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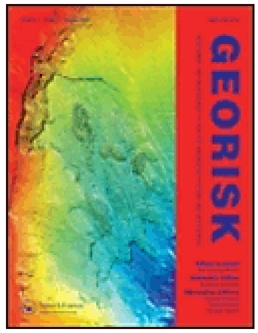

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RESEARCH PAPER

A mixed quantitative approach to evaluate rockfall risk and the maximum allowable traffic on road infrastructure

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ABSTRACT
Rockfall events constitute one of the most dangerous phenomena in mountainous areas, which can affect transportation routes. In a risk mitigation perspective, the quantification of the risk for pedestrians and vehicles represents a crucial aspect for Authorities. A method tailored to these elements at risk is herein presented. The proposed method is based on a mixed formulation of the Quantitative Risk Assessment and the Event Tree Analysis approaches. According to these procedures, an accurate evaluation of the annual probability of adverse outcomes can be computed considering all the scenarios which can lead to a fatality or to an injury. Vice versa, the method lets to evaluate the allowable traffic condition, given an acceptable threshold for the risk. Furthermore, it serves to quantify the risk reduction in case of installed passive mitigation measures and, thus, to plan the priority of intervention works. An application on a study case in the Italian Alps illustrates the potentialities of the methodology.

KEYWORDS
Rockfall hazard; quantitative risk assessment; mitigation measures; event tree analysis

1. Introduction

Rockfall is generally ascribed among the most threatening natural hazards, due to its unpredictability and abruptness (Fell et al. 2005). This phenomenon can involve several elements at risk, e.g. people, infrastructure, villages, and environment (Castelli et al. 2004). In this sense, the consequent damages can be physical, social, economical, and environmental (Castelli et al. 2002). Referring, in particular, to road infrastructure, a complete evaluation of the consequences should involve damages to the road, power and communication networks, and vehicles, the eventual traffic interruption, the consequences on the surrounding economic activities and on the alternative routes, or, in absence of these lasts, the loss of connection to villages, and, above all, the possible fatalities (Bonnard, Forlati, and Scavia 2004; Li et al. 2009).

In this sense a quantification of the risk as number of fatalities per year is often required by Authorities, in order to manage the risk and to predispose effective

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mitigation plans (Domènech, Alvioli, and Corominas 2020). This means that (i) an appropriate hazard analysis (Crosta, Frattini, and Fusi 2007) combined with (ii) a consequences analysis have to be performed. As for the other landslide phenomena, an accurate hazard analysis starts from the identification and characterization of the danger, aimed at defining one or more realistic scenarios, from which propagation analyses have to be performed. This means that data collection and field observation processes are fundamental steps, whose accuracy has a great impact on the result (Agliardi, Crosta, and Frattini 2009; Moos et al. 2018). In the rockfall framework, the estimation of the possible released volumes as well of their return period constitute a challenging aspect, also for the difficulties in collecting data from past events. Due to the abruptness and the site-specific nature of the phenomenon, the propensity to the detachment and its temporal probability are difficult to evaluate (Saroglou et al. 2012). The consequences analysis, comprising the estimation of vulnerability and value of the elements at risk, includes the evaluation of the intensity of the phenomenon, i.e. the volume and the energy of the possible impacting blocks, to which a reaching probability has to be defined (Corominas et al. 2014). Moreover, increasing the scale of analysis, i.e. the extension of the studied area, the costs for complete surveys increase exponentially.

For a medium-large scale of analysis, e.g. a rock face from about 1 to 10 kilometers wide (Van Westen, Castellanos, and Kuriakose 2008), the knowledge of all the variables involved, a realistic modelling of the phenomenon, and an accurate evaluation of the consequences are difficult to achieve (Straub and Schubert 2008; Wang et al. 2014; Ferrero, Segalini, and Umili 2015; Scavia et al. 2020; De Biagi, Marchelli, and Peila 2020). Consequently, often qualitative or semi-quantitative risk assessment are only performed (Budetta 2004; Guzzetti, Reichenbach, and Ghigi 2004; Andrianopoulos, Saroglou, and Tsiambaos 2013; Budetta and Nappi 2013; Pappalardo, Mineo, and Rapisarda 2014; Mineo 2020). Nevertheless, in the perspective of risk management, a quantitative evaluation of both hazard and risk is necessary, for its reproducibility and comparability.

Among the quantitative methods, Quantitative Risk Assessment (QRA) and Event Tree Analysis (ETA) are generally adopted.

