they are very poor producers of clay as a fine fraction. The coarse fraction of loose material is represented by the following:
 - Rare mega-boulders of 15–20 m³ with sphericity from sub-discoidal to spherical and rarely sub-prismoidal and roundness from sub-angular to sub-rounded;
 - Common boulders of 2–10 m³ with sphericity from sub-discoidal to spherical and rarely sub-prismoidal and roundness from sub-angular to sub-rounded;
 - Abundant blocks of 0.50–1 m³ with sphericity from spherical to sub-discoidal and rarely sub-prismoidal and roundness from sub-angular to sub-rounded;
 - Very abundant cobbles/pebbles with sphericity from spherical to sub-discoidal and roundness from angular to sub-angular;
 - Very abundant gravels with sphericity from sub-prismoidal to sub-discoidal and roundness from angular to very angular.



Figure 13. Typical loose material produced by catchments belonging to group FMBR.



Figure 14. Typical loose material produced by catchments belonging to MCBR group.



Figure 15. Typical loose material produced by catchments belonging to group CCBR.

3.3. Morphometric Classification and Outcropping Bedrock Percentage

Even if all the Susa Valley catchments are potentially able to generate SGFs/SFFs, according to [50] (Figure 3), just 78 catchments out of 208 have historical documented events. To explain this anomalous behavior, landslides (Figure 16), DSGSDs (Figure 17) and outcropping bedrock distribution were considered.

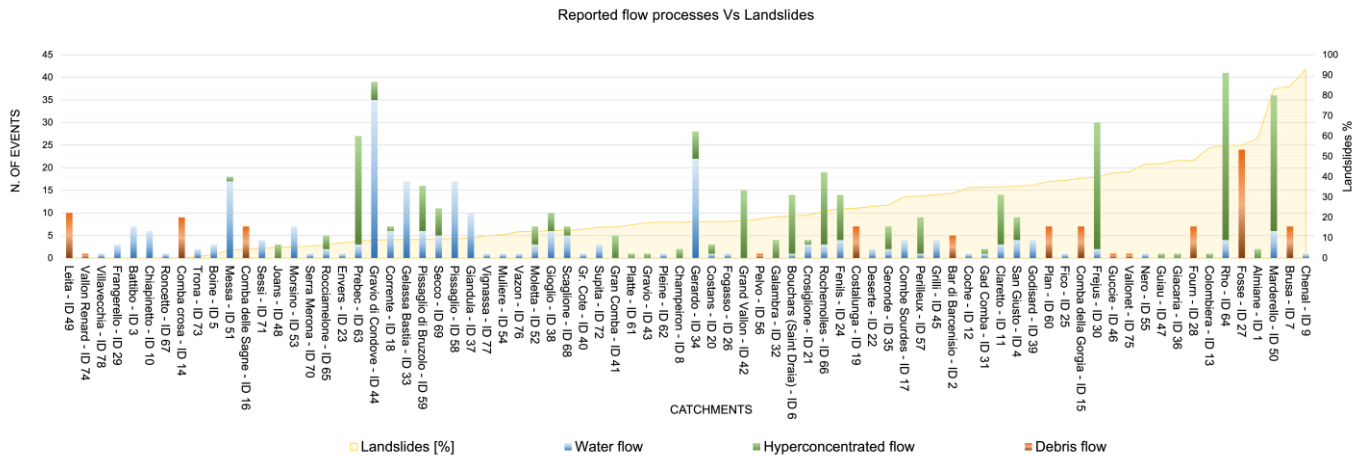


Figure 16. Relationship between landslides' distribution and flow process types.

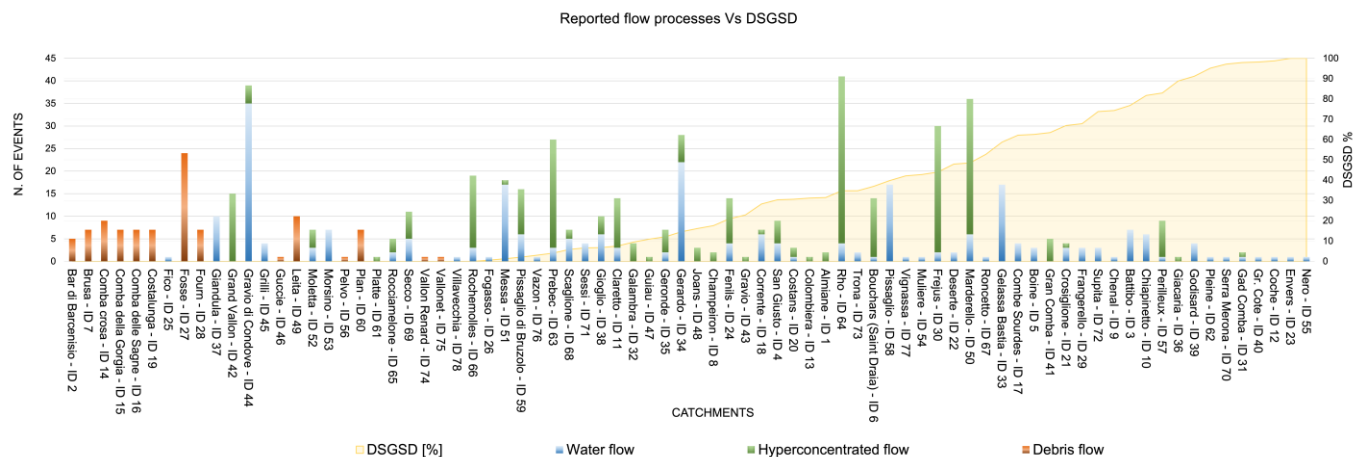


Figure 17. Relationship between DSGSDs' distribution and flow process types.

As shown in Figures 16 and 17, landslide and DSGSD's distribution seems to have no particular influence on the type of flow process, as demonstrated by the absence of trends linked to the presence or absence and relative abundance of such gravitational phenomena within the catchments. A multivariate statistical analysis [62] applied to the Susa catchments demonstrates that debris flows and hyperconcentrated flows exhibit strong and moderate positive correlations, respectively, with the percentage of outcropping bedrock (Pearson correlation coefficient $\rho = 0.533$, p -value $< 10^{-5}$; $\rho = 0.233$, p -value $= 0.03$). On the contrary, water flows are negatively correlated with outcropping bedrock percentage ($\rho = -0.364$, p -value $= 0.002$). As depicted in Figure 18, when the outcropping bedrock exceeds 20%, the likelihood of hyperconcentrated flows increases, and the outcropping bedrock threshold rises to 55% for debris flows.

Indeed, the catchments of Susa Valley that have not documented historical SGF/SFF events are characterized by a low percentage of outcropping bedrock, generally under 10% (Figure 19).

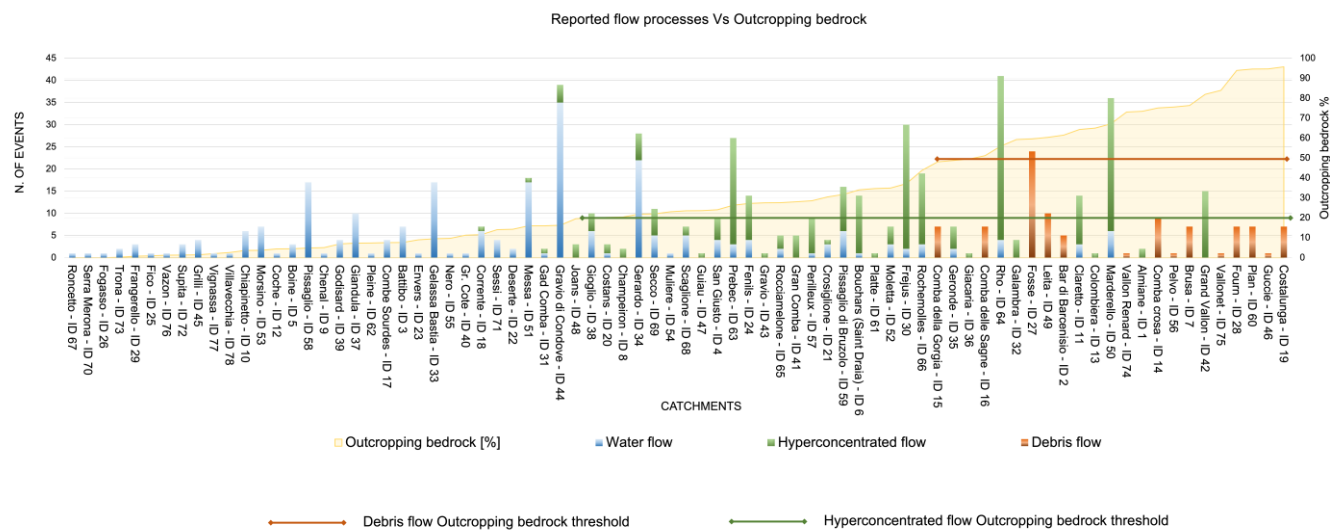


Figure 18. Outcropping bedrock thresholds vs. flow process type.

