Abstract: Debris flow is one of the most dangerous natural processes in mountain regions and it occur in a wide variety of environments throughout the world. In the Italian Alps, some tens of thousands of damaging debris flow and, in general, torrential floods associated to intense sediment transport in secondary catchments have been documented in the last 300 years. These have caused socio-economic damage, damage to anthropogenic structures or infrastructures and in many cases casualties. Often, in the same basins, the occurrence of debris-flow processes recurs many years later. Prediction can often be spatial and based on the magnitude of the largest known process, while the temporal forecast is the most uncertain. It is also possible to increase the resilience of the population and of the territory. The present study aims at investigating different levels of debris-flow hazard in urban areas on Alpine alluvial fans and proposes a strategy for debris-flow prevention based on historical research and on a simplified analytical approach, methods that also involve relatively low costs. For such analysis, Ischiator stream catchment (ca. 20 km²) and its alluvial fan (NW Italy) were selected. This area was partly affected by historical torrential flood associated to intense sediment transport and debris-flow processes. Present-day instability conditions along the slope and the stream network were detected and synthesized through surveys and aerial photo interpretation integrated by satellite images (period 1954–2021). An estimation of the potential amount of moving detritus, referred to as debris flow, was carried out regarding the June 1957 debris-flow event, based on the predictive models. The individual hazard index value was estimated based on different methods. The results indicate that 56% of the area is exposed to flood associated to intense sediment transport hazard, which fluctuates from high to very high levels; such results are supported by debris-flow historical records. Since today almost half of the settlement (Bagni di Vinadio) is located on potentially risk-exposed areas, the urban evolution policy adopted after the 1957 event failed to manage the risk connection to debris-flow activity.

Keywords: geomorphological analysis; debris supply prediction; historical data; debris flow and torrential hazard; resilience

1. Introduction

Debris-flow events are particularly dangerous to life and settlements because of their high velocities and the destructive force of the mass involved. Debris flows are capable of destroying homes, roads and bridges, sweeping away vehicles, knocking down trees and obstructing streams and roadways with thick deposits of mud and large stony debris, and they are obviously able to cause victims [1–3]. Debris flows are typically associated
with periods of heavy rainfall or rapid snowmelt [4,5]. Under the action of heavy rainfall, the eluvial–colluvial cover of the slopes can be saturated and fluidized, giving rise to shallow landslides; these landslides are often at the origin of the debris-flows triggering. In addition, the areas burned by forest and brushfires can prove critical. In extremely dry soils, the drainage action on the water ceases, the transpiration action of the plants decreases and so does the ability of the same plants to retain the underlying soil. This means that in the event of heavy rainfall, land affected by fires or severe drought is more prone to landslides (e.g., [6–10]). Knowing the behavior, trigger mode and dynamic processes of debris flow, through detailed historical investigation, can serve to prevent and mitigate harmful effects [11–23]. In some geomorphological conditions, the alluvial fan processes tend to follow more predictable patterns [24–26] and floods associated with intense sediment transport may remain within defined channels as they discharge down slope [27,28]. Even if there is always some degree of unpredictability of the debris-flow hazard on all alluvial fans, some portions of these different hazard levels can be defined. The risk related to debris flows has also been enlarged with the increase of urbanization on alluvial fans. Consequently, detailed debris-flow hazard assessments and associated risk are necessary. Detailed investigation of a number of cases can contribute to a better understanding of the problem and help to identify possible strategies for forecasting and prevention.

The importance of the cognitive phase in identifying and applying debris-flow risk mitigation procedures in alluvial fan areas has been recently highlighted by several contributions from the scientific community that has been working for decades to identify empirical methods and algorithms for estimating debris potential [29–31], as well as in relation to debris flow’s destructive power [32,33]. The attention for debris-flow assessment is further enhanced when coupled with urban planning [34,35] and natural hazard maps (e.g., [36]).

Through an accurate historical analysis, more than 5,000 debris-flow events or floods with intense solid transport, damaging effects and often victims, have been identified in the Italian Alps [13,37,38] (Figure 1).

Figure 1. Distribution of the torrential processes that have produced damage, and often casualties, in the last 250 years in the Italian Alps. Historical research was conducted by the authors up to 1970, while, for subsequent events, surveys were also carried out in the affected areas.
Similar processes are also recognized in various mountainous parts of Italy [39–41]. From this survey, the magnitudes were obtained of historical debris-flow processes, in some of them also the economic damages and the triggering causes. Many watercourses show processes with high frequency (one case every year), or only once a century, strongly limiting the risk awareness and the overall attention (social, urban planning, etc.). The fact that the frequency of debris-flow events is very low leads to a lack of attention to potential damaging effects. Moreover, for other geo-hydrological processes, if a rather long period of time elapses between an event and the previous one, there is generally a loss of individual or collective historical memory, thus increasing the risk of exposure due to little or no perception of the latent hazard.

An in-depth study on vulnerable areas is therefore necessary to understand possible mitigation strategies, especially where there are historical, cultural, economic and social conditions that are binding for the existing anthropic fabric, even if small. In fact, areas vulnerable to geo-hydrological processes are portions of the territory exposed to potential damages; logically, exposed structures and assets should be removed or displaced from the damaging action of debris flow.

