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A Novel Approach to Assess the Influence of Rockfall Source Areas: The Case Study of Bardonecchia (Italy)

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Abstract: In this research article, we propose a practical methodology for evaluating the affecting potential of detachment areas in rockfalls. Our innovative approach combines an assessment of the visibility of rockfall source areas, with reference to specific rockfall scenarios and elements at risk, considering the rockfall Susceptibility Index to Failure (SIF) of these areas. The result is the characterization of source areas through a rockfall Source Affecting Index (SAI), which considers both the morphology of the slope and the geostructural conditions of the rock walls. This information can be very useful since it aids in optimizing more in-depth analyses, as well as the placement of monitoring instruments or stabilization systems. The proposed methodology has been implemented in the open-source software QGIS through the development of an easy-to-use plugin named Ranking of the Affecting Potential of Detachment Areas in Rockfalls, or "RADAR". RADAR is designed to be used in conjunction with QPROTO, a well-known QGIS plugin for preliminary rockfall susceptibility/hazard analyses based on a visibility analysis and a simplified mechanical method. To demonstrate the effectiveness of the proposed approach, an application to a case study located in the Western Alps (Bardonecchia, Italy) is presented and discussed in the paper.

Keywords: rockfalls; QPROTO; RADAR; Susceptibility Index to Failure (SIF); susceptibility maps

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1. Introduction

Rockfalls represent widespread occurrences that pose substantial risks to individuals, structures, infrastructure, and the surrounding environment. They are increasingly spreading in both mountainous and coastal regions due to the adverse effects of climate change and global warming, as has been documented by several authors [1–4].

The assessment of rockfall hazards and associated risks serves to identify downstream conditions and assess whether mitigation measures or other countermeasures are necessary to protect the exposed elements at risk. In particular, the assessment of hazard scenarios encompasses various complex tasks, starting from the identification of potential detachment areas (rockfall sources), the estimation of block volumes, the evaluation of their stability conditions, and the determination of their probability of failure. These tasks have been extensively addressed in many studies [5–12].

However, when conducting extensive studies related to widespread rockfall phenomena, such as those often occurring in mountain valleys, quick, simplified methods are essential for all stages of the analysis, including the characterization of rockfall sources. In particular, a preliminary delineation of the detachment areas capable of endangering exposed elements enables an effective placement of monitoring instruments and risk mitigation measures, as well as the identification of particular sectors on which additional and more detailed analyses are required.

To this end, a ranking procedure of the rockfall source areas was defined. This is based on the rockfall Source Affecting Index (SAI), which takes into account the proneness to the instability of rockfall source areas and the capacity of the same sources to hit specific elements at risk. Specifically, a quick and innovative methodology has been developed that, by combining the rockfall Susceptibility Index to Failure (SIF) of the detachment areas [13] with the results of a propagation analysis performed on selected elements at risk, results in a rockfall Source Affecting Index (SAI), which has to be considered in relative terms for a given site.

The evaluation of SAI has been incorporated into a newly developed plugin for the QGIS software, Version 3.34.1, an open-source Geographic Information System (GIS) that is free to use, supported by an active community of developers and users, and widely utilized for various territorial analyses https://www.qgis.org/it/site/ (accessed on 2 December 2023).

The new plugin is named Ranking of the Affecting Potential of Detachment Areas in Rockfall (RADAR), which can serve as a valuable and expeditious tool for authorities in land use and infrastructure management.

To validate the RADAR plugin, the proposed methodology is applied to a particularly critical alpine region situated within the municipality of Bardonecchia, located in the Susa Valley, part of the Piemonte region in Italy. In this context, a comprehensive 3D analysis of rockfall runout is performed using the established QGIS Predictive ROckfall TOol (QPROTO) plugin [14], along with the newly introduced RADAR plugin.

2. A New Methodology to Assess the Release Influence of Rockfall Source Areas

The RADAR plugin is aimed at identifying, within a large widespread source area, the sectors where rockfall phenomena are most likely to affect specific exposed elements. These sectors are considered the most critical zones within the source areas, with reference to those specific targets.

The method starts from a preliminary assessment of slope areas prone to diffuse instability (source areas) whose detachment propensity characterization is accomplished through the SIF index. Then, a preliminary 3D propagation analysis is carried out in a GIS environment by means of the Cone method [15,16], implemented using the QPROTO plugin, which is based on a simple frictional model to provide the maximum runout area of unstable rock blocks through the definition of visibility cones. Subsequently, the application of the RADAR plugin enables the identification of the most critical source areas affecting the selected elements at risk.

2.1. An Overview of Runout Susceptibility Analysis with QPROTO

QPROTO is a QGIS tool developed by Politecnico di Torino and Arpa Piemonte and presented in [14], where a detailed description of its functioning can be found. The plugin allows rockfall runout analyses to be carried out based on a visibility analysis and the cone method [15,16]. Since these simulations do not analyze the probability of stopping of blocks along the trajectory (i.e., they are based on the minimum reach angle value), and because the trajectories are not influenced by the rock block volumes, they can be considered to be preliminary analyses.

A set of source points generating rockfalls is assumed as viewpoints, each associated with a visibility cone. The geometrical characteristics of the cone can be related to the physical and mechanical characteristics of the falling block and the runout zones of the slope through the definition of two angles [15,16]: the energy line angle, ϕ_p, which represents the global block–slope interaction as an equivalent friction, and the lateral spreading angle, α, which takes into account the intrinsic variability of rockfall trajectories. These angles can be correlated to some characteristics of the falling block and the slope, as described by Castelli et al. [14]. Figure 1 illustrates a schematic representation of the visibility cone from a generic source point, as defined in QPROTO. Referring to this figure, the energy angle ϕ_p is delineated in the vertical plane as the angle formed between the horizontal plane and the energy line. Meanwhile, the lateral angle α is established through the projection of the energy line onto the horizontal plane and its alignment with the dip direction of the source point.

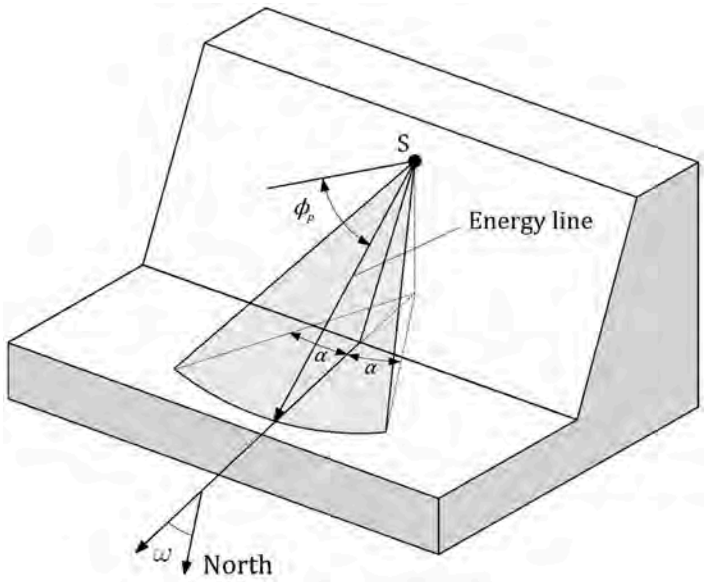

Figure 1. Spatial definition of the visibility cone as defined in QPROTO: ϕ_p is the energy angle, α is the lateral angle, and ω is the dip direction.