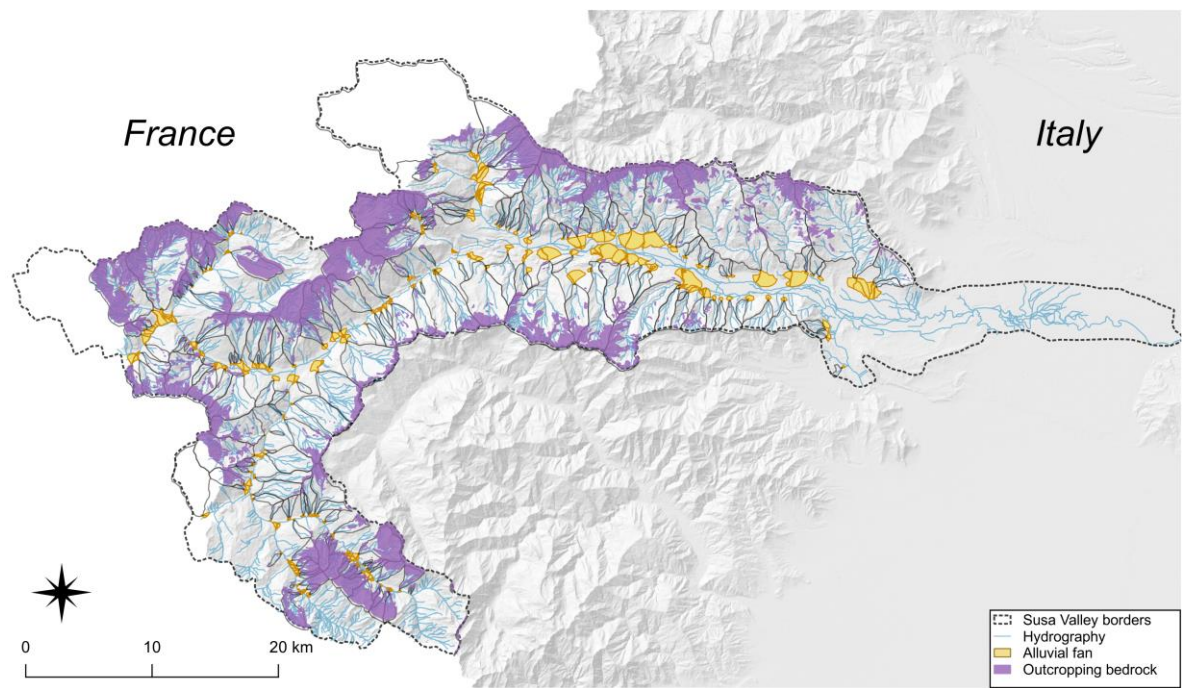


Figure 19. Distribution of outcropping bedrock within the catchments. The catchments with a low percentage of outcropping bedrock have not documented SGF/SFF events.

3.4. Alluvial Fan Caracterization

Having concluded the analysis of the parameters within the catchment areas, attention was directed toward the macroscopic characterization of their respective alluvial fans. Even upon initial comparison, significant relationships were delineated based on the ratio between the catchment area and the area of the respective alluvial fan. A clear distinction emerged between catchments characterized by a high ratio of the alluvial fan area/catchment area and catchments characterized by significantly lower values. This difference makes sense when observed in relation to the lithological group to which the catchment belongs. By averaging these values per lithological group, the results shown in Table 2 are obtained.

Table 2. Average ratio between the catchments' area and alluvial fans' area.

Catchment Type	Mean Area (%) of Alluvial Fan Compared to the Area of the Feeding Catchment
FMBR	20
MCBR	5
CCBR	10

Catchments belonging to the FMBR group display a small-sized alluvial fan characterized by moderate slopes and irregular shapes (Figure 20).

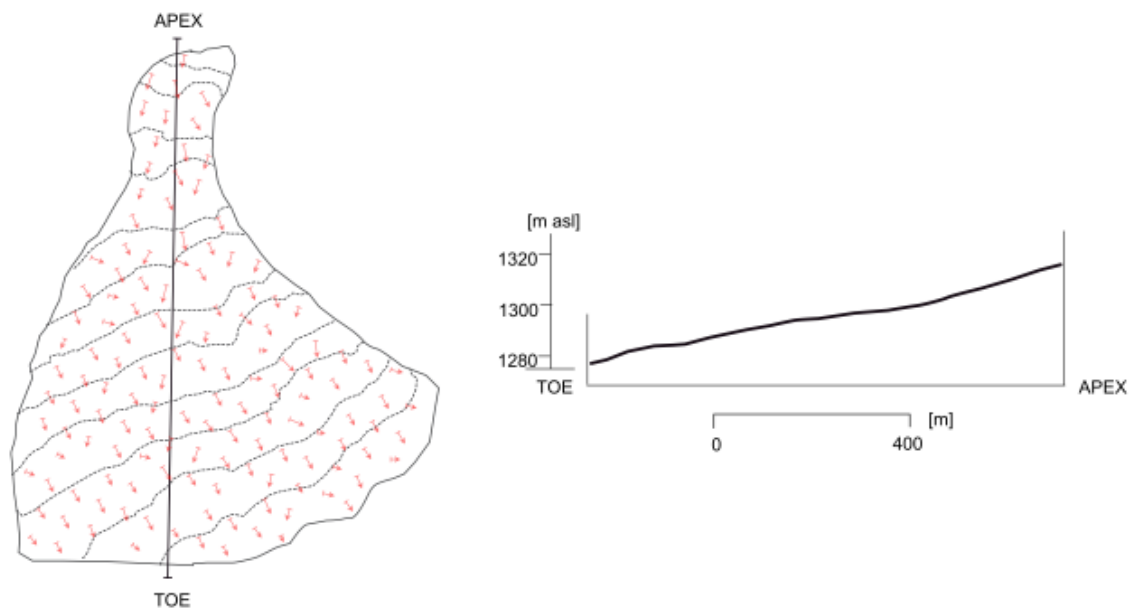


Figure 20. Typical shape of FMBR alluvial fan (example from Rio Frejus—ID 30). Slope gradient distribution of preserved depositional surface of alluvial fan is indicated by red arrows. Slope distribution of alluvial fan surface shows low variation from apex to toe (**left image**). Longitudinal section (**right image**) is characterized by moderate slope gradient and quite regular profile.

Where observable (in minimally or not anthropized alluvial fans), there is a prevalence of levee deposits compared to lobes (representing low energy transport deposits during the terminal phase of an SGF event), distributed evenly between the apex and toe zones, except in the most distal areas from the main channel axis. Similarly, the transition from the apex zone to the central body to the toe of the alluvial fan is not marked by quick changes in the slope of the top surface.

Catchments belonging to the MCBR group reveal a wide and gently sloping alluvial fan, which in plan view shows a regular fan-shaped geometry (Figure 21).