In some cases, however, vulnerable areas are closely linked to the territory by the natural resources to which they are bound (mining areas, energy resources, economic, cultural, historical, etc.) and cannot be relocated. It is therefore necessary to recognize vulnerable areas by analyzing various factors in detail, including past events and the geomorphological peculiarities in which they are located. This cognitive process is a first step towards increasing resilience. The above reflections have pushed the authors to illustrate one of the 800 documented debris-flow cases of catchment in Piedmont, in northwestern Italy [16]. The study aims at proposing a strategy for debris-flow prevention based on historical research and on a simplified analytical approach. The Ischiator catchment (municipality of Vinadio, Cuneo Province, Western Alps) was chosen as an exemplification for this complementary study. The Ischiator basin is also known as Vallone dei Bagni, Valley of “Baths”, for its historical thermal-water housing (spa). Bagno di Vinadio is a small alpine village which, thanks to its centuries-old tradition and its high-quality thermal waters, hosts tourism linked to resorts and spa activities. The tourism attraction of Bagno di Vinadio thermal baths has been known since the Roman Age.

In the Italian alpine mountains, there are dozens of spas that boast a long cultural, social and economic history linked to the natural waters that flow at temperatures of up to 60 °C; these structures have been known since Roman times. Due to the therapeutic properties of the waters, Bagno di Vinadio has been described since the 16th century. During the Royal Savoy period, the site rose to prominence as a place of residence and treatment for officers of the royal army. The first nucleus of buildings intended to exploit the beneficial properties of the waters, dating back to the mid-eighteenth century, underwent subsequent extensions and a radical transformation at the beginning of the twentieth century; in more recent years, it has been joined by a Grand Hotel, now equipped with a beauty farm, conference center and sports areas. The other spas in the surrounding area have a similar history. However, these sites are subject to periodic damaging effects of debris flow: in the area at least two other spas have been seriously damaged by flood events associated to intense sediment transport (Terme of Pigna village, about 60 km southeast of Vinadio for the 2014 event [42] and Terme of Valdieri village, about 20 km from Vinadio, repeatedly damaged by the events of June 1957, June 2000, November 2016, 2019 and 2–3 October 2020) (Figure 2). By their nature, therefore, thermal sites cannot be relocated to less vulnerable locations and must be preserved as places of culture and history, with a long track record of resilience.

For hazard assessment and implementation of mitigation strategies, all cognitive tools must be made available [43]. Detailed digital terrain models are sometimes not available, nor are significant precipitation datasets available to assess refined thresholds for triggering debris flows, so only integrated studies can provide adequate support, both in the preparation of event scenarios and in the planning of mitigation measures.
2. General Settings
2.1. Geology and Geomorphology of the Ischiator Catchment

The Ischiator catchment (length 7 km, maximum width 2.8 km) runs straight from SW to NE, at the height of Monte Vaccia turns 90° towards the SE and joins the Vallone Corborant at Bagni di Vinadio (altitude 1300 m a.s.l.).

The Ischiator catchment is located northeastward of the Corborant Peak (Figure 3), which belongs to the crystalline Argentera massif (Maritime Alps) [47]. The bedrock outcrops extensively appear on the left slope along the valley, while the right slope is masked by vegetation, especially in the middle-lower valley stretch. An important shear zone, namely the Valletta Shear Zone (VSZ) [48], also known as the Ferriere–Mollières Line [49], crosses the valley from NW–SE, separating two major geo-lithological and geomorphological ambits (Figure 3).

The landscape is the product influenced by marine climates that have enhanced the modelling effects of glaciation; for a long time, glacial tongues have cut deep into valleys and helped shape the valley floor, periodically replenishing its margins with immense quantities of debris derived from the demolition of valley sides and high cirques. The upper geo-morphological sector, with its typical glacial conformation, in which several small alpine lakes are inserted, presents vast steps and almost entirely bare thresholds, with more abundant accumulations of detrital and morainic masking as one proceeds downstream (including rock glaciers).

The lower sector of the Ischiator basin, angled at 90° to the middle and upper parts, is incised in a “V” shape by river erosion. Both slopes are covered by woodland, and the slopes are largely covered by a modest thickness of soil with little pedogenetic evolution.

In the case study of the Ischiator catchment, the fan area is exposed to various degrees of debris-flow hazard. A detailed study has provided the validation of magnitude-estimating models, checking morphological analysis of the fan as compared with the hazard zoning of areas affected with different severity by the June 1957 event, confirming once again the importance of historical data [2,44–46].

The Ischiator catchment, for a long while, has undergone torrential processes; man-made protection works since long ago had been conducted by the Italian Forestry State Corps to cope with the rushing floods associated with high sediment discharge. Historical research has revealed numerous technical documents referring to interventions planned or underway, especially from the late 1800s to the first half of the 1900s. Traces of works or artefacts (especially weirs) in a poor state of conservation were also observed during the surveys. The hydraulic works still present are located in the terminal sector of the main shaft or along the tributaries close to the basin closure.