The intersection between the cone and the topographic surface defines the boundary of the propagation zone and allows one to define a set of points under the influence of the source, i.e., the terrain points that can be reached by rockfalls originating from that source. Since the visibility analysis made using QPROTO is carried out through raster files, the visible points (called "finalpoints" in QPROTO) are considered as the centroids of the cells of the Digital Terrain Model (DTM) used in the analysis.

In order to run the QPROTO plugin, a number of attributes must be associated with each source point, describing the topographic conditions of the slope, the characteristics of the block, the parameters of the visibility cone, and the detachment propensity of the source point. A list of the required attributes is provided in Table 1.

Table 1. List of attributes of the source points needed to perform a propagation analysis using QPROTO and RADAR (modified from [14]).

No.	Attribute	Description
0	ID	Identification number of the source point
1	Elevation	Height of the source point a.s.l. (m)
2	Aspect	Dip direction ω of the slope in the source point (°)
3	Energy angle	Energy line angle ϕ_p of the cone with apex in the source point (°)
4	Lateral angle	Lateral angle α of the cone with apex in the source point (°)
5	Visibility distance	Distance to which the analysis can be extended, i.e., the maximum runout distance assumed for rockfalls originating from the source cells (m)
6	Detachment propensity	Propensity of each source point to generate rockfalls (it can be for example the SIF) (-)
7	Boulder mass	Mass of the block (kg), utilized for the computation of the kinetic energy of masses at various points on the slope—a method not employed in this study

On the basis of the QPROTO analysis, runout susceptibility maps can be obtained by combining the information on the frequency of invasion (how many source points can "view" a DTM cell located in the runout zone?) and a detachment propensity of each source. In this regard, it is important to notice that the frequency of invasion is not a temporal parameter describing how often a specific DTM cell is affected by rockfalls; rather, it is a measure of the extent of the detachment areas with an influence on that DTM cell. This measure is obtained by counting the number of overlayed visibility cones at that point. Moreover, the rockfall source points' detachment propensity allows one to carry out weighted frequency runout analyses and produce more reliable rockfall runout susceptibility (i.e., relative hazard) maps.

2.2. An Overview of the SIF Index

A semi-quantitative methodology to estimate the detachment propensity of potentially unstable rock blocks has been recently proposed by Napoli et al. [13] and resulted in a rockfall Susceptibility Index to Failure (SIF) assuming values in the 0–1 range. This index is evaluated according to the presence and intensity of various causative factors (predisposing/preparatory and triggering) related to different scales of investigation (from detailed to regional scales) and environmental conditions (coastal marine or mountain environment), recognized in the literature as the main causes of rockfalls. Details on the causative factors and their weighting are reported in [13].

Although an intensive use of the SIF index is needed to validate the scores assigned to the different causative factors, it is particularly promising and useful since it can be easily computed in a GIS environment and introduced in a QPROTO (preliminary) runout analysis as an attribute of the source point (see Table 1). As mentioned in Section 2.1, this operation facilitates the obtaining of more reliable rockfall runout susceptibility maps.

2.3. Assessment of the Release Influence of Rockfall Source Areas: The RADAR Plugin

The methodology for determining the most influential rockfall sources with reference to specific elements at risk was implemented in the QGIS plugin Ranking of the Affecting Potential of Detachment Areas in Rockfalls (RADAR). RADAR uses basic vector processing functions, is native to QGIS, and can be used in QGIS versions after 3.16.

The RADAR analysis is focused on the "finalpoints" vector file produced using QPROTO; it is, therefore, designed to be used sequentially with QPROTO. On the basis of the results of a QPROTO runout analysis, specific elements at risk can be highlighted such as structures, infrastructures, residential areas, touristic areas, existing protective measures, etc. On the other hand, each of these elements at risk is affected by the different points of the source area with a different frequency, i.e., there are sectors of the source area that most affect the element at risk.

The principal innovation of this study lies in the introduced methodology. Precisely, the proposed approach uniquely orients the analysis toward the source area where rockfalls pose a risk. Consequently, an inverted perspective, in contrast to conventional methods (from source to element at risk), is employed. In this context, the term RADAR, besides serving as an acronym, has been employed to encapsulate the essence of identifying source areas that pose the most significant threat to exposed elements.

The inputs required for the RADAR analysis are:

(a) The *source points* vector, also used in the preliminary runout susceptibility analysis conducted with QPROTO (Table 1);
(b) The *finalpoints* vector, which represents the set of points visible from the source points, in accordance with the cone method and with the parameters used to define the visibility cones. In other words, it represents the points that can be impacted by rockfall events originating from the source points;
(c) The *critical areas* vector: a set of polygons containing the elements at risk, located in the invasion area, on which the RADAR analysis is focused. These polygons have to be defined by the user.

As the main steps of the analysis, first, the correspondence between the source points and those *finalpoints* invading the selected elements at risk is assessed. In this way, a Geometrical Affecting Index (GAI) can be computed as the percentage of the critical area that can be impacted by a rockfall coming from each source point. In the next lines, and in Equation (1), the process of how to calculate it is described.

Then, the GAI is combined with the SIF index characteristics of each source point in order to introduce the result of the actual detachment propensity of the source. The final result (Source Affecting Index—SAI) can, therefore, be intended as a "weighted" GAI that includes the influence of the morphology of the slope (through the visibility analysis), the physical characteristics of the falling blocks and run-out zone of the slope (through the definition of the cone parameters), and the conditions and runout susceptibility to the failure of the source zones (through the SIF).