Where observable (minimally or not anthropized alluvial fan), there is a prevalence of lobate forms in the central and distal zones, while levee deposits are more concentrated in the apical zone. The transition from the zone dominated by levees to that with prevalent lobes is characterized by a gradual decrease in the slope of the alluvial fan's surface from the apex to the toe.

Catchments belonging to the CCBR group show a small-sized alluvial fan with steep slopes, especially in the apex zone, and a drop shape in the plan view (Figure 22).

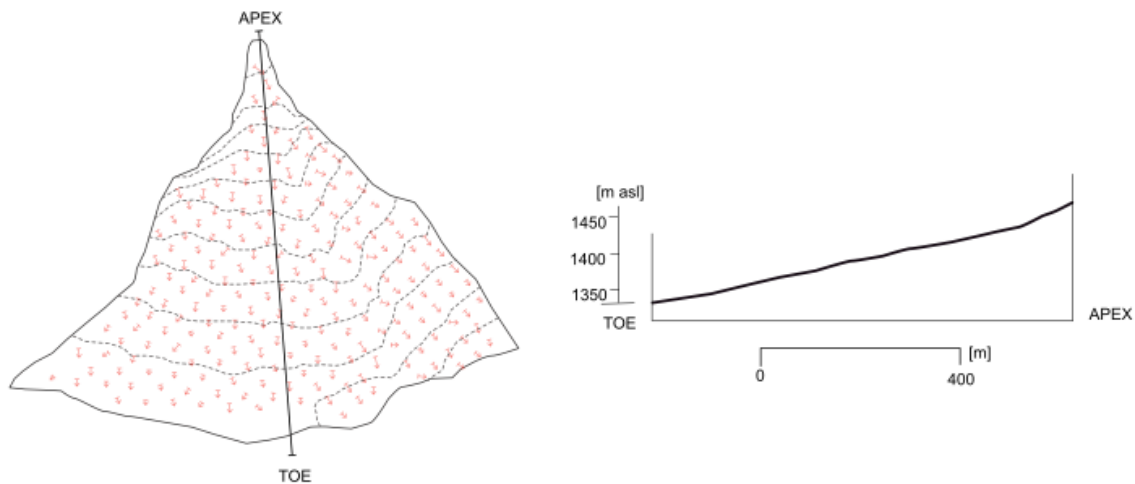


Figure 21. MCBR alluvial fan shape (example from Rio Fosse—ID 27). Slope gradient distribution of preserved depositional surface of alluvial fan is indicated by red arrows. In plan view, alluvial fan has regular and wide fan shape (**left image**). Longitudinal section is characterized by smooth, gentle and regular slope from apex to toe (**right image**).

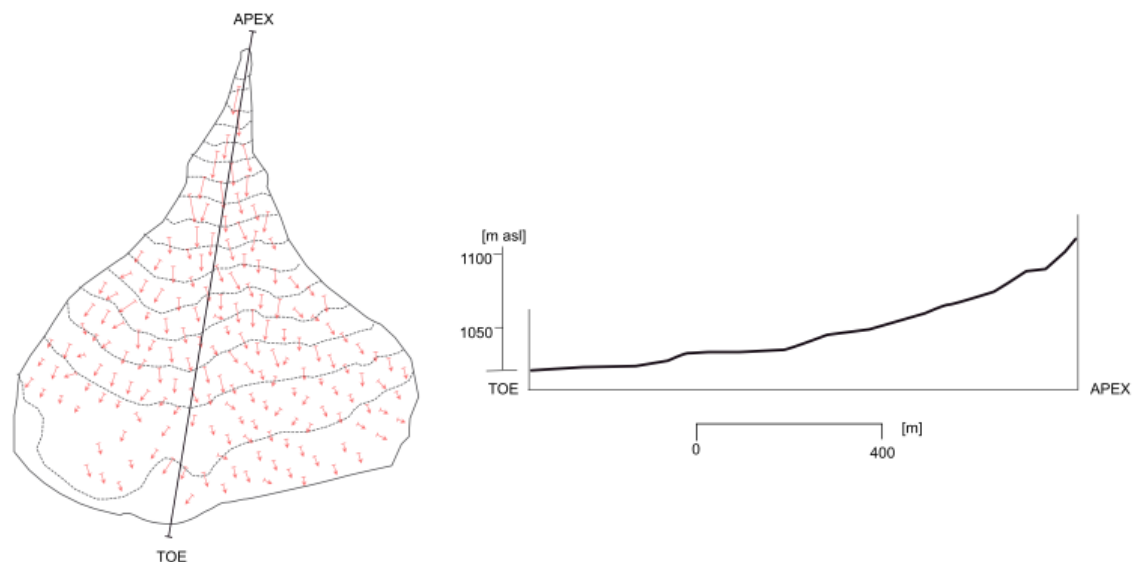


Figure 22. CCBR alluvial fan geometry (example from Rio Secco—ID 69). Slope gradient distribution of preserved depositional surface of alluvial fan is indicated by red arrows. Slope of fan surface is strongly irregular with greater slope values in apex zone. In plan view, alluvial fan is drop-shaped (**left image**). Longitudinal section (**right image**) is characterized by significantly higher slope gradients showing abrupt and sudden changes corresponding to grain-size variations of sediment.

A clear distinction in grain-size distribution is noticeable between the apex zone and the rest of the alluvial fan body. Indeed, larger boulders, organized into lobes and subordinate boulder trains, are concentrated in the apex zone, and through more or less quick changes in the slope of the fan surface, there is a progressive decrease in the presence of boulders and an increase in granulometric heterogeneity as one proceeds toward the toe of the alluvial fan. However, there are alluvial fans of CCBR catchments that display a smaller-sized alluvial fan with a modest slope and a lobe shape in plan view (Figure 23).

In this sub-type of the CCBR alluvial fan, there are no marked variations in the grain-size distribution of the alluvial fan body, as indicated by minimal changes in slope. Boulders are significantly less common than in the previous CCBR alluvial fan type, and granulometric heterogeneity, although gravels, cobble and pebble-dominated, is noticeable along the entire length of the alluvial fan. The CCBR catchments feeding this sub-type of

alluvial fans are dominated by SFF processes (hyperconcentrated flows with low sediment concentration and water flows).

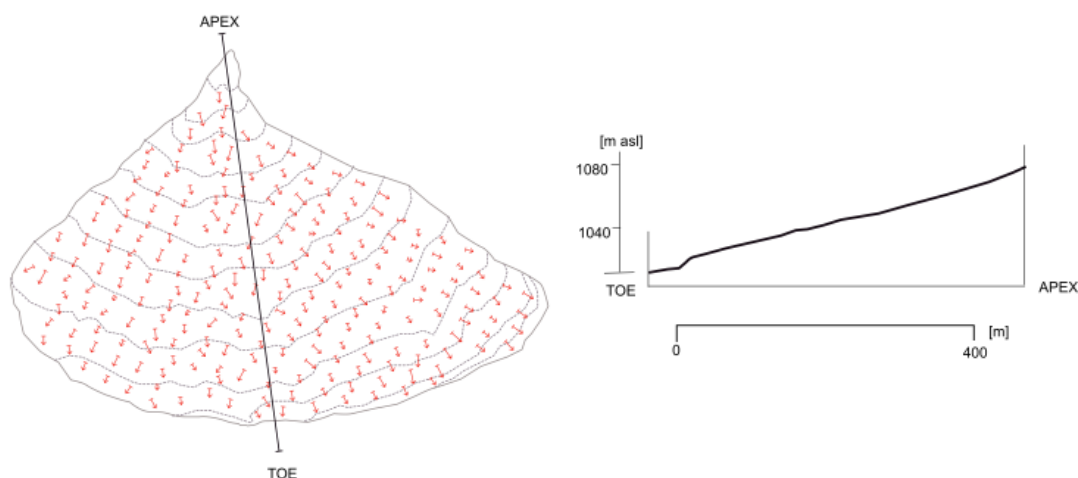


Figure 23. Geometry of CCBR alluvial fan exclusively formed by hyperconcentrated flow and water flow processes (example from Rio Geronde—ID 35). Slope gradient distribution of preserved depositional surface of alluvial fan is indicated by red arrows. In plan view, alluvial fan shows lobe shape (**left image**). Slope is regular and characterized by longitudinal profile (**right image**) with moderate values compared to CCBR alluvial fan dominated by debris flows.