Considering that the exposed area consists of q elements at risk and p rock blocks that can detach, with different volumes, QRA computes the risk R through the following formula:

$$R = \sum_{l=1}^{p} \sum_{m=1}^{q} \left(P^{l}_{(T:B)} P^{l,m}_{(S:B)} E^{m} V^{l,m} W^{m} \right), \tag{1}$$

where $P^{l}_{(T:B)}$ is the temporal probability, i.e. the probability of occurrence, of the detachment of the l-th block and $P^{l,m}_{(S:B)}$ is the spatial probability that this block reaches the m-th element at risk, and E^m, $V^{l,m}$, W^m are the exposure, i.e. the probability that a given element is at the impact location where the rock block detaches, the vulnerability, and the value, respectively.

The event tree analysis is a logical based procedure in which both success and failure are evaluated, starting from a single initiating event and defining all the possible alternative pathway options which can develop. The latter are mapped as branches and the nodes serve as transition from one position to another along the event tree, defining binary (Yes/No) mutually exhaustive possibilities, realizing different scenarios. The end points identify a unique outcome, whose probability is given by the product of the conditional probabilities along their own pathway. The probability of more outcomes is given by the sum of the probabilities of each outcome. The value of each occurrence probability depends on different parameters, to which a certain degree of uncertainty is inevitably associated (Macciotta et al. 2017).

Considering element at risks whose exposure is different from one, i.e. moving vehicles on roads (Peila and Guardini 2008; Mignelli, Lo Russo, and Peila 2012; Budetta, De Luca, and Nappi 2016; Mineo et al. 2017), or trains on railways lines (Macciotta, Martin, and Cruden 2015; Macciotta et al. 2017), ETA are generally adopted. Nevertheless, this method starts from the occurrence of an initiating event, i.e. the impact of a block, on the considered element. On the contrary, QRA allows to precisely define the probability that a given release volume reaches a specific area in a specific time. In some cases QRA is adopted for all the risk assessment procedure, for vehicles (Bunce, Cruden, and Morgenstern 1997; Michoud et al. 2012; Mavrouli and Corominas 2018), and for pedestrians (Ansari, Ahmad, and Singh 2014), but disregarding a complete evaluation of all the scenarios leading to a fatal accident and accounting for the impact between the block and the element at risk, only. Furthermore, the assessment of the risk for vehicles or pedestrians has to be performed along a road, i.e. a linear system characterized by portions over which different possible source zones insist, differing for release volume and detachment temporal probability. The reaching probability can also vary for each point of the road. Consequently, an accurate analysis requires the knowledge of several parameters and variables, sometimes difficult to achieve.

A mixed quantitative approach, allowing to overcome the limitations of both methods and accounting for the difficulties in obtaining all the required inputs, is here introduced. This method provides the risk in terms of annual probability of having at least one fatality, approximated to the number of fatalities per year. Alternatively, for a given value of risk defined as acceptable, the correspondent allowable traffic conditions can be determined. This represents a key-point for risk management in mountain areas (Marchelli 2020). A study case in the North Western Italian Alps is provided and the results are discussed. Finally conclusions and further developments are presented.

2. A mixed quantitative approach: QRA & ETA methodologies

In this section, the proposed methodology to quantify the risk is outlined, subdividing the QRA and ETA procedures and describing the mixed formulation. A deep overview of all the steps constituting the risk analysis is introduced and discussed.

2.1. *QRA procedure*

In rockfall risk assessment for road infrastructures, the knowledge of the position and the number of blocks which can potentially reach the track constitutes a crucial point. The process starts from the identification of the rockfall-prone areas, i.e. the possible source zones. In the framework of a medium-large scale of analysis, the propensity to the detachment is difficult to estimate, and, for this reason, it is implicitly considered in the temporal detachment probabilities of the identified prone to fall area. The second step is represented by the choice of one or more rockfall realistic scenarios, in terms of initial volume and return period, according to which the hazard analysis is performed. In this sense, a single value of the block volume is generally not able to take into account the natural variability of the geometrical characteristics of the discontinuity sets (Stavropoulou 2014; Mavrouli, Corominas, and Jaboyedoff 2015; Mavrouli and Corominas 2017; Umili et al. 2020), although the possible fragmentation along the path is neglected (Ruiz-Carulla, Corominas, and Mavrouli 2015, 2017; Marchelli, De Biagi, and Peila 2019; Marchelli and De Biagi 2019; Marchelli et al. 2019).