More in detail, the plugin performs the following operations:

1. An intersection is performed between *finalpoints* and *critical areas* to determine the subset of *finalpoints* that are included within the *critical areas*, referred to as critical points, and collected in the vector file *finalpoints_crop*. This result represents a set of points located at the centers of the DTM cells that can be impacted by rockfall events originating from the source points.
2. The correspondence between the critical points and the source points is analyzed. For each source point, the number of critical points belonging to *finalpoints_crop* is determined. This value is included in the attribute table of the *source points* vector as *Distinct_FP*. The correspondence analysis is carried out on the basis of the unique identification code of each source point, listed in the attribute tables of the two vectors. Since each DTM cell inside the *critical areas* vector can contain more than one *finalpoint* (several *finalpoints* may overlap inside that cell if it is involved in rockfalls originating from different sources), it is necessary to treat these overlapping *finalpoints* as distinct entities.
3. For each source point, the ratio between the corresponding *Distinct_FP* value and the number of DTM cells contained in *critical areas* and containing at least one *finalpoint* (i.e., the number of distinct geographical *finalpoints* contained in the critical areas, named *Total_DFP*) is calculated and multiplied by 100. The result of this operation (Equation (1)) is the GAI of each source point, included among the attributes of the *source points* vector. This index represents the influence of each source with reference to a particular element at risk, describing its capability to reach any point of the "critical areas" vector. The GAI ranges between 0 (no influence, for source cells that do not generate any *finalpoint* within the critical areas) and 100 (maximum influence, for source cells whose *finalpoints* intersect all the DTM cells of *critical areas*).

$$\frac{Distinct\_FP}{Total\_DFP} \cdot 100 \ = \mathrm{GAI}\ (\%) \tag{1}$$

4. In order to take the susceptibility to the failure of the source points into account, for each source point, the GAI is weighted to SAI using the SIF index of that source, as shown in Equation (2). This leads to the SAI of each source point, equal to or lower than the GAI, which is finally included among the attributes of the *source point*'s vector.

$$\mathrm{GAI} \cdot \mathrm{SIF} = \mathrm{SAI}\ (\%) \tag{2}$$

The final result of RADAR is the characterization of each source point with new attributes, namely, *Distinct_FP*, *Total_DFP*, GAI, and SAI (Table 2), that can be used to create source influence maps.

It is important to note that the GAI and SAI indices of a source point are dependent on the choice of the exposed elements, i.e., the critical areas. A certain source point may be highly influential on one exposed element (e.g., a road) but less influential concerning another element (e.g., a residential area). Consequently, the release relevance of the detachment points is not absolute; however, it is related to the considered exposed elements.

The new RADAR plugin will be available for download and use in the dedicated repository of the open-source software QGIS. In the meantime, it can be found in the public GitHub repository https://github.com/LorenzoMilan/QGIS-RADAR (accessed on 28 November 2023) for download and installation in QGIS from a zip file.

In order to show the procedure and discuss the results, the application to a real case study located in the Western Alps (Bardonecchia, Italy) is presented in Section 3.

Table 2. List of attributes of the source points computed using the RADAR plugin.

No.	Attribute	Description
8	*Distinct_FP*	Number of DTM cells contained in the critical areas that are visible from a given source cell. *Distinct_FP* is, therefore, a different number for each source point.
9	*Tot_DFP*	Number of distinct finalpoints contained in the critical areas (i.e., the total number of DTM cells contained in the critical areas and containing at least one finalpoint). *Tot_DFP* has, therefore, the same value for each source point.
10	GAI	Geometrical Affecting Index of the source point.
11	SAI	Source Affecting Index of the source point (i.e., the GAI multiplied by SIF).

3. Application of the Proposed Methodology

As mentioned in the introduction, the methodology proposed in this study has been applied to the alpine region of Melezet, located within the Bardonecchia municipality (Susa Valley, North-Western Italian Alps), presenting notable engineering challenges due to extensive and large-scale rockfall events affecting urbanized areas.

3.1. The Case Study of Melezet (Bardonecchia, Italy)

The hamlet of Melezet is located in the municipality of Bardonecchia. In this location, on the left orographic side of the Dora di Melezet Valley, for many years, there have been long-standing reports of rockfalls and mass movements from the rock mass known as "Rocce del Rouas" (Figure 2). This is a sub-vertical slope composed of dolomitic limestone, approximately 50 m high and oriented north–south, overlooking the Provincial Road SP 216. This road serves as an international connection between Italy and France and is the access route to Valle Stretta, a highly frequented tourist destination.

Figure 2. Geographical overview of the Melezet area.

Extending from the base of the rock walls to the valley floor, covering a vertical drop of approximately 180 m, the slope is covered by debris materials of varying granulometry and is a witness to numerous past rockfall events. Due to the unstable character of this slope, rockfall barriers and embankments were installed in the past to protect the road and the buildings.

Records of landslides in this area indicate multiple main events occurring in 1938, 1939, 1940, 1941, 1942, 1970, 1980, 2000, and 2010. Rock blocks, with volumes ranging from 1.5 to 50 m^3, reached the valley floor on several occasions, posing a threat to buildings and Provincial Road SP 216. Such main events were alternated with relatively quiet periods during which only the detachment of individual small blocks occurred [17,18].

In particular, on 21 May 2010, the largest recorded rockfall occurred in the area (Figure 2) and affected the Provincial Road SP 216, which was completely buried by blocks, seriously endangering a group of buildings and completely demolishing two that were fortunately unoccupied. This event involved the collapse of a rock mass portion approximately 30 m in height and 20–25 m in width, mobilizing around 2000 m^3 of material. Large blocks (up to over 50 m^3) rolled downhill along the existing debris slope.

Rockfall protection barriers located on the slope were completely destroyed, and the existing rockfall protection embankment along the provincial road, while containing some blocks, was filled and partially breached at the top [18]. Figure 3 shows the rock wall from which the collapse occurred, while Figure 4 shows some blocks that damaged the rockfall barriers, the road, and the buildings at the base of the rock wall.

Figure 3. View of the examined rock slope [18].

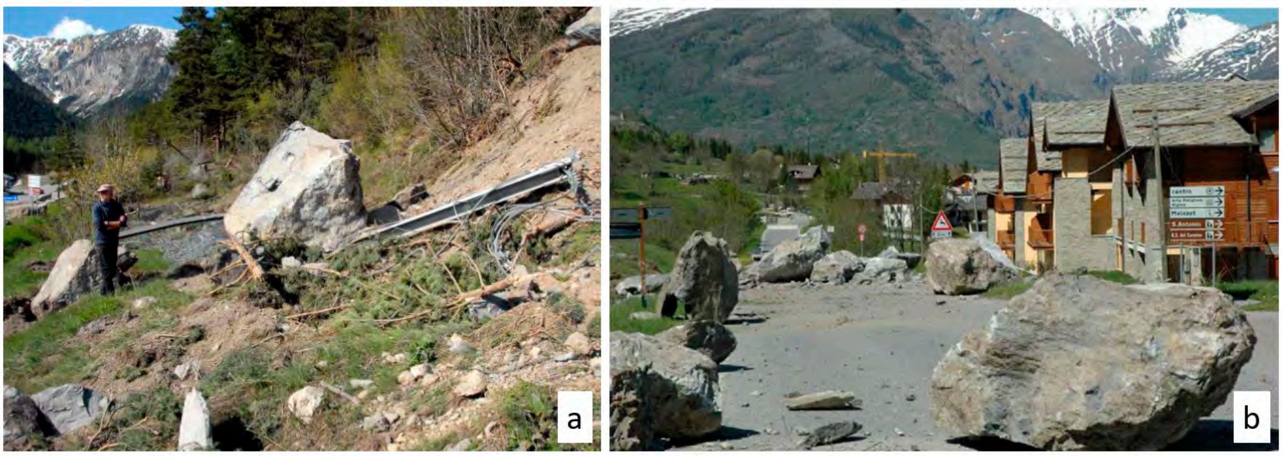

Figure 4. Some of the blocks that detached from the slope during the 2010 event and caused damage to the existing rockfall barriers (**a**) and the SP 216 road (**b**) [18].