3.5. Deposit Description

Concurrently with the analyses conducted at the catchment scale, investigations were carried out in situ and in a laboratory, characterized by significantly higher resolution. The channel and alluvial fan deposits were analyzed to identify the sedimentary processes specific to each catchment type. Surveys along the entire length of the main channels led to the mapping of deposits and highlighted the relationships between deposits resulting from different sedimentary processes. Furthermore, differences in sedimentary processes occurring in different catchments were highlighted, resulting in depositional styles unequivocally linked to the macroscopic characteristics observed in each catchment. Direct observation of deposits in the field allowed for a characterization of deposits based on the morphological description and spatial orientation of larger clasts. Subsequent image analysis conducted on photographs taken of the most significant stratigraphic sections and/or representative deposits enabled a more accurate statistical approach regarding sedimentological characteristics (grain size and orientation of coarser deposits, structure and texture of the entire deposit). Field observations, supported by image analysis, highlighted the following conditions for the catchments investigated. Along the main channels of the catchments belonging to groups FMBR, MCBR and CCBR, mainly three types of depositional styles were observed, interpretable, respectively, as waterlaid deposits (SFF), hyperconcentrated flow deposits (SGF/SFF) and debris flow deposits (SGF). The distinctive features lie in the grain size, clast axis orientation, texture and structure of the deposits: waterlaid deposits are characterized by gravelly sediments with an open work or partially open work structure, where larger clasts are imbricated at low angles with the major axis (a) oriented perpendicular to the transport direction. The characteristics of such deposits are similar for all types of catchments. In the FMBR catchment, the clasts constituting the levee deposits are characterized by high-angle imbrication, reaching even verticality, with the major axis (a) predominantly oriented parallel to the direction of transport, as schematized in Figure 24. The deposits are characterized by a clast-supported structure, and the matrix is abundantly present. The levee deposits of type FMBR are characterized by narrow, steep and strongly asymmetric shapes in the cross section (Figure 24); they also feature a frontal boulder or any blocking object, such as a log, followed by progressively smaller clasts, as schematized in Figure 24.

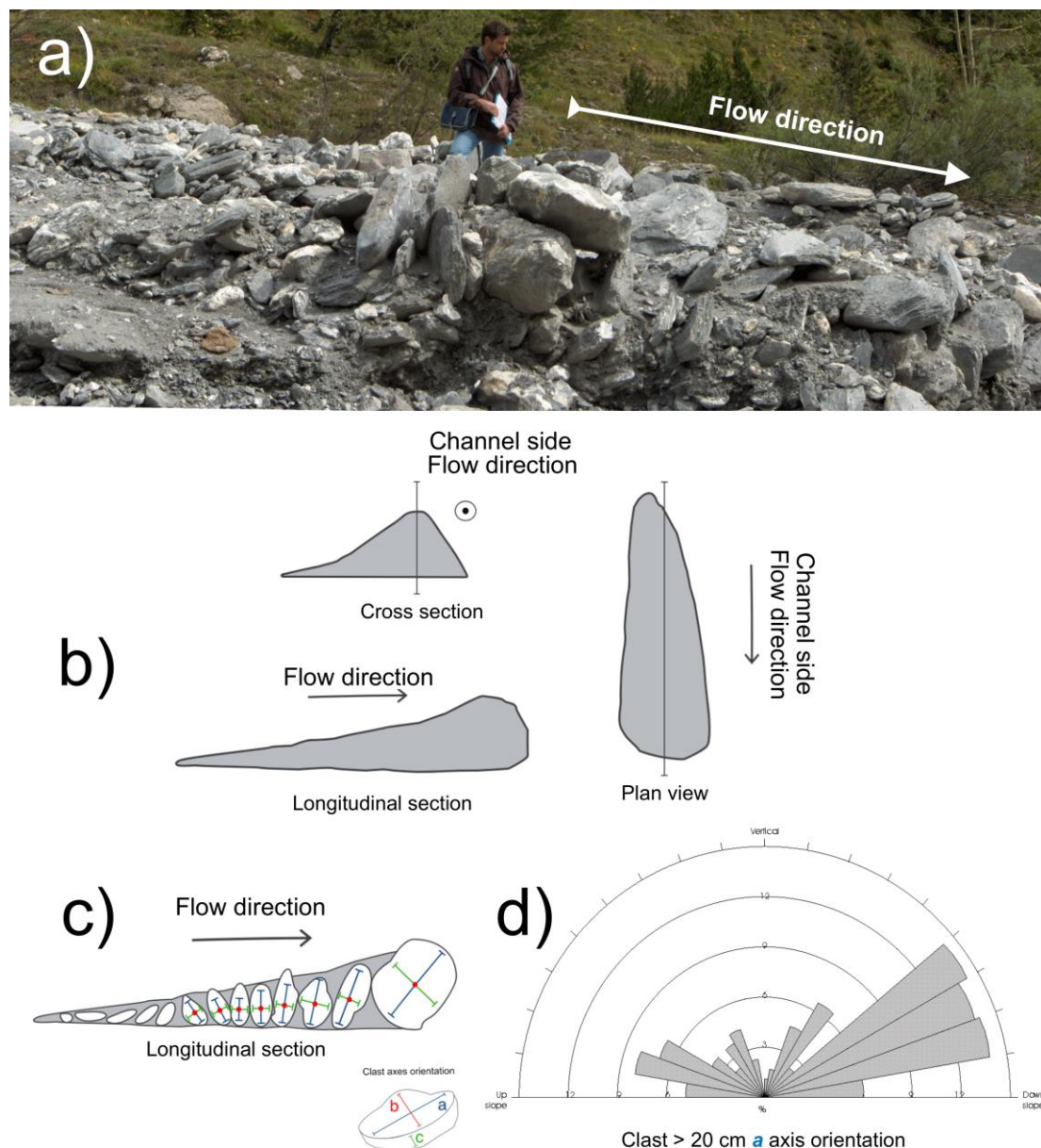


Figure 24. (a) Levee deposit for catchment belonging to group FMBR (example from Rio Frejus—ID 30). Note steepness of lateral depositional surfaces of deposit and frontal lock-block and abundance of matrix between high-angle imbricated clasts. (b) Schematization of cross section, longitudinal section and plan view of levee deposit. (c) Schematization of clasts' orientation and size distribution in longitudinal section view. (d) Statistical distribution of clasts' (>20 cm) major axis (a) orientation from up to down slope.

As with FMBR catchments, in MCBR catchments, and even less pronouncedly, the SGF deposits are characterized by high-angle imbrication (Figure 25). SGF deposits are characterized by flat and symmetrical levees; they usually feature a frontal boulder followed by progressively smaller clasts with the major axis (a) oriented according to the flow direction forming a high angle with the horizontal plane (Figure 25).

Levee deposits are characterized by a clast-supported structure, although it may appear to be confused with an open-work structure if the observation is limited to the surficial portion of the deposit. This effect is due to the winnowing action of the recessive process (liquid tail) that characterizes the concluding phases of SGF phenomena; indeed, by removing the surficial clasts, the true nature of the deposit can be observed.