Figure 2. Effects of floods associated to intense sediment transport on thermal facilities close to Bagni di Vinadio (fewer than 60 km away) for recent events: (a) Terme di Pigna [42], 2014 event and (b) Terme di Valdieri (photo by the authors during surveys for the severe event occurring in October 2020).
According to Sacchi [50], the Ischiator valley can be subdivided from S–W to N–E into three units: the Corborant series, the Laroussa series and M. Sejta rocks. The Corborant series is composed of two types of alternatively outcropping migmatites: the Mount Corborant peak (3007 m a.s.l.) is the highest point in the crest that divides the catchment, and towards the origin of Ischiator, is composed of ochiadiine gneiss. The Laroussa series is exposed along both sides of the valley and comprised between some mylonitic strips and the Corborant series [47,50]. Downward to the VSZ, the Monte Sejta rock complex occurs [47]. The prevailing facies along both slopes in the lowest part of the valley are biotitic anatessite, chloritic and biotitic gneiss, amphibolite and amphibolite gneiss and aplitic granite. The Monte Sejta peak, (2407 m) and the northwest and southeast facing slopes, are mainly sculpted in biotitic anatessite; in such rocks the metasomatic process has attained its maximum intensity, even without producing the anatessitic granite [49].

Some authors consider the Argentera massif as a whole [46]; it consists of the Terrane Tinée to the SW, separated by the Ferriere–Mollières cutting area [51,52]. The two terranes are characterized by distinct lithological associations and metamorphic evolutions [53].

Through field recognition, it is easy to understand the cause of accelerated erosion along the left slope, especially where the valley makes a right-angle bend, just upward to the alluvial fan on which the Bagni di Vinadio village is located. In this area, the left valley slope is incised in chloritic–biotitic, greenish to dark grey finely-grained gneiss, scarcely or not schistose, combined in alternance with two large mylonitic strips. Inside such gneiss, a micrograined, aplitic granite is inserted, anatessi-originated and sharply connected to the gneiss without transitional facies [50].

In general, both the morphology of the main valley and the tributaries are deeply molded by the Würm glacial exaration processes (Figure 4). The main glacier was mainly fed by the head cirque and a minor glacier was inflowing from the right slope. Along the longitudinal valley profile, four main valley steps are found [54]. Quaternary terrains are
found along the whole valley axis near the streambed and correspond to scree slope and remnants of glacial deposits.

Figure 4. A bird’s-eye down-valley view of the Ischiator catchment, upper part: typical U-shaped slopes owing to the glacial activity.

At the inflow of the Ischiator in the Vallone dei Bagni, a multiple fan topography is developed, made by debris-flow deposits of different age. Right of the torrent, near the main housing of Bagno di Vinadio, a widely expanded remnant of the oldest deposits still exists, where the most recent urban growth has taken place; a high terrace scarp connects such deposit to the present-day alluvial fan.

The present study area belongs to a high-relief energy-dominated area, with sharply-dipping slopes; in the lower reach, the right slope has stronger relief energy than the opposite south-facing slope.

2.2. Hydro-Meteorological Hazards and Vulnerability in Case Studies

The Ischiator basin is located in the alpine context, where torrential processes and debris flows occur very frequently (Figure 1 and Table 1). Historical research has shown that tributary streams do not suffer equally from the effects of extreme weather events; in fact, each sub-basin is configured with its own geo-hydrological activity, with its own timing of reactivation of unstable processes, as observed in other Alpine contexts [55]. The study of past events, therefore, allows the recognition of a natural predisposition to debris flows, providing reliable scenarios of occurrence for magnitude and damaging effects in the areas of invasion; however, only targeted studies of long historical series can provide indications on the possible thresholds of occurrence and timing of possible reactivation [56,57].

Numerous rehabilitation works have been carried out in the Ischiator basin since the second half of the 19th century (especially those carried out in the period 1951–1953 and those to repair the damage caused by the 1957 debris flow), for which a large amount of historical documentation was found. However, the situation of geo-hydrological instability has worsened considerably, as was noted during recent inspections.
Table 1. Main flood associated to intense sediment transport, debris flow and hydrogeological processes occurred in the Ischiator catchment, organized per 50 years periods. For any period, a level of severity was assigned (low = L, medium = M, high = H and very high = VH) based on all available documentary information [58,59]. Details for all events can be found in the Table A1.

| Date       | Number of Events | Intensity  |
|------------|------------------|------------|
| Ante 1850  | 6                | H to VH    |
| 1851–1900  | 3                | H to VH    |
| 1901–1950  | 1                | H          |
| 1951–2000  | 5                | M to VH    |
| Post 2000  | 1                | L          |

Another important landscape-shaping agent in the catchment is the stream activity, with numerous deeply incised drainage segments, along which (also avalanche-triggered) instability processes are diffused. The final valley reach is characterized by sharp incisions, especially along the left slope, with intense accelerated erosion events, shallow slides and tectonically induced weathering as a first step toward the rockfall process. Since the early 20th century up to the sixties, such critical sites have been modified due to slope regulation and reforestation works accompanied by check dams building in the ravines to avoid rapid degradation. The main left-bank tributary of the Ischiator stream, the Comba Vaccia torrent (n. 14 in Figure 3), is still regarded as a major problematic area because it is incised in debris slope deposits, in glacial reworked deposits, mixed avalanche and in debris-flow-triggered materials (Figure 5). In the vicinity of the Bagni di Vinadio village (Figure 3), on the right slope, such lower-valley reach sharply changes in dip, roughly forming a 90° angle. This is only possible due to the occurrence of tectonic elements crossing perpendicularly with the main valley axis in this area. Such conditioning is the main cause of the instability processes (Figures 5–7) and of the accelerated erosion in the ravines on the left side of the valley.

Figure 5. A horizontal pan of the left slope of the Ischiator catchment, showing widely exposed bare detritus, as it appeared in 1957 (archives of the IRPI-CNR, Torino, unpublished).