A road can be subdivided into n portions. Each k-th portion is homogeneous since a unique temporal $P_{(T:B)_l}$ and a spatial $P_{(S:B)_l}$ probabilities can be assigned. Eqn.(2) can be rewritten as:

$$R = \sum_{k=1}^{n} \sum_{l=1}^{p} \sum_{m=1}^{q} \left(P^{l,k}_{(T:B)} P^{l,m,k}_{(S:B)} E^{m,k} V^{l,m,k} W^{m,k} \right). \tag{2}$$

In the framework of road risk analysis, considering vehicles and people as elements at risk, a reasonable solution could be to assume that even small blocks produce consequences. Hence, the evaluation of a correlation between release volume and return period (De Biagi et al. 2017; De Biagi 2017) can be neglected and the return period of an event can be estimated, independently from the l-th magnitude or volume class, through an inventory of past events (Dussauge-Peisser et al. 2002). Consequently, Eqn. (2) simplifies, neglecting the summation over the p total block volumes. Moreover, the terms $P^{k}_{(T:B)}$ and $P^{k}_{(S:B)}$ are evaluated with reference to the system on which the elements at risk are moving, i.e. the road, rather than the elements themselves, i.e. vehicles (or pedestrians). The resulting Eqn. (2) becomes:

$$R = \sum_{k=1}^{n} \left[\underbrace{P^{k}_{(T:B)} P^{k}_{(S:B)}}_{\text{QRA}} \overbrace{\underbrace{\sum_{m=1}^{q} \left(E^{m,k} V^{m,k} W^{m,k} \right)}_{\text{ETA}}}^{PIM^k} \right]. \tag{3}$$

The under-breaks highlight the mixed nature of the risk analysis. The first addends relate to the QRA, while the summation over the q elements at risk reflects the ETA. In the following section (Sec.2.2), the procedure to obtain the term PIM^k is explained.

2.2. *ETA procedure*

As already mentioned, the ETA approach starts from the occurrence of an initiating event, starting from which all the possible developments and outcomes are considered. In the case herein considered, the starting event is the block reaching the road. Following the procedure suggested in Peila and Guardini (2008) and Mignelli, Lo Russo, and Peila (2012), starting from this, two scenarios can develop: the blocks can hit the element at risk or not, and in the last case, blocks not hitting the road can rebound on the track, even damaging its surface or stopping on the path. The outcomes depend on the considered element at risk and, thus, the authors here enhance the method for both people in vehicles and pedestrians. In this sense, a different vulnerability, i.e. degree of loss, is applied: the proposed method assumes that any block of any size or velocity hitting a pedestrian causes a fatality, i.e. a unitary vulnerability, while, in case of people on a vehicle, it can cause fatality or injury, according to the speed and the size of the vehicle, the number of people inside, the ratio between decision and stopping sight distances, and the traffic conditions. In the ETA framework, it should be addressed that the evaluation of the exposure, the vulnerability, and the value of the element at risk are implicit in the branches probabilities.

The red pane of Figure 1 displays the proposed tree structures for both vehicles and pedestrians, where the red node represents the starting event. Considering people in a vehicle, three end points refers to a fatal accident as outcome, and, thus, for each k-th portion of road, the probability to have a fatal accident PIM^k is:

$$PIM^k = PIM_i^k + PIM_s^k + PIM_d^k, \tag{4}$$

where the subscripts i, s, and d refer to the case that (i) a moving vehicle is hit by the falling block, (s) a moving vehicle impacts on the block stopped on the road, or (d) a moving vehicle skids for damages on the road caused by the rebounding of the block on it. For simplicity of notation the following equations do not account for each k-th portion of road.

The probability of stopping P_f or rebounding $(1 - P_f)$ can be computed through trajectory analyses, while the probabilities of damages on the road P_t or of fatal accident are computed on the bases of annual national statistics. Explaining in detail the branches inside the three scenarios, the occurrence of the first case, i.e. "the block hits the vehicle", requires the contemporaneity in time and in space of the falling block and the moving vehicle which is expressed by the temporal-spatial probability $P_{(S:T)_i}$:

$$P_{(S:T)_i} = P_{(T:P)_i} P_{(S:P)_i}, \tag{5}$$

where $P_{(T:P)_i}$ and $P_{(S:P)_i}$ are the temporal and spatial probabilities, respectively. These probabilities can be computed as the probability in time and space that one (subscript $_1$) vehicle is hit throughout the year, multiplied by the hourly traffic $n_{v/h}$ and the annual number of hours n_h for which this traffic condition is valid, i.e.:

$$P_{(S:T)_i} = P_{(T:P)_{i,1}} P_{(S:P)_{i,1}} n_{v/h} n_h. \tag{6}$$

In detail:

$$P_{(T:P)_{i,1}} = \frac{t_t}{8760}, \tag{7}$$

where t_t is the transit time of a vehicle in hours. The spatial probability is given by:

$$P_{(S:P)_{i,1}} = \frac{L_v}{l_k}, \tag{8}$$

where L_v is the length of the vehicle and l_k the length of the road portion in meters.