Following the event, the area underwent risk mitigation measures, including the provisional rerouting of the provincial road, rescaling and consolidation of critical sections of the rock wall, and design and construction of a new rockfall embankment. Nevertheless, the rock slope has continued sporadically shedding blocks, as reported by the residents of Melezet, making the area particularly critical and necessitating further analyses for the assessment of the residual rockfall risk of the area.

The case study of Melezet is, therefore, presented in this paper to show an application of the proposed approach to assess the affecting potential of the rockfall sources within the whole area. All the analyses were carried out in the QGIS environment by means of the QPROTO and new RADAR plugins, as described in Sections 3.2 and 3.3, respectively.

3.2. Runout Susceptibility Analysis through the Plugin QPROTO

The identification of the potential release areas was performed in QGIS on the basis of the topographical and morphological features of the site, then refined according to the information collected during geological in situ surveys. The rockfall source points used for the runout analysis conducted through the QPROTO plugin were derived using the methodology previously applied by Castelli et al. [14]. Specifically, this set of source points was obtained from 11 homogeneous areas defined based on reports compiled by technicians with extensive on-site experience. These homogeneous areas were delineated as sections of the rock face with uniform characteristics, including slope orientation, elevation, and structural conditions. Within each homogeneous area, a set of points was generated using a Digital Terrain Model (DTM) with a resolution of 5 m, representing the topography of the slope after the event in May 2010. These points were randomly selected at the center, and 50% of the grid cells had inclinations exceeding 45°. The outcome was a shapefile comprising 1687 points (Figure 5).

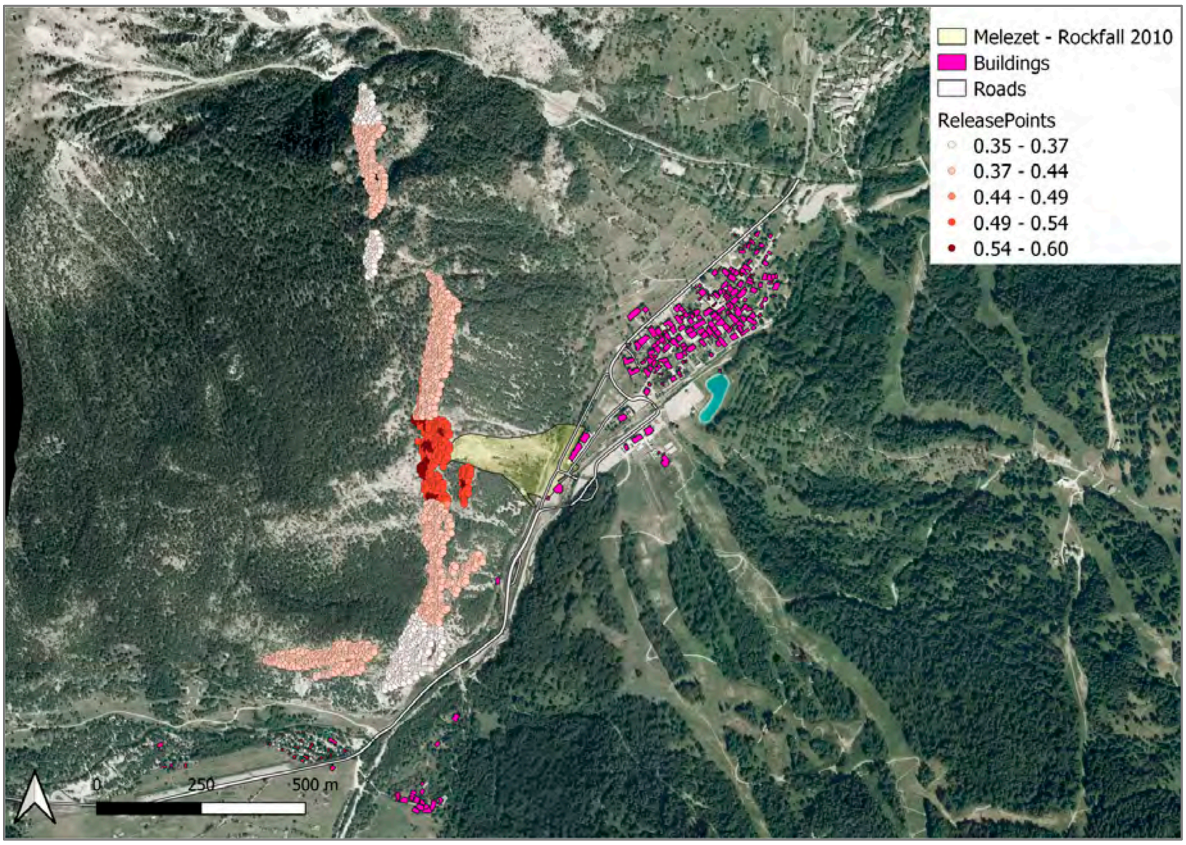

Figure 5. Localization of the source points considered in the QPROTO analysis. The color scale and legend refer to the SIF value assigned to each point.

Then, the attributes listed in Table 1 were associated with each point: elevation and aspect were easily obtained from the DTM, energy angle in the vertical plane (φ_p = 34°–38°), lateral angle in the horizontal plane (α = 10°), visibility distance (800 m), boulder mass (2500 kg), and detachment propensity.

The energy line angle value was determined using the method proposed by Castelli et al. [14], correlating it with the average slope inclination, the presence of vegetation, and the block volume. Specifically, the scenario examined in this analysis pertains to blocks of 1 m^3.

The detachment propensity (i.e., SIF index) was defined according to the methodology proposed by Napoli et al. [13]. As visible from Figure 5, the release points located on (or close to) the detachment area of the 2010 rockfall event had the highest SIF indexes, with values ranging from 0.5 up to 0.6, while the other source points had lower SIF index values, from 0.35 up to 0.5. This difference can be ascribed to parameters, such as the inclination of the slope, past rockfall events, and fracturing degree, which were assigned higher weights above the 2010 rockfall invasion area with respect to the other source points.

The runout susceptibility map obtained through the QPROTO analysis is illustrated in Figure 6. The runout susceptibility is quantified numerically as the propensity-weighted frequency of rock block passages (i.e., the sum of the SIF indexes of all the source points that can reach that DTM cell). Through the SIF index, areas with equal passage frequency (i.e., DTM cells observed by the same number of source points) can be differentiated based on the instability potential of the corresponding source points.