The stream characteristics are rapidly evolving in the final reach above the intra-mountain stream stretch, giving rise to an inclined bed profile or fall. Immediately below such a fall, the Ischiator stream forms a deep and rectilinear incision and produces debris deposits having acquired a notable amount of kinetic energy. In the second half of such reach, the channel is embedded more markedly in the valley bottom, presently filled with glacial deposits in the form of a narrow gorge. In this stretch, erosion and bedload transport processes prevail, accompanied by the tributary ravines in the left slope which supply sufficient amount of coarse debris during extreme rainfall. To reduce the effects of rushing floodwater associated to intense sediment transport, several check dams and weirs were built along the main stream and tributaries. In the lowest reach, the torrent flows through a canyon-shaped gorge, then debouches onto the alluvial fan.
Elevated fan deposits belong to the older formation, while the lower deposits close to the stream belong to the newer formation. This double-shaped fan mostly extends towards the right, composed of rocky slope, and its old, elevated portion supports a large part of the Bagni di Vinadio housing. As frequently happens in mountain regions, the recently built settlement occupies active an alluvial fan sector, due to which sudden debris flow during huge floods generally turns towards the right; while in the left side of the channel above the thermal water housing, a large pier-made embankment hinders another diversion toward an old and ephemeral channel.

Figure 6. Present-day slope degradation processes on the left slope of the Ischiator torrent. Several deep ravines are infilled by huge detrital amounts, which feed the drainage network.

Figure 7. A detail of the head zone of a ravine out of those shown in Figure 6. The highly unstable conditions of the highly fractured bedrock can be noticed, as well as the debris mantle continuously filling up the stream incisions.

3. Materials and Methods

3.1. Census of Regulation and Protection Hydraulic Works

The present-day situations of instability over the slopes and along the stream network were detected and synthesized in detail through photointerpretation (images available for the period 1954–2016, Table 2), satellite images (Google Earth®, available in medium resolution since 2012) and field surveys (summer and autumn 2007, summer 2008–after 30 May event, summer 2021). The photointerpretation was conducted by a single operator
in order to maintain an overall uniform grade of subjectivity. Technical records, projects and documents were consulted and confronted to improve objectivity for the regulation and protection of hydraulic works description and for the instability evaluation.

Table 2. Detail of the data image source.

| Years | Data Description                                      | Data Source/Archive               |
|-------|-------------------------------------------------------|-----------------------------------|
| 1954  | Stereoscopic aerial images B/W of T. Stura valley     | CNR-IRPI Archive                  |
| 1963  | Stereoscopic aerial images B/W of Piedmont Region     | CNR-IRPI Archive                  |
| 1975  | Stereoscopic aerial images B/W of Piedmont Region     | CNR-IRPI Archive                  |
| 1991  | Stereoscopic aerial images B/W of Piedmont Region     | CNR-IRPI Archive                  |
| 2000  | Stereoscopic aerial images B/W–2000 flood event effects in the Piedmont Region | CNR-IRPI Archive |
| 2010  | Stereoscopic aerial images—Infrared                   | Piedmont Region webgis            |
| 2009–2011 | Stereoscopic aerial images—Shadowed relief          | Piedmont Region webgis            |
| 2016  | Stereoscopic aerial images color—Flood event effects in Piedmont Region | Piedmont Region webgis |
| 2021  | Satellite images                                      | GoogleEarth                       |

All the regulating and protection works executed in the catchment (93 artifacts in total, as check dams, weirs, repulsory levees, embankments, levees, bridges and wades) were mapped using GIS in order to understand whether the interventions were effective in reducing critical situations in the stream network (Figure 8).

![Figure 8](image-url) - A detail of GIS map with the database of the interventions in the stream network (check dams, weirs, repulsory levees, embankments levees, bridges and wades are shown).

The inherent technical data were collected, geo-referenced and arranged in form of the SICOD (Sistema Informativo Catasto Opere di Difesa—Informative System of Defense...
Work Cadastre managed by each Italian Region) database set up by the Piedmont Region; such a database aims to review the up-to-date efficiency conditions of the regulation works and other artifacts along the alpine stream network realized in the past.

3.2. Method for Magnitude Debris-Flow Evaluation

The problems arising out of the flow regime of the Ischiator torrent mainly depend upon its mass sediment transport capacity produced by the first-order incisions. An estimation of the potential amount of moving detritus, in case of an extraordinary rainfall event, was carried out based on two predictive models [60,61]. For such estimation, the Ischiator catchment was divided into n. 22 minor subcatchments along the left-valley slope and SW-exposed topography having similar morphology, elevation and vegetal cover (Table 3); for every subcatchment, the bedrock is mainly gneiss and anatessite granite (Figure 3). The number of subdivisions corresponds to the natural minor tributary of the lower geo-morphological sector of the Ischiator basin, which corresponds to the principal debris source of debris-flow processes.