The probability that the impact is fatal $P_{i,fatal}$ can be computed as the product between the coefficient of usage of the vehicle C_p, representative of the number of people inside, and the probability of one fatality, assumed equal to 0.2 as suggested by Bunce, Cruden, and Morgenstern (1997). Following the principles of the ETA, the probability of a fatality is:

$$PIM_i = P_{(S:T)_i} P_{i,fatal}. \tag{9}$$

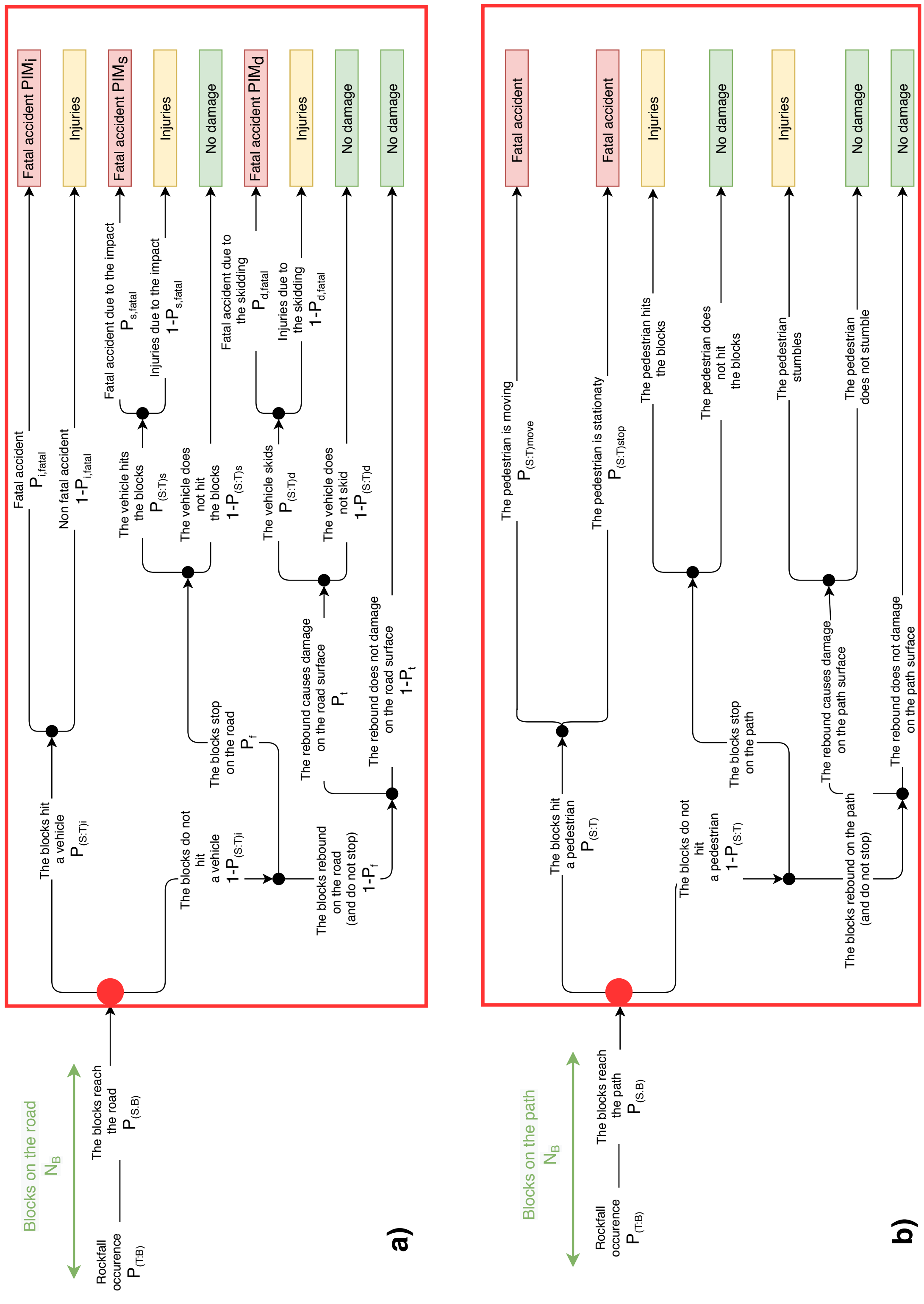

Figure 1. Proposed mixed QRA and ETA method for persons in a vehicle on a road (a) and pedestrians on a path (b). The red panes highlight the tree structures of the ETA from the occurrence of the initiating event, i.e. the block reaching the road or the path, represented by the red bullets.