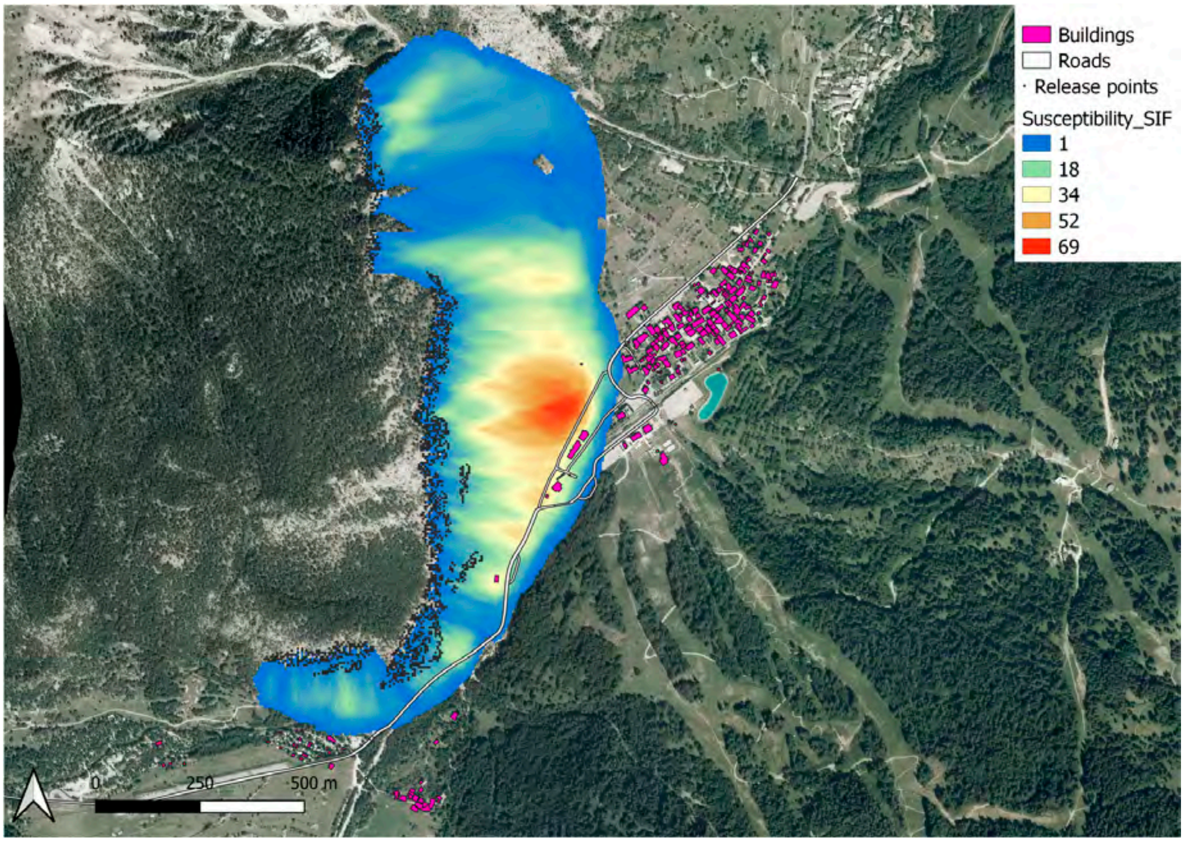

Figure 6. SIF-weighted runout susceptibility map obtained by means of the QPROTO plugin.

As can be seen in the figure, the highest runout susceptibility values are obtained in correspondence with the portion of the rock face that overlooks the original route of the provincial road, where the huge collapse of May 2010 took place. It is worth pointing out that this result is strictly connected to the (cone) method used for the assessment of the propagation area and to its limitations: all the points falling within a generated cone are considered potential stopping points (points that can be reached by that source point). Therefore, the maximum susceptibility obtained at the base of the slope is a direct consequence of the local morphology and does not consider the statistical distribution of arrivals along the path.

3.3. Rockfall Sources Influence Analysis through the Plugin RADAR

As mentioned, RADAR requires three inputs: the *source points* shapefile, the *finalpoints* shapefile, and the *critical areas* shapefile, which are shown in Figures 5, 7, and 8. Regarding the critical areas, three zones were selected, including a portion of the provincial road, the rockfall embankment, and a zone of residential properties with gardens and parking areas within the zone of invasion produced through the QPROTO analysis.

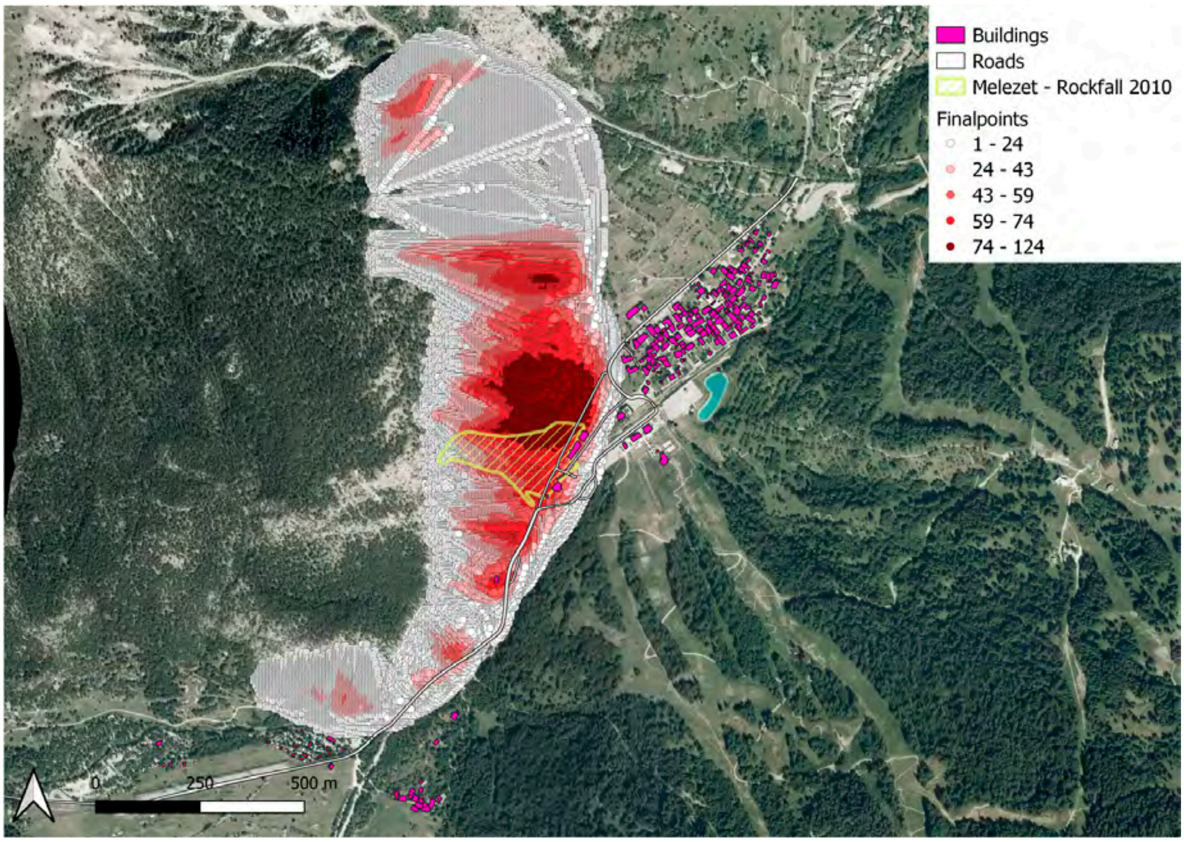

Figure 7. Finalpoints map obtained through the QPROTO analysis. The legend and the color scale indicate the number of source points potentially reaching each finalpoint.