Table 3. Morphometric parameters of the subcatchment of the Ischiator basin.

| Catchment Number (See Figure 3) | Effective Area (km$^2$) | Average Slope % |
|--------------------------------|--------------------------|-----------------|
| 1                              | 0.353                    | 79.17           |
| 2                              | 0.316                    | 77.88           |
| 3                              | 0.071                    | 89.92           |
| 4                              | 0.367                    | 97.83           |
| 5                              | 0.118                    | 106.37          |
| 6                              | 0.092                    | 106.09          |
| 7                              | 0.036                    | 90.13           |
| 8                              | 0.461                    | 93.20           |
| 9                              | 0.039                    | 101.87          |
| 10                             | 0.569                    | 80.95           |
| 11                             | 0.085                    | 93.87           |
| 12                             | 0.227                    | 76.95           |
| 13                             | 0.395                    | 76.34           |
| 14                             | 1.072                    | 70.33           |
| 15                             | 0.899                    | 72.36           |
| 16                             | 0.129                    | 71.25           |
| 17                             | 0.232                    | 70.47           |
| 18                             | 0.449                    | 73.48           |
| 19                             | 0.122                    | 73.36           |
| 20                             | 0.044                    | 87.83           |
| 21                             | 0.098                    | 75.49           |
| 22                             | 0.094                    | 80.99           |

The first predictive model [60] is calibrated for catchments in the Western and Central Alps and is thus suitable for the present study area. The second one [61] was suggested for another application in the Western Alps (e.g., [62]). The results from these two methods are almost similar (such values differed by 3,000 m$^3$ over total volumes, accounting for 80,000 m$^3$). It must be said that the Tropeano and Turconi method [60] operates on the existing or potential instability conditions inside the whole catchment system (Figure 9), while the Hungr method [61] is suitable for estimating the final product of the actual instability agents, i.e., the virtual detritus supply available for unit length along homogeneous segments of the stream network only (Figure 10).

The [61] method should express a more major potential for sediments than that of [60]. The latter, in fact, implies simplifications in the ambit of the different typologies of incipient instability, attributing to any of these univocal mobilization modalities concerning depth of unstable layer and triggering time for its motion, even if they refer to broad-scale situations. The consequence is that the larger the catchment is it widens the doubtfulness about dynamic propensity of the portions of detritus cover far from the stream-flow incisions.
Figure 9. Identification of the areas of movable detritus along the secondary hydrographic network immediately available for mass transport (red areas) and of the areas of unstable debris cover, potentially movable along the slopes of the respective basins due to slope processes (landslides) activated during torrential events (blue areas). Tropeano and Turconi method [60].

Figure 10. Subdivision of the secondary catchment areas of the sub-basins according to the potential debris production (expressed in cubic meters of debris per linear meter), according to the Hungr method [61].
In the Hungr method [61], such problems do not exist because in all channel segments problems do not arise over the provenance of flow detritus. This may imply an exceedingly high-estimated amount of material movement produced through the catchment dynamics (processes). In addition, the authors used the Turconi and Tropeano formula [63], which takes into account all relevant morphometric parameters of the catchment, data generated through historical analysis to estimate frequency factor \(f\), field mapping and photointerpretation. The subcatchments were sub-divided into areas of <10 km\(^2\), in order to obtain good results.

The general expression is:

\[
M = \left(\frac{AE \cdot tgs \cdot r \cdot h \cdot (1 + n)}{10000}\right) / 1000\text{tot}
\]

where:
- \(M\): evaluation of magnitude of debris supply;
- \(AE\): actual catchment area (m\(^2\)) computed as \(A / \cos (\text{Iv})\);
- \(tgs\): average slope gradient (Iv) [%];
- \(r\): proportionality coefficient (between 0 and 1), that is the ratio between surface extent of the loose materials directly liable to be carried downstream and actual catchment area;
- \(h\): average thickness (m) of the debris package which could be delivered into the stream network;
- \(n\): adimensional coefficient comprised between 0 and 10, expressing the potential debris availability in case of an exceptional event (e.g., slope failure)/actual catchment area. The closer the value of the coefficient “\(n\)” is to \(n\). 10, the greater the level of instability in the basin, and consequently, the amount of material that can implement the debris mixture.
- \(f\): frequency factor, expressing the number of events occurring in a standard time lapse equal to 100 years.

In order to define the physical characteristics of all subcatchments, morphometric parameters were previously computed (Table 3). Data from historical archives are very much useful for the debris flow’s occurrence (e.g., [2,12,64,65]). From historical records, the number of debris-flow events for each subcatchment was collected to draw the frequency factor \(f\). The evaluation of the frequency of debris flows helps in understanding the relations between basin conditions, basin morphological evolution, sediment supply processes and debris-flow occurrence. In this case, the estimated return time for the most severe events in the Ischiator basin was considered equal to 100 years. the events of 1664, 1754, 1853 and 1957 were documented: the June 1957 event was the only severe event in the last 10 years. However, at least four medium-intensity events affected the main stream and some tributaries (the events of 1926, 1979, 1987 and 2000). In view of this, two different values were assigned to the frequency factor: \(f = 1.00\), considering one severe event every 100 years; \(f = 0.25\), considering four events in a century. This led to a double set of results that can probably be considered as a minimum and a maximum of the estimate of the movable debris potential.

Through geomorphological interpretation of aerial photographs and intensive field investigation, the areal extent of the debris/soil mantle and its thickness were assessed (factor \(h\)) for defining \(r, h\) and \(n\) coefficients. The approach illustrated above concerns the determination of both the actual subcatchment area and the surface occupied either by active debris/sediment deposits and/or by sediments in temporary equilibrium [66].

### 3.3. Hazard Map

Based on the estimation of debris, potential data calibration was conducted for the settled area of Bagni di Vinadio to prepare a hazard map of 1:5000 scale of the Ischiator fan area, solely based on the geomorphologic method proposed by Aulitzky [67], modified by Ceriani [68].