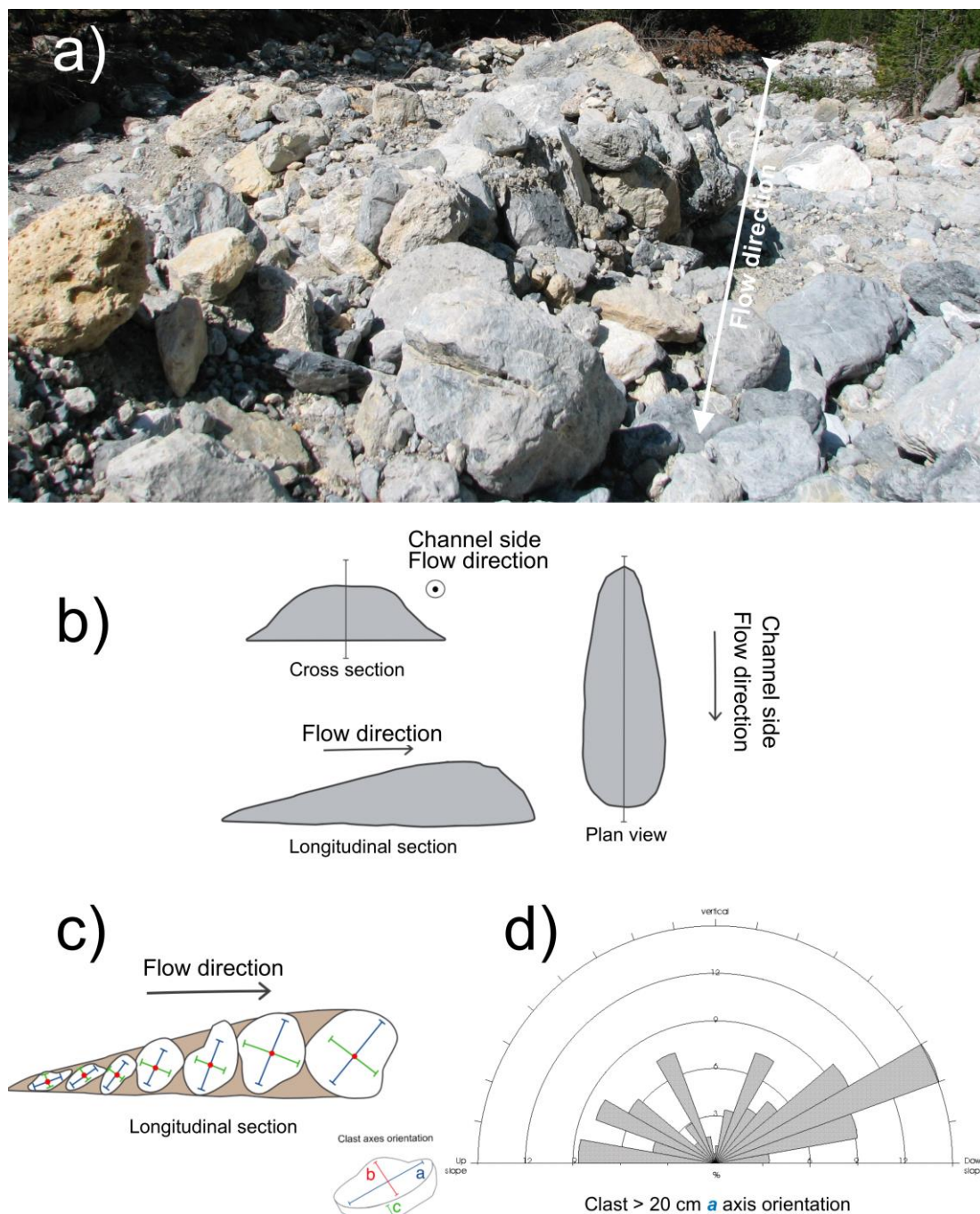


Figure 25. (a) Levee deposit for catchment belonging to group MCBR (example from Comba Crosa—ID 14). Note symmetry in front view of deposit and frontal lock-boulder and abundance of matrix between high-angle imbricated clasts. (b) Schematization of cross section, longitudinal section and plan view of levee deposit. (c) Schematization of clasts' orientation and size distribution in longitudinal section view. (d) Statistical distribution of clasts' (>20 cm) major axis (a) orientation from up to down slope.

Catchments of group CCBR do not yield levee-type deposits; instead, they produce something very similar called levee-like boulder trains. These deposits consist of an alignment of low-angle imbricated blocks/boulders with the major axis oriented perpendicular to the direction of transport; moreover, these deposits are usually matrix-free with an open-work or partially open-work texture (Figure 26).

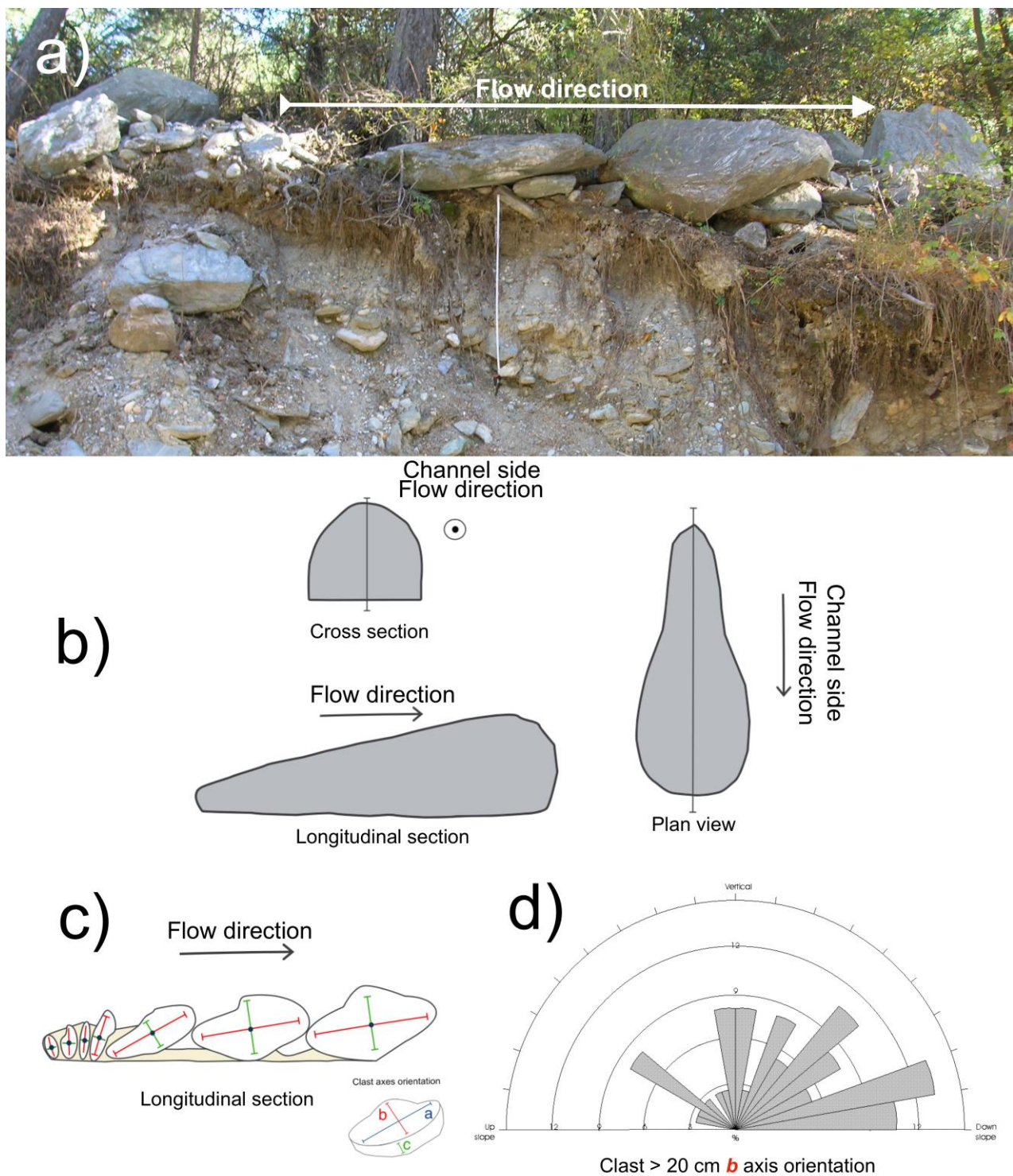


Figure 26. (a) Boulder-train deposit for catchment belonging to group CCBR (example from Rio Secco—ID 69). Note low-angle imbricated clasts and absence of matrix. (b) Schematization of cross section, longitudinal section and plan view of levee deposit. (c) Schematization of clasts' orientation and size distribution in longitudinal section view. (d) Statistical distribution of clasts' (>20 cm) intermediate axis (b) orientation from up to down slope.