Figures 9 and 10 depict the two maps showing the characterization of the source points obtained through the RADAR analysis. Specifically, in Figure 9, the influence of each source is assessed through the GAI, while, in Figure 10, it is evaluated through the SAI.

The comparison between these two maps and the map presented in Figure 5 (where the affecting potential of the detachment areas is assessed on the basis of the SIF index) is of particular interest (Figure 11). Specifically, it is possible to observe that the overall affecting index of the rockfall sources (SAI) is determined by both their propensity to generate rockfall events (SIF) and the physical and morphological possibility that these events affect critical zones (GAI).

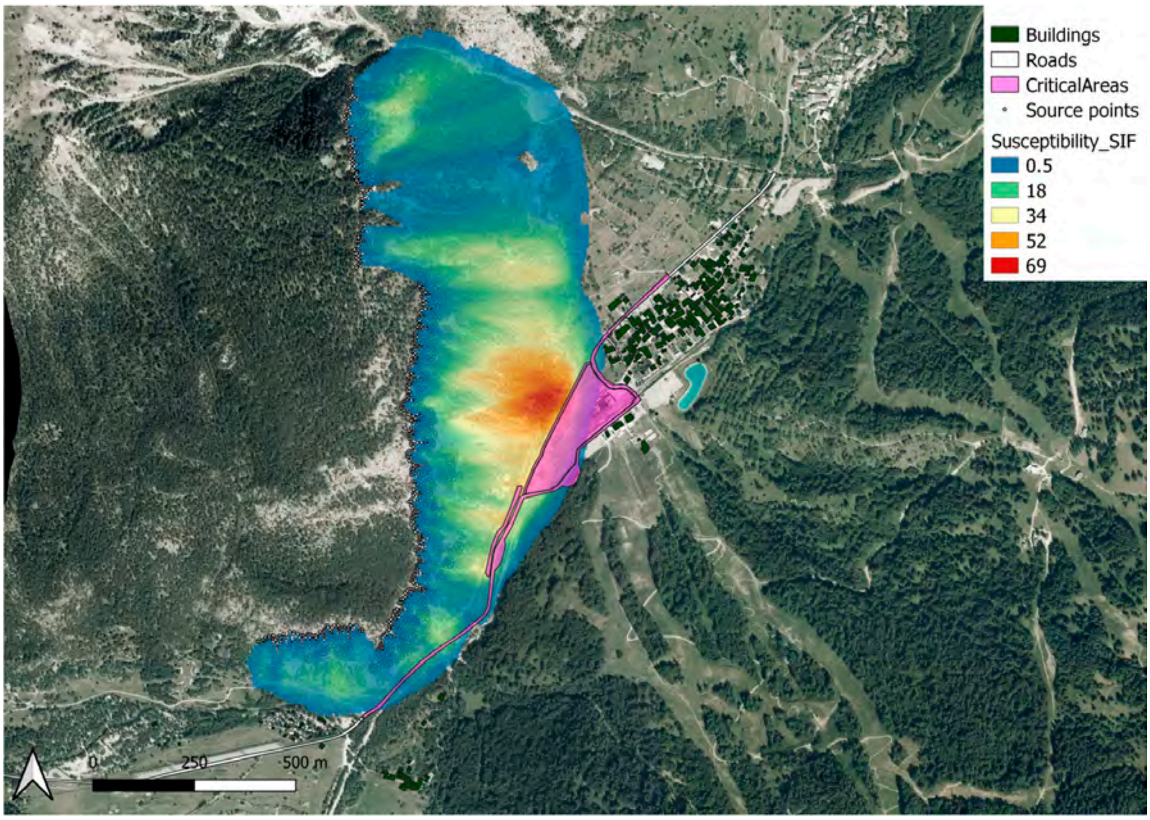

Figure 8. SIF-weighted runout susceptibility map obtained with QPROTO and the delineation of critical areas in purple (including the residential area and the roads) used in the analysis with RADAR.

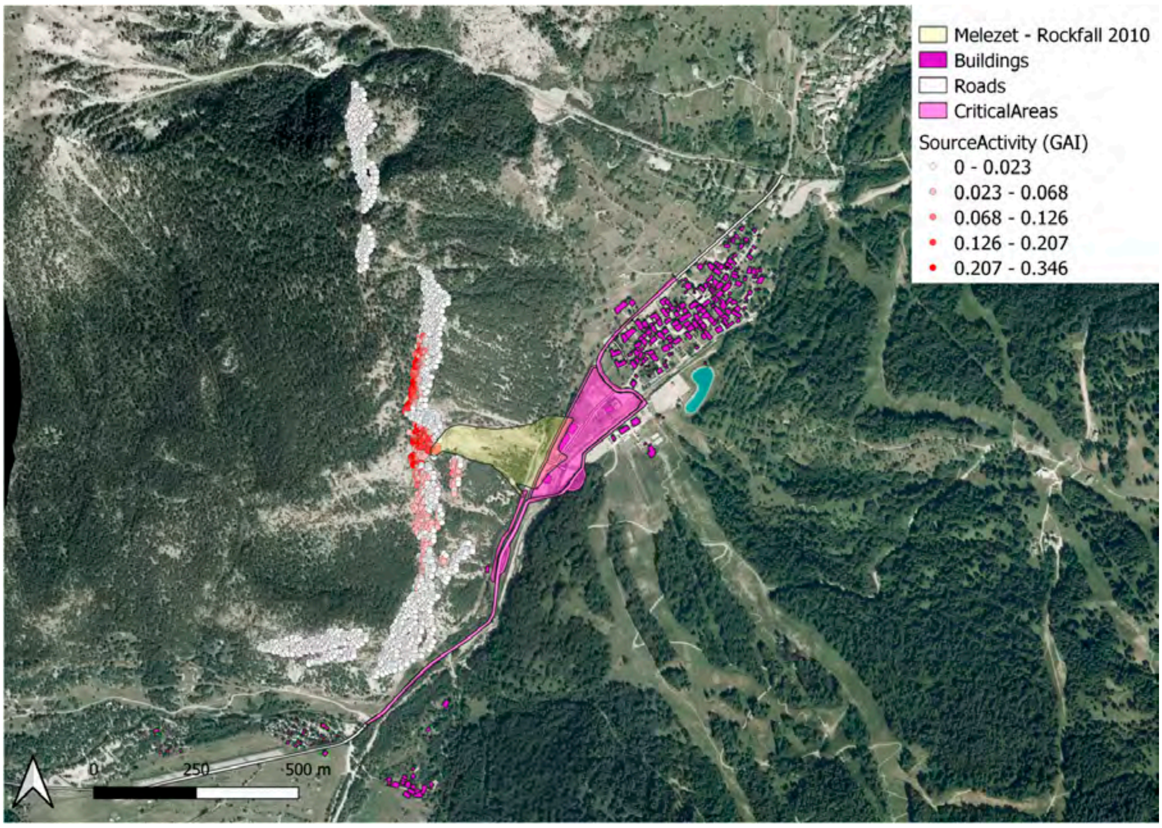

Figure 9. Affecting potential of the detachment areas of rockfall source points based on GAI.