Some methods are available for debris-flow hazard mapping [14,27,69,70] and for debris-flow hazard modeling [71–73]; the applicability of those methods is restrained by the
typology of the input data; in fact, some applications require the estimation of the thickness of deposits, grain-size characteristics, or precise definition of the area affected by several debris-flow events [74]; however, such data are not available for the present study area. For the present study, the [68] method was used because it is commonly used by some regional geological surveys in the Italian Alps. It is purely based on the geomorphological approach and fits with the debris-flow-exposed fan area.

An analytical comparison was made between the effects of the June 1957 intense debris flow, the hazard map and the urban growth of Bagni di Vinadio during the 1954–2021 period, deduced from historic and cartographic documents.

4. Results
4.1. State of the Hydraulic Defence Works

The census of the works by type, and state of conservation of the same, has made it possible to define that the situation of instability of the slopes and watercourses is considerably aggravated by the general state of abandonment of the works that are no longer maintained. It must also be taken into account that most of the repairs and check dams are at present out of order: 88% of these appears totally filled up by detritus, 71% out of such artifacts need to urgently be restored, being damaged and/or unbroken; 67% of counter-dams are almost buried under detritus, amongst these, 50% are cracked or eroded (Figure 11a–c). Such a scenario is impending above a settled area at potential risk of debris flow.

![Figure 11](image)

Figure 11. Overall and detailed view (a,b, respectively) of a channel-bed-regulating concrete dam (photo taken on 20 May and 23 June 2008). Notice how the situation has worsened due to a debris-flow event that occurred on 28–30 May 2008. Following further debris-flow events, the conditions of the existing structures along the Ischiator stream were even more worrying for their stability due to the amount of detrital material that would suddenly reach the streambed in case of collapse of the dam (c, in summer 2021).
The current defensive system is still based on the old embankment wall and repellent works that should ward off direct erosive activity of water flows (Figure 12). For a number of years, the competent administration has been considering projects for the containment of debris by means of a storage area, but these have not yet been implemented.

![Image of the embankment wall](a) ![Image of the erosion repulsion structure](b)

**Figure 12.** Image of the embankment wall (a) and of the erosion repulsion structure (b), respectively, longitudinal and transversal to the direction of the water flows, realized after 1957 and still representing the defense system for the built-up area partly visible on the right bank.

4.2. Debris-Flow Magnitude

An advantage of the predictive methods of [61,63], instead of others proposed in the literature, is that they are based on a practical examination of the onsite characters of the potential detritus amounts; intense ground-truth verification was carried out through photointerpretation throughout the study area. It is important to note that a little part of the output of debris-flow processes along the ravines of the left-valley slope of the Ischiator catchment comes down the mainstream channel. The main flow in this case acts as a conveyor belt, and channel morphology is conditioning the debris pulses downstream; deposits occur on flattish, evenly-distributed stream stretches and more acutely dipping channel stretches, resulting in the river cross-section narrowing and controlling the delivery of the debris and sediments.

The main flow in its lower reach interplays with tributaries. In this sector, there is a lack of fan deposits, although high sediment delivery capacity remained in the past. Among the processes occurring in the left slope, the true sediment delivery part in the Ischiator valley, debris flows largely prevail and the materials come down the major stream as they attain the confluence. Such processes evenly occur along a stretch of some 4 km, in which the ravines combine with the main flow along with an estimated detritus of 30,000 m³. Thus, the final stream stretch, just upstream to the fan apex, produces huge amounts of debris flow carried down the major stream. This was verified in the field using the method of Aulitzky [67]. As per the “frequency factor” technique [63], the total estimated debris amount delivered from the ravines in the left slope into the main stream ranges between 250,000 m³ and 530,000 m³ computed using as “frequency factor” values 0.25 and 1.00, respectively. Moreover, the Hungr method [61] yields a debris-supply value range between 410,000 m³ and 915,000 m³ (min–max, respectively) (Figure 13).

In spite of the apparent discrepancy between the cumulative values reported above, the result is almost similar for both the methods for single subcatchments. In most cases, the estimated values in both the methods result in a similar order of magnitude (thousands or ten thousands m³). In order to apply the Hungr method [61], multitemporal aerial photographs were analyzed, avoiding onsite calibration for some sites due to the inaccessibility in some incisions. Applying both the methods, it is found that the major portion of the predicted debris amount belongs to the Comba Vaccia ravine (Figure 3), and the values are 26.5% and 18.4% of the whole, respectively; historical documents also suggest that the Comba Vaccia tributary is the main contributor of the solid charge to the main torrent.
4.3. Hazard Map

Several documents and images, as well as the photographs taken just after the 1957 event, justifies the reliability of the [56] method, and it shows that 55.5% of the area classified as exposed to high or very high debris-flow danger was in reality affected by such an historical event (Figure 14). While just fewer than half of the settlement is edified on potentially risk-exposed area, this means that the urban planning policy adopted after the 1957 event did not take into account the numerous documents of the past, nor the morphology of the sites; the land-use planning has not managed the real risk associated with torrential activity.

![Hazard Map](image)

**Figure 14.** A detail of the hazard zoning map of the alluvial fan on which the Bagni di Vinadio inhabited area has grown.