In general, different traffic conditions, in terms of $n_{v/h}$ or maximum allowable velocity of the vehicle V_v, can be achieved during the year, especially in case of mountainous road, often closed or with traffic limitations during winter. To consider all the j-th traffic conditions during the year, for the mathematical properties of the ETA, all the PIM_i^j are summed. The same procedure is adopted for the other two scenarios with possible fatalities. Considering the notation reported in Figure 1, the temporal spatial probability that a vehicle impacts against a stopped block can be obtained by:

$$P_{(S:T)_s} = P_{(T:P)_{s,1}} P_{(S:P)_{s,1}} n_{v/h} n_h, \tag{10}$$

where:

$$P_{(S:P)_{s,1}} = \frac{\min\left(L_{va}, L_v, l_k\right)}{l_k}, \tag{11}$$

with

$$L_v = \frac{V_v}{n_{v/h}} 1000, \tag{12}$$

where L_{va} is the decision sight distance in meters, and V_v, the vehicle speed in kilometers per hour. $P_{(T:P)_{s,1}}$ can be computed with the same equation as $P_{(T:P)_{i,1}}$, Eqn.(7).

As mentioned above, the probabilities $P_{s,fatal}$ and $P_{d,fatal}$ can be computed from the annual statistics of fatal accident for similar type of road and causes. It results:

$$PIM_s = \left(1 - P_{(S:T)_i}\right) P_f P_{(S:T)_d} P_{s,fatal}, \tag{13}$$

and

$$PIM_d = \left(1 - P_{(S:T)_i}\right) \left(1 - P_f\right) P_t P_{(S:T)_d} P_{d,fatal}, \tag{14}$$

where $P_{(S:T)_d}$ can be computed as $P_{(S:T)_s}$. Inserting in Eqn. (4) the single contributions reported in Eqns. (9), (13) and (14), summed up for each j-th traffic condition, the annual probability of having a fatality on the k-th portion is obtained. It implicitly holds that the annual frequency of an event on the portion is one (event per year).

A similar approach can be adopted considering pedestrians. In this case the procedure can be simplified accounting for the fact that the pedestrian is able to see a stopped block or a damaged surface. A fatality occurs in case of impact, only. Both the cases of a pedestrian walking along the path with a velocity V_p, or having a rest for a while (t_{rest}) are computed. In the last case, t_{rest} is substituted to t_t in Eqn. (7).

2.3. *Merging QRA & ETA*

As previously stated, the ETA approach starts from considering the occurrence of an initiating event, in the present case the block reaching the road. This is characterized by a certain occurrence probability in space and time, which can be assessed to evaluate the risk. The risk can be computed through Eqn. (3) as:

$$R = \sum_{k=1}^{n} \left(P^k_{(T:B)} P^k_{(S:B)} PIM^k \right). \tag{15}$$

The estimation of $P^k_{(T:B)}$, which refers to the frequency of blocks released in the source area, is generally difficult to achieve. On the contrary, information on past events is typically related only to those phenomena which have affected sensitive structures or infrastructures, and thus, only the blocks reaching the road are recorded. From a catalogue of past events, the annual number of blocks reaching the road N_B is determined. Data of past events can be generally related to a section of road rather than to the whole track or a specific point. The authors suggest to extend the recorded data, and thus, the computed N_B to all the portions of road a block can reach from the source zone, once determined. To attain this goal and to produce a more accurate evaluation of the hazard, the authors suggest to perform trajectory analyses, aiming at evaluating not only the extension of the affected area, but also the reaching probability $P^k_{(S:B)}$ for k-th portion of the road. In this way, a frequency N^s_B, i.e. the frequency of events on a given s-th portion, can be evaluated as:

$$N^s_B = \frac{P^s_{(S:B)} l_s}{\sum_{k=0}^{n} \left(P^k_{(S:B)} l_k \right)} N_B. \tag{16}$$