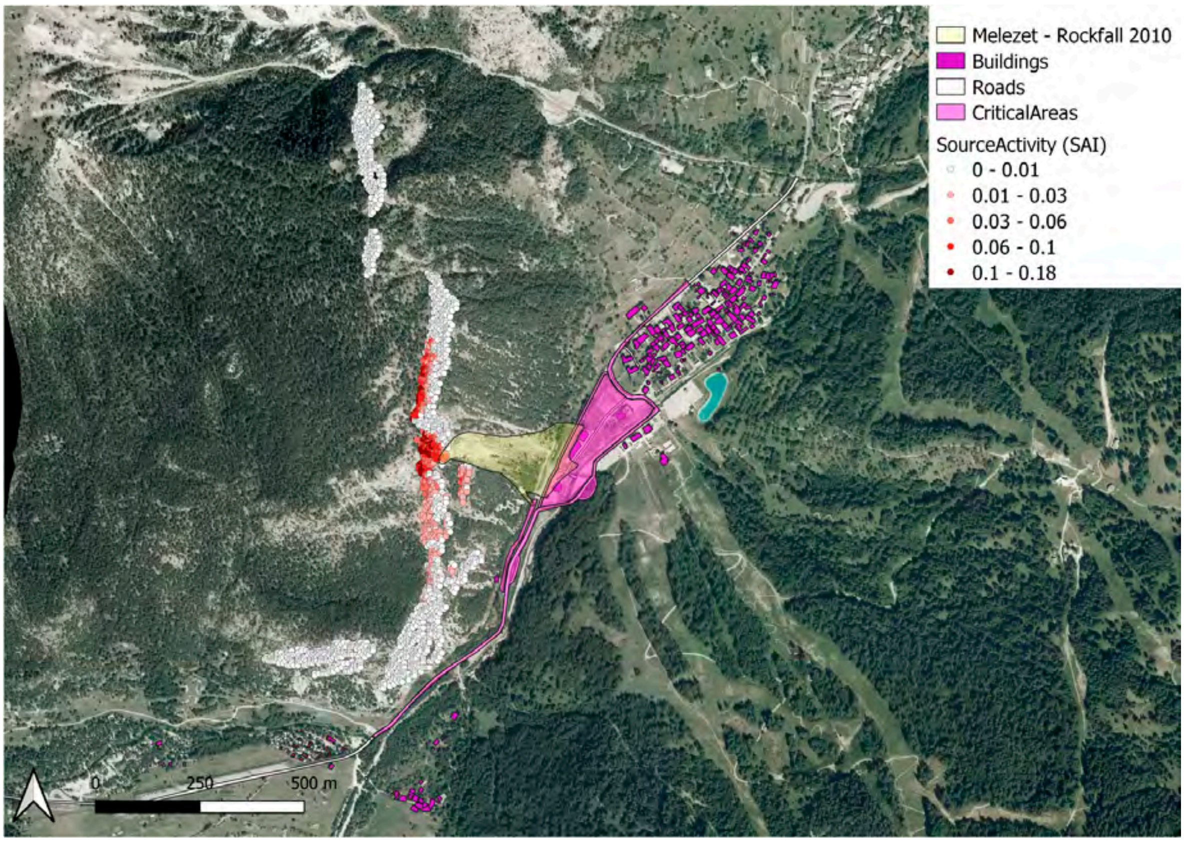

Figure 10. Affecting potential of the detachment areas of rockfall source points based on SAI.

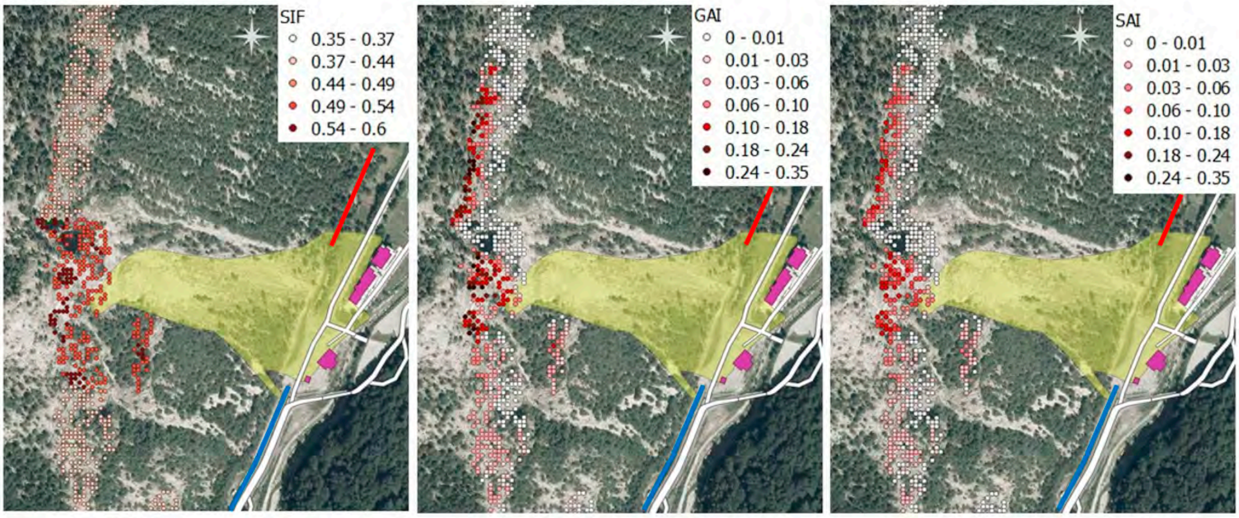

Figure 11. Comparison among the characterization of the source points based on the SIF, GAI, and SAI indexes. The position of the old and new embankments is indicated in blue and red, respectively.

In fact, from Figure 11 it is clear that many source points with a high SIF index exhibit much lower SAI values, due to their low capacity to reach the selected critical areas. This difference can be ascribed to the irregular morphology of the slope, which can affect the result of a viewshed analysis (i.e., low GAI values).