Levee-like boulder train deposits are not the most common depositional style for group CCBR. Indeed, it is more common to find lobe deposits, which, contrary to what happens for FMBR and MCBR catchments, do not necessarily indicate flow processes characterized by lower energies compared to the processes responsible for boulder train deposition.

The lobe deposits of CCBR catchments are usually composed of fan-shaped lobes formed by low-angle imbricated boulders with the major axis (a) oriented perpendicular to the transport direction, as for the boulder trains. Moving away from the apex of the alluvial fan, as previously mentioned in Section 3.4, and proceeding toward the toe of the fan, a progressive decrease in boulders' number was observed. Thanks to open excavations for the construction of private structures, gravelly-sandy facies gradually prevail, which gradually pass to sand and silt (Figure 27) moving toward the distal part of the toe.



Figure 27. Section in a distal portion of the Rio Secco—ID 69 alluvial fan. Sandy-gravelly layers completely devoid of blocks are visible.

The grain-size analyses conducted on matrix samples taken from SGF deposits in catchments of types FMBR, MCBR and CCBR produced results consistent with those shown in Figure 28.

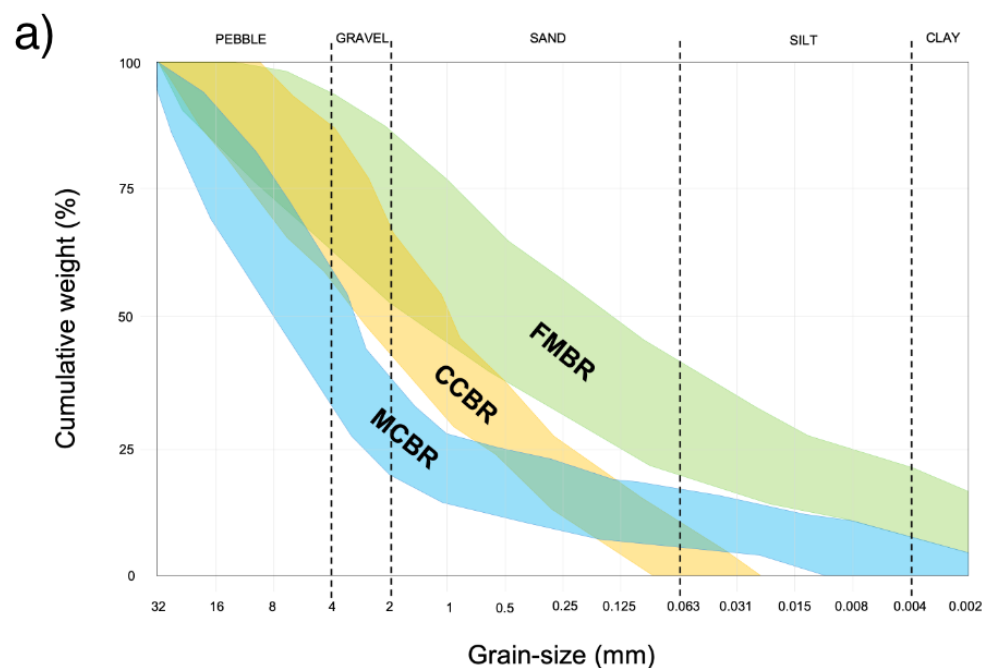


Figure 28. Cont.

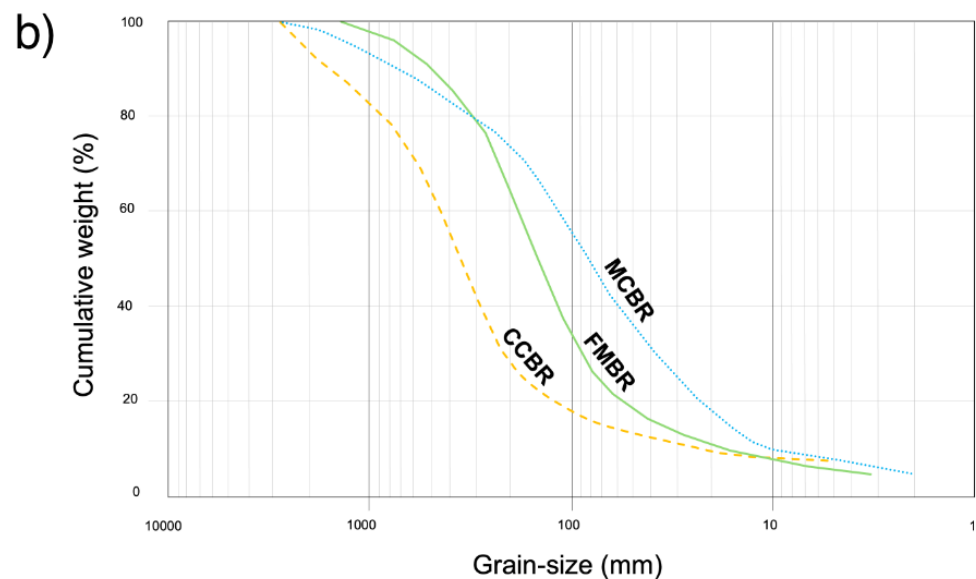


Figure 28. (a) The graph shows a marked difference in the amount of fine matrix (clays) depending on the group considered as average reference values obtained from aerometry performed on matrix samples (5 kg) collected along the main channels and the alluvial fans. (b) Different distributions of coarse clasts characterizing the three catchment groups.

Decreasing amounts of clay and clayey silt are observed, starting from group FMBR and ending with group CCBR, as indicated by the average values of clay/clayey silt contents for the three catchment groups summarized in Figure 28.

4. Discussion

The results show diversity in the flow phenomena behaviors occurring in the 78 analyzed catchments. However, common and recurring aspects are evident, allowing for the identification of groups of catchments with similar behaviors. Among the various predisposing factors characterizing the catchments, the predominant lithology of the bedrock and the outcropping bedrock percentage prevail over all others in defining the behavior of the flow processes that can occur in a given catchment. It has been demonstrated that the outcropping bedrock percentage (as opposed to the percentage of vegetated area) characterizing a catchment determines the likelihood of flow processes occurring in that catchment and, if so, the type of flow processes that may occur. Regarding the characteristics of flow phenomena, such as the sedimentological and morphological features of in-channel deposits and alluvial fans, the frequency and predominant seasonality of occurrence and the rainfall values required for the initiation of such phenomena, the predominant lithology appears to be the primary influencing factor. In fact, a reassessment of analyzed data, categorized by lithological group (FMBR, MCBR and CCBR), reveals a marked clustering of the results dependent on this classification. In Figure 29, the flow process types shown in Figure 8 are presented ordered by lithological group.

The analysis of the graph clearly shows, for example, that CCBR catchments are less prone to SGF phenomena compared to MCBR and FMBR catchments:

- FMBR catchments show 12% DFs, 61% HFs and 27% of WFs for a total of 326 flow events;
- MCBR catchments show 100% DFs for a total of 50 flow events;
- CCBR catchments show 2% of DFs, 29% HFs and 69% of WFs for a total of 238 flow events.

In Figure 30, the predominant seasonality of occurrence of SGF/SFF events shown in Figure 9 is presented again distinguished by lithological group.