In other words, the frequency is distributed according to the reach probabilities on the path. Then, merging the QRA and ETA approach, the initiating events can be considered as Bernoulli trials, i.e. simple experiments with a random binary outcome (Agliardi, Crosta, and Frattini 2009), and thus, according to Hungr et al. (1998), it can be stated that the risk expressed as annual probability to have a fatal accident, for a given road is:

$$R = \sum_{k=1}^{n} \left[1 - \left(1 - PIM^k \right)^{N^k_B} \right]. \tag{17}$$

For N^k_B less than 100, and PIM^k less than 10^{-3}, performing a McLaurin series expansion, Eqn. (17) can be approximated as:

$$R = \sum_{k=1}^{n} \left(N^k_B PIM^k \right). \tag{18}$$

For greater values of N^k_B, or higher values of PIM^k, the percentage difference between the results obtained with Eqn. (17) and those with Eqn. (18) is greater than 4% and, thus, considerably significant.

The proposed method can serve also to stakeholders to manage the risk and (i) make decision in restricting the traffic, or (ii) predispose protective mitigation measures, predict the risk reduction and decide the priorities of intervention. In the former case, chosen an acceptable level of risk, the allowable traffic can be evaluated, in terms of number of vehicles or passages allowed during the year or in a specific period, or in terms of minimum or maximum velocity required. In the latter case, once located and designed the passive works, new propagation analyses can be performed, evaluating a new spatial reaching probability $P^k_{(S:B),new}$. Considering that passive systems do not affect the released zones, the annual frequency of block reaching the portion of road $N^k_{B,new}$ is:

$$N^k_{B,new} = \frac{P^k_{(S:B),new}}{P^k_{(S:B)}} N^k_B. \tag{19}$$

Thus, the risk can be re-evaluated through Eqn.(18) and, therefore, the effectiveness of the mitigation measures can be assessed.

3. Example

The presented study case deals with the assessment of the rockfall risk for life loss along two roads and a pedestrian path in a mountainous area. As protective measures cannot be adopted, the proposed method was adopted to quantify the level of risk for different traffic conditions, in order to manage the access to the pedestrian path and to control the road traffic, once defined the acceptable risk threshold. The study area is located in the North Western Italian Alps, in a mountainous area affected by rockfalls of different magnitude and intensity as reported in the local landslide inventory.

3.1. *Geomorphological setting*

The regional geological and structural setting of the study area is characterized by rocks belonging to the Piedmontese Calcescist Zone with green stones that are covered by quartzites, marbles and mycascists, consisting of two main groups of ophiolitic units. In the area under examination, the rocks of the Zermatt-Saas eclogitic units mainly outcrop, consisting of dominant ophiolites and metasedimentary covers, with widespread eclogitic relicts and metamorphic overprint in green schist facies, from incipient to complete. Often there are extensive sequences of ophicalci, well exposed in numerous quarries, possible evidence of tectonic denudation processes of the mantle (Dal Piaz et al. 2010) From a structural point of view, the valley has an East-West direction and is set along a tectonic depression of Oligogenic Age. The fault, direct E-W, constitutes a tectonic system about 2 km wide that develops defining an asymmetrical graben. A detailed topographic survey was performed to investigate and characterize the area through photogrammetric helicopter surveys. Laser scanners were taken from the opposite side of the valley in order to detect and characterize the rock mass in the study area, limiting the shadow zones as much as possible and reducing the disturbance of the abundant vegetation along the slopes. The data were processed and elaborated in order to define the possible source areas of possible detachment (most fractured areas, past events source zones, unstable blocks). Even though the slope under study is characterised by the outcrop of different geological units, all sectors are affected by the same main systems of discontinuity, even if they may be more or less represented according to the different orientation of the outcrops. The potential mechanisms that could give rise to instability phenomena were identified by performing kinematic analyses, and an homogeneous trend was observed in all sectors, considering the similarity of the geomechanical (friction angle), structural (location of discontinuity families) and morphometric (location of slopes) context of the area under investigation. The most fractured zones, where sliding and toppling mechanisms were observed, were identified. Additionally, from the surveys, a distribution of the volumes and the of the potentially unstable blocks was evaluated. Figure 2.a reports the identified source zones, from which propagation analyses were performed, considering the different possible released volumes. In this particular context, with the assumption that any block of any size or velocity hitting a pedestrian or a vehicle causes a damage, the performed propagation analyses aimed at evaluating the worst scenario in terms of reach probability, starting from the detachment of blocks of any possible volume defined from the surveys, neglecting the return period associated to each volume.

The propagation analyses were performed with the 3D code Rockyfor3D (Dorren 2015), with a digital elevation model with a grid 1x1 m, considering 5k runs per cell as a statistically representative sample of simulations. Consequently, the reach probability $P_{(S:B)}$ was defined for the entire study area.