Conversely, some source points that may be considered less critical due to their low SIF values are worthy of attention because they possess significant GAI values (capable of impacting large portions of exposed elements) and, therefore, have high SAI values. These are, for example, the source points located north of the 2010 scar. The new embankment shown in Figure 2 has already been constructed. Based on the documents at our disposal, it is evident that the design of this embankment was carried out following a laser scanner survey of the rock wall and a kinematic collapse model. Therefore, it is reasonable to assume that, in some way, the model used by the designers considered the result we obtained through a different approach. However, it can be noted that the new embankment is not providing protection to the buildings but only to a portion of the provincial road. Regarding the extent of the embankment, according to the information available, it was defined based on the residual risk analysis of the built-up areas on the valley floor. The decision to divert the road and not to protect the buildings was made by local authorities to avoid over-sizing risk mitigation measures (due to their huge costs), and also because the residual risk would not have been acceptable, in any case.

4. Discussion and Conclusions

In this research article, a novel methodology has been proposed and applied for evaluating, in relative terms and for the site under investigation, the influence of rockfall source areas, with reference to specific elements at risk. The affecting potential of the detachment areas, quantified by using the SAI index, is founded on both susceptibility to failure (i.e., SIF index) and the outcomes of empirical cone method analyses conducted using the open-source software QGIS with the plugins QPROTO and RADAR (susceptibility to propagate). The methodology proposed in this study integrates these two facets of susceptibility, aiming to achieve a more accurate and reliable result in terms of runout susceptibility maps. This integrated approach underscores the cohesive unity of the entire methodology.

The procedure has been implemented in a plugin within QGIS, serving as a valuable tool for the rapid assessment and mapping of the large-scale affecting potential of the detachment areas associated with widespread rockfall occurrences. These maps enable the swift identification of the most problematic areas within extensive slopes and valleys and are important for land planning purposes. In fact, these are the slope sectors where detailed analyses, monitoring tool installation, or consolidation work should be carried out.

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References

1. Bray, M.J.; Hooke, J.M. Prediction of Soft-Cliff Retreat with Accelerating Sea-Level Rise. *J. Coast. Res.* **1997**, *13*, 453–467.
2. Mirhadi, N.; Macciotta, R. Quantitative Correlation between Rock Fall and Weather Seasonality to Predict Changes in Rock Fall Hazard with Climate Change. *Landslides* **2023**, *20*, 2227–2241. [CrossRef]
3. Theodore, P.; Thomas, H.; Adonis, V.; Theophanis, K.; Emmanouel, O.; Charalampos, D. Erosion Status of a Sea Cliff Promontory Bounding an Ecologically Important Beach. *J. Coast. Conserv.* **2020**, *24*, 19. [CrossRef]
4. Gariano, L.S.; Guzzetti, F. Landslides in a Changing Climate. *Earth Sci. Rev.* **2016**, *162*, 227–252. [CrossRef]
5. Corominas, J.; Van Westen, C.; Frattini, P.; Cascini, L.; Malet, J.P.; Fotopoulou, S.; Catani, F.; Van Den Eeckhaut, M.; Mavrouli, O.; Agliardi, F.; et al. Recommendations for the Quantitative Analysis of Landslide Risk. *Bull. Eng. Geol. Environ.* **2014**, *73*, 209–263. [CrossRef]
6. Crosta, G.B.; Agliardi, F.; Frattini, P.; Lari, S. Key Issues in Rock Fall Modeling, Hazard and Risk Assessment for Rockfall Protection. In *Engineering Geology for Society and Territory-Volume 2: Landslide Processes*; Springer: Berlin/Heidelberg, Germany, 2015.
7. De Biagi, V.; Botto, A.; Napoli, M.L.; Dimasi, C.; Laio, F.; Peila, D.; Barbero, M. Estimation of the Return Period of Rock Falls According to the Block Size. *Geoing. Ambient. Min.-GEAM* **2016**, *147*, 39–48. (In Italian)
8. Ferrari, F.; Giacomini, A.; Thoeni, K. Qualitative Rockfall Hazard Assessment: A Comprehensive Review of Current Practices. *Rock Mech. Rock Eng.* **2016**, *49*, 2865–2922. [CrossRef]
9. Jaboyedoff, M.; Dudt, J.P.; Labiouse, V. An Attempt to Refine Rockfall Hazard Zoning Based on the Kinetic Energy, Frequency and Fragmentation Degree. *Nat. Hazards Earth Syst. Sci.* **2005**, *5*, 621–632. [CrossRef]
10. Umili, G.; Bonetto, S.M.R.; Mosca, P.; Vagnon, F.; Ferrero, A.M. In Situ Block Size Distribution Aimed at the Choice of the Design Block for Rockfall Barriers Design: A Case Study along Gardesana Road. *Geosciences* **2020**, *10*, 223. [CrossRef]
11. Turner, A.K.; Duffy, J. Modeling and Prediction of Rockfall. In *Rockfall: Characterization and Control*; Transportation Research Board: Washington, DC, USA, 2012.
12. Mavrouli, O.; Corominas, J.; Jaboyedoff, M. Size Distribution for Potentially Unstable Rock Masses and In Situ Rock Blocks Using LIDAR-Generated Digital Elevation Models. *Rock Mech. Rock Eng.* **2015**, *48*, 1589–1604. [CrossRef]
13. Napoli, M.L.; Barbero, M.; Castelli, F.; Castelli, M.; Lentini, V. A Semi-Quantitative Approach to Assess the Propensity of Rockfall Source Areas to Instability Based on the Susceptibility Index to Failure (SIF): The Case Study of Capo Calavà (Italy). In Proceedings of the CNRIG 2023: Geotechnical Engineering in the Digital and Technological Innovation Era, Palermo, Italy, 5–7 July 2023; Springer Nature: Cham, Switzerland, 2023; pp. 715–723.
14. Castelli, M.; Torsello, G.; Vallero, G. Preliminary Modeling of Rockfall Runout: Definition of the Input Parameters for the QGIS Plugin QPROTO. *Geosciences* **2021**, *11*, 88. [CrossRef]
15. Onofri, R.; Candian, C. *Indagine Sui Limiti Di Massima Invasione Dei Blocchi Rocciosi Franati Durante Il Sisma Del Friuli Del 1976. Considerazioni Sulle Opere di Difesa*; Regione Autonoma Friuli-Venezia-Giulia, CLUET: Trieste, Italy, 1979; pp. 1–42.
16. Jaboyedoff, M.; Labiouse, V. Technical Note: Preliminary Estimation of Rockfall Runout Zones. *Nat. Hazards Earth Syst. Sci.* **2011**, *11*, 819–828. [CrossRef]
17. Consorzio Forestale Alta Val di Susa. *Lavori Di Mitigazione Del Rischio Del Versante Roccioso in Frazione Melezet a Difesa Abitato-Progetto Definitivo*; Relazione Geologico–Tecnica e Sismica: Oulx, TO, Italy, 2014.
18. Piemonte, A. *SIFRAP—Sistema Informativo Fenomeni Franosi in Piemonte Codice Frana: 001-76293-00*; Rocce Del Rouas; Comune Di Bardonecchia: Bardonecchia, Italy, 2011.