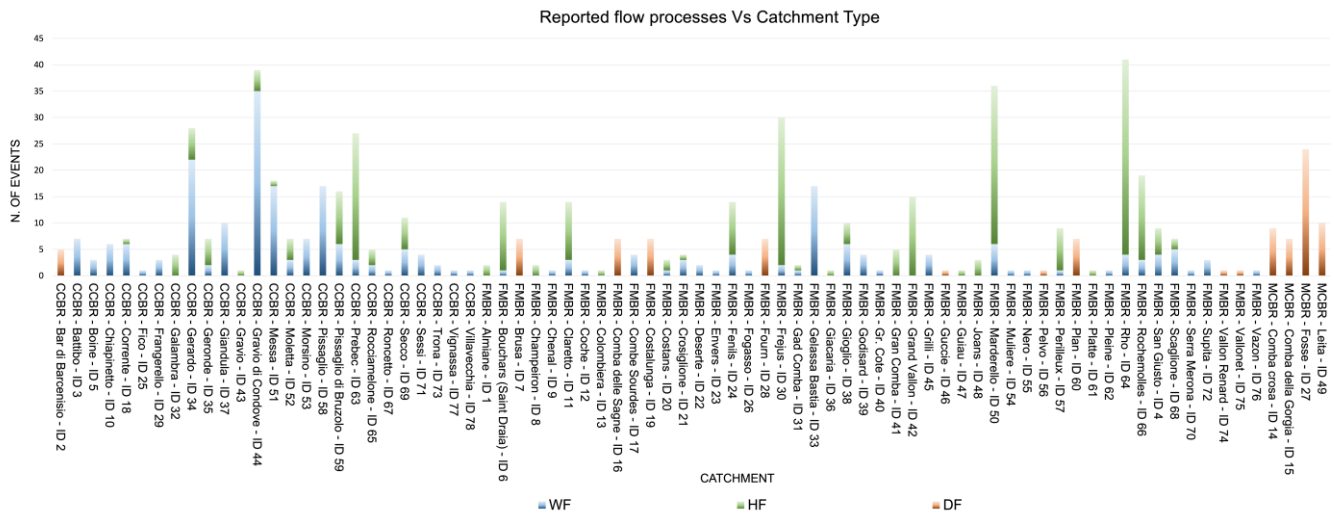


Figure 29. Flow process type distinguished by catchment lithological group.

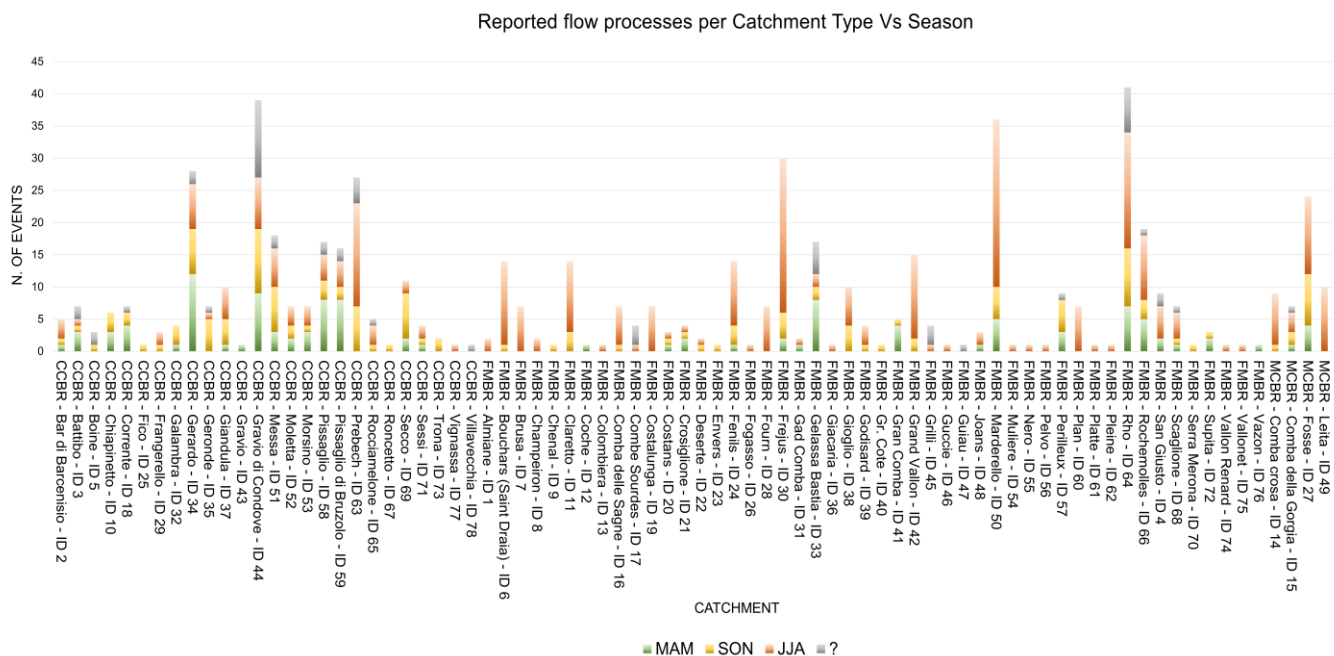


Figure 30. Flow event seasonality distinguished by catchment lithological group.

The FMBR and MCBR catchments are characterized by a prevailing occurrence of SGFs/SFFs in JJA with 67% in JJA for both, respectively, 18% and 22% in SON and 16% and 10% in MAM. On the contrary, the flow events in CCBR catchments show balanced occurrence in every season (34% in JJA, 35% in SON and 30% in MAM). Differences in terms of frequency and triggering rainfall are also outlined by lithological group (Figures 31 and 32).

CCBR catchments are characterized by a low frequency of flow process occurrence identified with an average quiescence of 25 Yrs (max 75 Yrs, min 19 Yrs). The occurrence frequency increases for FMBR catchments with an average value of about 6 Yrs (max 12 Yrs, min < 1 Yrs), while for the MCBR catchments, it is about 4 Yrs, varying from 4 Yrs to 5 Yrs. Particularly interesting is the analysis of triggering rainfall, which clearly distinguishes the three groups (Figure 32).

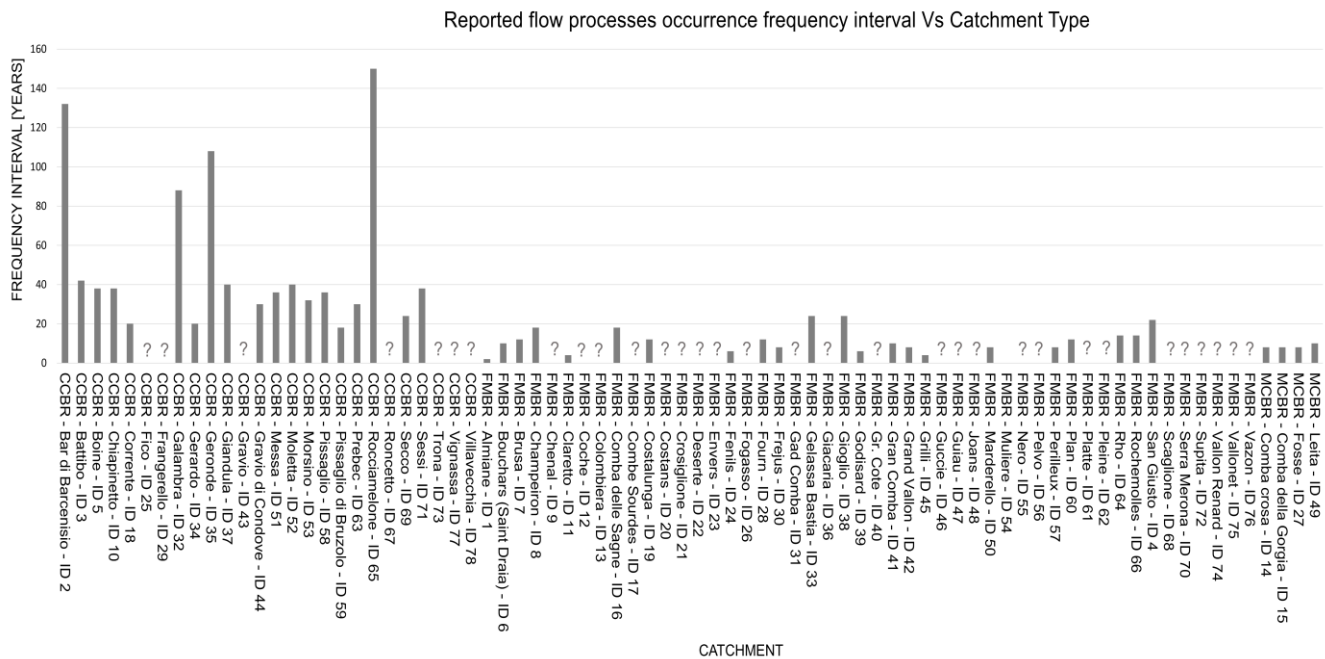


Figure 31. Flow event frequency distinguished by catchment lithological group.