Multitemporal aerial photographs indicate that urban growth of the settlement took place during the 1954–2021 period and a large part of housing developed just in the right-central sector of the fan area with the highest danger potential, and the amount of coarse sediment deposits could be of several thousand m$^3$. The spatio-temporal occurrence of debris-flow events was assessed based on several historical documents [2]. A diachronous appraisal of the landscape evolution throughout the last centuries was prepared from old
manuscripts, historical reports, technical documents, local memory booklets and newspapers, both found in local and CNR-IRPI archives. A rare document dating back to 1775 depicts (Figure 15) the Ischiator torrent as it appeared in the painter’s eyes. Both from pictures and from the legend of it, it is clearly found that a channel branch in the left was flowing very close to the thermal-water housing (already in use at such a time) and a branch of the channel bared since old times through the boulder dam already cited. In fact, above the edifice, the legend bears the inscription ‘Ripari’ (repairs, protections). We do not know if such a term should refer to a planned or already existing kind of embankment, or simply to a refuge location in case of a super-elevated flood associated to intense sediment transport that is naturally immune to debris-flow effects. The right branch of the Ischiator is depicted as more incise and larger than the left one, which in turn appears as longer and forming several bends. A reference is also reported about the location of the old parish, which was possibly destroyed by the right branch of the torrent, and the new parish was rebuilt after the event.

Figure 15. A rare lithograph reproduction dating back 1775 in which the Bagni thermal housing, on the Ischiator alluvial fan, is depicted (A), as well as the thermal springs (B). Other inscriptions are the old Bagni village (C) and the ruins of the San Rocco Chapel (D), partly destroyed by debris flow occurring in 1754 by the Ischiator torrent (E). Defense structures (F) are also depicted.

From both photointerpretation and field survey, it can be hypothesized that in reality an historical channel branch on the right of the fan used to exit, which is scarcely recognizable today due to intensive anthropogenic influence. At last, the coarse bedload transport events that took place before 1775 affecting the Bagni di Vinadio area were characterized by large or gigantic blocks in the border of fields, as portrayed in the lithograph, which presumably are the remnants of old alluvial fan deposits.

The present-day fan area of the Ischiator stream is exposed to various degrees of debris-flow hazard over 0.084 km², i.e., over 88.2% of it. In order to define the area covered by deposits left by the June 1957 debris flow, which is deemed the largest to have occurred
in the last century, a cross-control was drawn between the computed map and historical evidence (Figure 16).

Figure 16. Coarse channel bottom, debris-flow deposits and bank erosion processes that occurred in June 1957 on the alluvial fan of the Ischiator stream near the Bagni di Vinadio built-up area, looking upstream (archives of the IRPI-CNR, Torino, unpublished).

5. Discussion

The Ischiator basin is in a high state of degradation and geo-hydrological instability, aggravated by the neglect of defense and mitigation works for the torrential processes.

Four series of magnitude values were plotted on a same graph, and one may find that they are as a whole overlapping; in some cases, in spite of some discrepancies, the trend of estimations is good. In addition to this, it is important to note that the best fit between the values found in the two methods above reported concerns about the small catchments (areas fewer than 1 km$^2$): as the area increases, the span of discrepancy arises in the predicted magnitude values (Figures 17 and 18).
During the last decades, the study of debris flow has strongly increased processes knowledge in terms of hazard and risk assessments [75–77]. Several approaches have examined debris-flow hazard assessments through GIS statistical analysis (e.g., [78,79]) or dynamic approaches with interpretation of aerial or satellite images [72,80–85]. Specific studies at the local cases are not so common, and often numerical models based on fieldwork are necessary to determine the hazard in the debris-flow deposition areas [14,61,70,86–90].

This study focuses on potentially re-activable paroxysmal processes in the Ischiator catchment, along the stream network and especially the main channel; these carry a huge amount of coarse detritus and bedload deposits, severely endangering the fan area. Although such a phenomenon in the lowermost channel stretch has been quiescent for decades, the study evidences possible critical situations along the minor tributaries directly inflowing in the main stream just above the fan apex.

There are several critical factors that require complex investigations and ad hoc assessments to contain the damaging effects of debris flow and torrential processes. These factors...
are: (1) the high vulnerability of the urbanized areas located along the alluvial fan of the Ischiator stream; (2) the high danger induced by the debris flow along the hydrographic network; (3) the impossibility of relocate these buildings, which are bound to the natural resource of thermal waters, which offer an important resource at a local level with no other attractive resources if not linked to excursion tourism.

6. Conclusions

In the Alps, there are numerous sites with a long economic or cultural tradition bound to the territory (thermal areas, religious or sacred places, geosites, etc.). They are often located in isolated locations with high exposure to debris flow or flood associated to intense sediment transport. Therefore, mitigation strategies must be implemented to reduce potential damage and increase resilience. In this paper, several themes are addressed with this aim: on the one hand, the evaluation of the magnitude of the natural process with different methods compared, on the other hand a classification of the areas with increasing criticality, by means of simple and locally rapid tools to propose, compared with historical and geomorphological data.

The integration of the research methodology proposed in this paper allowed to evaluate that 55.5% of the area in case of a debris-flow event would most probably be severely damaged. In fact, if a risk analysis and risk map would be developed, all this area would be classified at high or very high risk. This area corresponds to the one concerned by the historical event of 1957, taken as a reference. In the Ischiator stream case, the critical geo-hydrological condition is very much clear and documented in detail, but the same cannot be said for other catchments in the alpine chain. It is also important to note that urbanistic choices have once more been underestimated for the possible occurrence of natural processes, which may act unpredictably with the dynamics and evolution of triggering conditions, startup and re-activation of phenomena. Unfortunately, these factors were not linked with the temporal sequences of human activities. This study should offer opportunities to think about risk-reducing and land-management activity in advance, increasing the attention of the community.