The investigated elements at risk are two roads: a high traffic path (R1) and a local route (R2), and a pedestrian path (P1). The reach probability was individuated for each element, discretised in 1 m-long portions (Figure 2.b).

3.2. *Inputs of the analysis*

The catalogue of past rockfall events occurred in the study area was used to determine the annual frequency of possible arrival on the road. The historical data allowed the localization of the deposit areas of past phenomena and, thus, the path was divided into sections of homogeneous temporal occurrence probabilities (Figure 2.c). Considering the South exposure of the area and its altitude, the roads are kept open all the year round, without seasonal difference in the traffic condition, i.e. n_h is equal to 8760 hours, that is one year.

Table 1 and Table 2 report the adopted input data for the analysis. The maximum allowable velocity was considered as representative of the velocity of the vehicle depending on the usual safety limits. The decision sight distance was evaluated according to (MIT 2001) on the basis of the type of road, the velocity, and the slope of the road. For a pedestrian the velocity was computed as function of the mean slope of the path of 20% (Márquez-Pérez, Vallejo-Villalta, and Álvarez-Francoso 2017). Precautionary, four occupants per vehicle were assumed in the calculation, resulting in a C_p equal to 1.85 (Mignelli, Lo Russo, and Peila 2012). The probability of stop or rebound on the infrastructure was computed through the performed trajectory analyses, while P_t was assumed equal to 0.2 according to the annual statistics of damaged surface for impacting element following the procedure suggested by Peila and Guardini (2008). The probability of fatal accident for impact on a stopped block $P_{s,fatal}$ or due to the damaged surface $P_{d,fatal}$ were estimated analyzing the statistics of the last ten years for fatality occurred for impact against an obstacle, or for damaged surface or avoided obstacles, respectively (http://dati.istat.it/).

The considered statistical data refer to high traffic road for R1 and to urban road for R2.

3.3. *Results and Discussion*

The analysis method explained in Sec. 2 was implemented to define the allowable traffic conditions, in terms of number of vehicles or pedestrians per hour, in the hypothesis