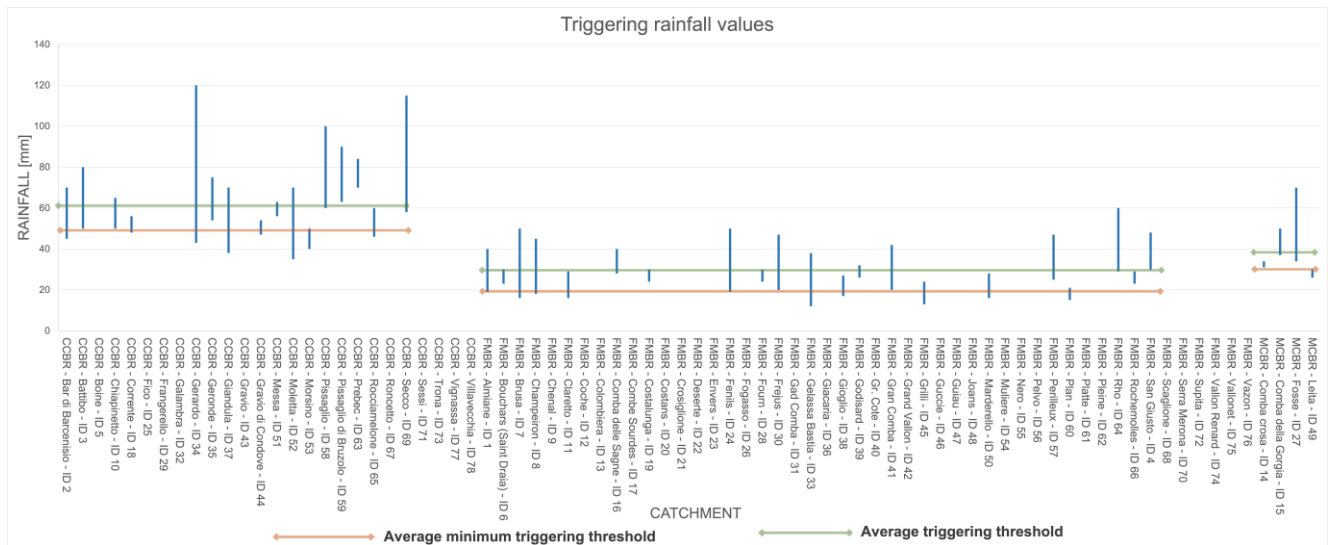


Figure 32. Flow processes triggering rainfall values distinguished by catchment lithological group.

The SGF/SFF initiation for CCBR catchments is linked to average minimum rainfall values of 50 mm/h, a very high value compared with the 20 mm/h of catchments FMBR and the intermediate value of 30 mm/h for the MCBR catchments. Considering these outcomes, the sedimentological features of SGFs described in Section 3.5 and the reported damage degree in historical documentation, it is possible to estimate the intrinsic hazard of each lithological group and establish a classification of the relative hazard degree of the three groups, as reported in Table 3.

It is worth specifying that the Intensity in column 4 is estimated based on reported damage and the characteristics of SGFs [17,20]. Specifically, Low/moderate, Moderate/high and High/very high are defined also considering the flow propagation capacity (inversely proportional to viscosity), the average size of the coarse fraction of mobilized sediment and the velocity (energy) of the flow (resulted inversely proportional to viscosity, also highlighted by depositional styles). These parameters are partly deduced from the analysis of historical documentation and partly from field observations of SGF deposits. Table 3

considers two groups of parameters (time and intensity) to assign a relative hazard degree to the catchments. Time columns include SGF frequency and SGF relative occurrence (occurrence of SGF instead of SFF characterizing a catchment group) as proportional parameters to hazard and the return period of critical rainfall values as a parameter inversely proportional to the hazard. The score assigned to the time components is between 0.1 and 0.3, in order to balance the weight of the temporal factor with the intensity of the phenomenon (which varies between 0.3 and 1). The weighting of time components with the intensity of the phenomenon determines the degree of relative hazard of SGFs that can occur in catchments belonging to the three groups identified. Therefore, although the CCBR catchments are characterized by long quiescence times, with the occurrence of SGFs much less frequent than the other two groups, they are more dangerous due to the greater intensity linked to the events of SGFs historically documented. On the contrary, the FMBR catchments, despite the frequent occurrence of SGFs, are not characterized by particularly intense events, ranking at the lowest point on the danger scale.

Table 3. Time and intensity parameters to estimate the relative hazard degree of SGF for each catchment group.

Catchment Group	Time		Intensity		Relative Hazard Degree
	SGF/SFF Frequency	Rainfall Return Period *	SGF Relative Occurrence **	SGF Intensity	
FMBR	Moderate (0.2)	Low (0.3)	Moderate (0.2)	Low/moderate (0.3)	Low (1.0)
CMBR	High (0.3)	Moderate (0.2)	High (0.3)	Moderate/high (0.4)	Moderate (1.2)
CCBR	Low (0.1)	High (0.1)	Moderate (0.2)	High/very high (1)	High (1.4)

* It refers to the return periods for average minimum values of critical rainfall. ** It refers to SGF vs. SFF occurrence.

5. Conclusions

The study conducted on the 78 catchments of the Susa Valley with 614 flow events documented from 1728 to 2023 allowed an exhaustive characterization of SGF/SFF phenomena and the identification of the relationships with geological-geomorphological settings and rainfall values determining the initiation of SGFs/SFFs. The research work showed that the individual use of different approaches to define the type of process that can occur in an Alpine catchment does not guarantee a low uncertainty about the identification of the processes that can occur there. It was demonstrated that the adoption of only morphometric classification methodology partially explains how the nature of catchments can influence the generation of a specific type of flow process and only by considering other factors, such as the outcropping density of the bedrock, can provide a correct interpretation to determine the most likely expected phenomenon. It was also shown that the lithological nature of the catchments is directly related to the behavior of SGFs and their sedimentological and depositional characteristics, as well as to the features of the alluvial fans. Indeed, by statistical analysis of a significant sample of data, a catchment classification into three main groups distinguished by substantially different characteristics including the triggering rainfall threshold values was obtained. The resulting classification mainly based on the dominant lithology and outcropping percentage of bedrock forming the catchments led to an estimation of the absolute and relative hazard characterizing the catchments of the Susa Valley.

The study clearly underlines that is needed to assess SGF/SFF phenomena, as well as their predisposing and triggering causes, in a targeted manner adapted to the local context, rather than adopting a uniform approach with presumed global validity. At the same time, the method developed in this study offers a flexible approach that can be adapted to variations in geological-climate conditions and their reciprocal interactions in any territorial context where SGFs occur. This approach can therefore provide a useful model to support planning and risk management in areas prone to such phenomena, enabling more targeted and effective measures of mitigation and prevention.

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