While a hazard analysis focuses on natural processes, the method of risk analysis additionally includes the qualitative or quantitative valuation of elements exposed to these hazards, i.e., their individual values and the associated vulnerability [91–94]. This would initiate a system of hazard assessment, mitigation and reduction in the existing hazards and integrated programming aimed at the identification of mitigation measures. These also include the concept of “compulsory insurance”: a well-established tool in several states but not yet consolidated in the Italian reality.

In this paper, we also tried to highlight the elements of the geomorphological and geological analysis, integrated by historical knowledge of the processes that have affected a specific area. These elements often provide essential hazard information for fast and low-cost identification of critical elements. Additional investigation of the elements of risk can be submitted through the multidisciplinary integration and comparison of methods already known in the literature, which are often used in nonsectoral and integrated approaches, preferring those more complex and difficult to validate.

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Appendix A

Table A1. Main flood, debris flow and hydrogeological processes occurred in the Ischiator catchment. For all events a level of severity was assigned (low = L, medium = M, high = H, very high = VH) based on all available documentary information.

| Date                   | Damage Description                                                                                                                                                                                                 | Data Source                        | Intensity |
|------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------|-----------|
| Middle of the 18th Century | Destruction of the former buildings on the right side of the Ischiator alluvial fan. A votive chapel in Bagni destroyed by the Ischiator flood. The flooding of the Ischiator Stream removed the access bridge to the Vinadio spa. | CNR-IRPI Archive                  | VH        |
| 17 August 1754         | Several roads and crossings damaged. Eroded bridge abutments in the Bagni di Vinadio district. Damage to various roads and crossings totalling LIT 2931 (equivalent to approximately EUR 15000 today). A debris flow with high magnitude produces deep bank erosion, triggering lateral landslides. The spa was flooded with debris. The existing longitudinal defences on the side of the stream were destroyed. The military barracks were also flooded. | Archive of the Vinadio Municipality | H         |
| 26–27 August 1834      | The flooding of the Ischiator Stream removed the access bridge to the Vinadio spa. Eroded bridge abutments in the Bagni di Vinadio district. Damage to various roads and crossings. | Archive of the Vinadio Municipality | H         |
| October 1839          | The huge amount of solid matter transported along the Ischiator Stream caused the removal of several bridges, others seriously damaged, and serious damage to roads, houses and hydraulic regulation works. Damage to the bridge over the Ischiator near the spa; damage also to the banks near the spa. Several weirs in the tributaries of the Ischiator were damaged (e.g. in the Comba Vaccia basin). | Archive of the Vinadio Municipality | H         |
| October–November 1926 | An intense flood removes bridges along the Stura Stream. Damage to the spa bridge. The threat to the houses in the Ischiator alluvial fan was particularly serious: the waters overflowed the right bank in the area of the Spa hotel. | Archive of the Vinadio Municipality | VH        |
| 3 August 1853         | The Ischiator Stream brought considerable debris to the alluvial fan, diverting its course and constituting a very serious danger for the inhabitants of the Bagni di Vinadio district. Damage to the access bridge to the village of Bagni di Vinadio, bank erosion. The floods have brought considerable solid transport. Debris removal and rectification of the riverbed planed. The intense rainfall triggered widespread mobilisation and transport of debris along the minor incisions on the left-hand side of the slope, also causing some road closures. | Archive of the Vinadio Municipality | H         |
| 10 July 1873, May 1894 | The Ischiator Stream brought considerable debris to the alluvial fan, diverting its course and constituting a very serious danger for the inhabitants of the Bagni di Vinadio district. Damage to the access bridge to the village of Bagni di Vinadio, bank erosion. The floods have brought considerable solid transport. Debris removal and rectification of the riverbed planed. The intense rainfall triggered widespread mobilisation and transport of debris along the minor incisions on the left-hand side of the slope, also causing some road closures. | Archive of the Vinadio Municipality | H         |
| 18–19 May 1977        | The Ischiator Stream brought considerable debris to the alluvial fan, diverting its course and constituting a very serious danger for the inhabitants of the Bagni di Vinadio district. Damage to the access bridge to the village of Bagni di Vinadio, bank erosion. The floods have brought considerable solid transport. Debris removal and rectification of the riverbed planed. The intense rainfall triggered widespread mobilisation and transport of debris along the minor incisions on the left-hand side of the slope, also causing some road closures. | Archive of Italian Forestry Corps | M         |
| 1979                  | The steep slope below the municipal road was affected by a rapid debris flow. There was no direct damage to human infrastructures, but a possible retrogressive development of the landslide could involve the municipal road and the aqueduct. The landslide material reached the Ischiator Stream riverbed. | Dott. Geol. P.F. Sorzana, personal communication | H         |
| 24–25 August 1987     | Intense torrential flooding concomitant with that of the main watercourse, considerable debris deposits in Pianche di Vinadio. | Dott. Geol. P.F. Sorzana, personal communication | H         |
| 13 June 2000          | Intense torrential flooding concomitant with that of the main watercourse, considerable debris deposits in Pianche di Vinadio. | ARPA Piemonte [59] | L         |
| June 2020             | Intense torrential flooding concomitant with that of the main watercourse, considerable debris deposits in Pianche di Vinadio. | ARPA Piemonte [59] | L         |
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