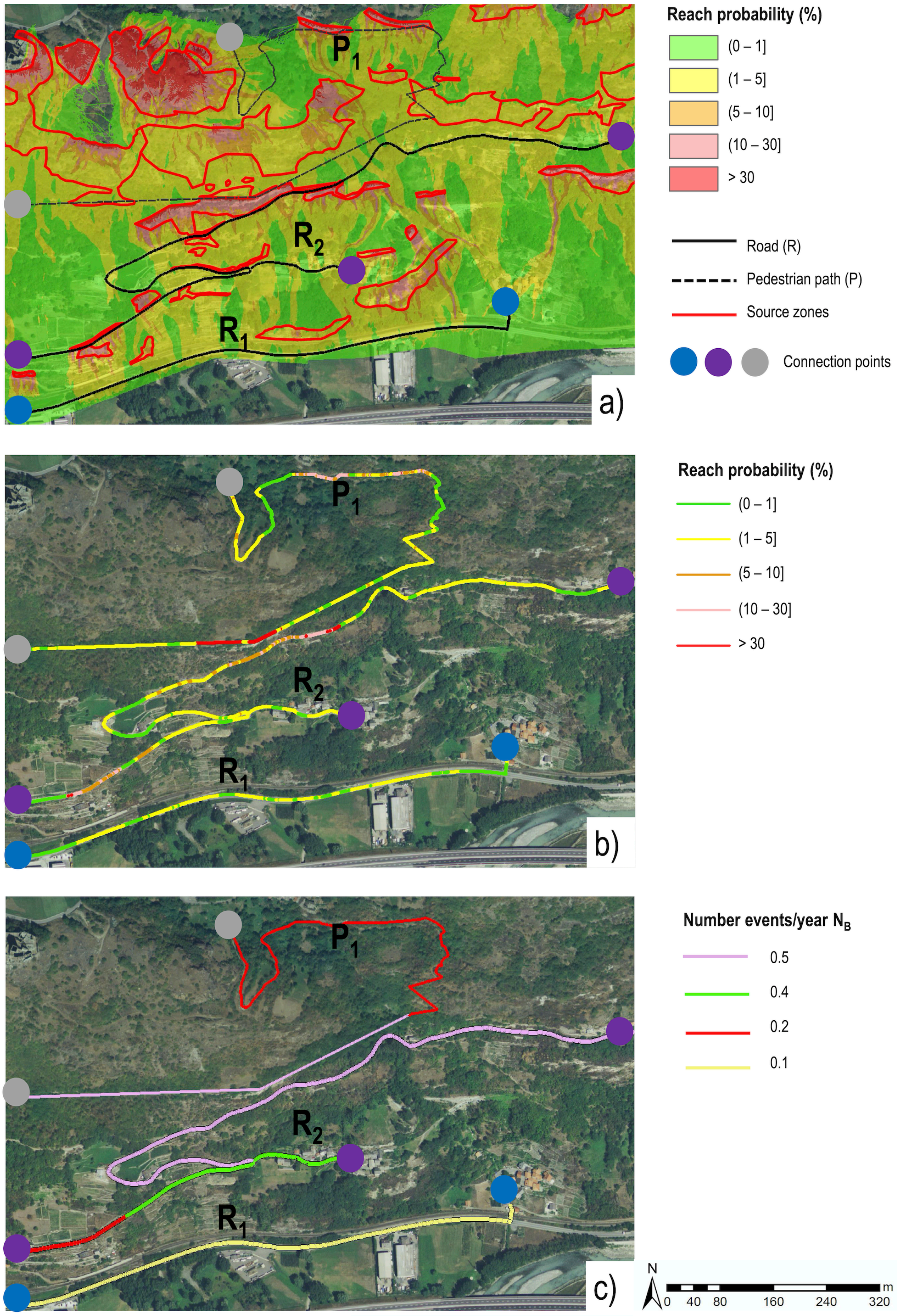

Figure 2. In (a): identification of the source zones for the propagation analyses and resulting reaching probabilities $P_{(S:B)}$. In (b): reaching probability $P^k_{(S:B)}$ for each k-th point of the roads R1 and R2 and the pedestrian path P1. In (c): number of blocks per year reaching a section of the roads or of the pedestrian path N_B, derived from recorded data from past events.

Table 1. Input data for the assessment of the risk for the roads R1 and R2.

Input data	R1	R2
V_v (km/h)	70	30
L_v (m)	5	5
L_{va}	100	30
C_p (-)	1.85	1.85
$P_{i,fatal}$ (-)	0.2	0.2
P_f (-)	0.5	0.5
$P_{s,fatal}$ (-)	0.041	0.035
P_t (-)	0.2	0.2
$P_{d,fatal}$ (-)	0.026	0.018
L_{road} (km)	1.841	0.984

Table 2. Input data for the assessment of the risk for the pedestrian path P1.

Input data	P1
V_p (km/h)	4.5
L_p (m)	0.6
t_{rest} (h)	0.05
L_{path} (km)	1.687

of an homogeneous use of the roads during the year, given a value of R. The choice of an acceptable threshold value constitutes a crucial aspect in the analysis and this aspect, unavoidable to manage the risk, is still under debate in the scientific community (Enright 2015).

With reference to landslides, Reid et al. (1989) report an interesting comparison between voluntary and involuntary risks, and Starr (1969) asserts that the average magnitude of the discrepancy between voluntary and involuntary risk is estimated in three orders of magnitude, due to the fact that voluntary risks are usually accompanied by the perception by the individual of being able to manage in such a way the risk scenario. Furthermore, it is considered that the risk associated with a landslide on a slope on which no action has been taken is more tolerable than the risk associated with a landslide on a slope onto which engineering works have been taken. The suggested value of acceptable risk is 10^{-3} per year (ANCOLD 1992; Fell 1994), while when a monitoring system has been installed on a landslide slope without any stabilizing intervention, the suggested value of acceptable risk is 10^{-5} per year. This reduction follows the fact that it is believed that the risk associated with a landslide on a slope on which no intervention has been done is more tolerable than the risk associated with a landslide on a slope on which engineering works have been done (Fell 1994).

Figure 3 displays the obtained results, while Table 3 reports the maximum hourly traffic for R equal to 10^{-6}, 10^{-5}, 10^{-4}, and 10^{-3}. It can be noticed that the maximum affordable traffic is higher in road R1 than in R2 since in the former the exposure is less as vehicles speed is higher and the number of events N_B is smaller. In this particular case, it is seen that a traffic value for which it results $R = 10^{-3}$ cannot be considered since the capacity of road R1 is reached.

In the case of R2, the resulting $N_{v/h}$ is very low, and, for the pedestrian path, the minimum risk is $R = 10^{-4}$. Nevertheless, it must be noticed that several k-th portions of both R2 and P1 display quite high annual frequency of events N_B, i.e. 2 events per

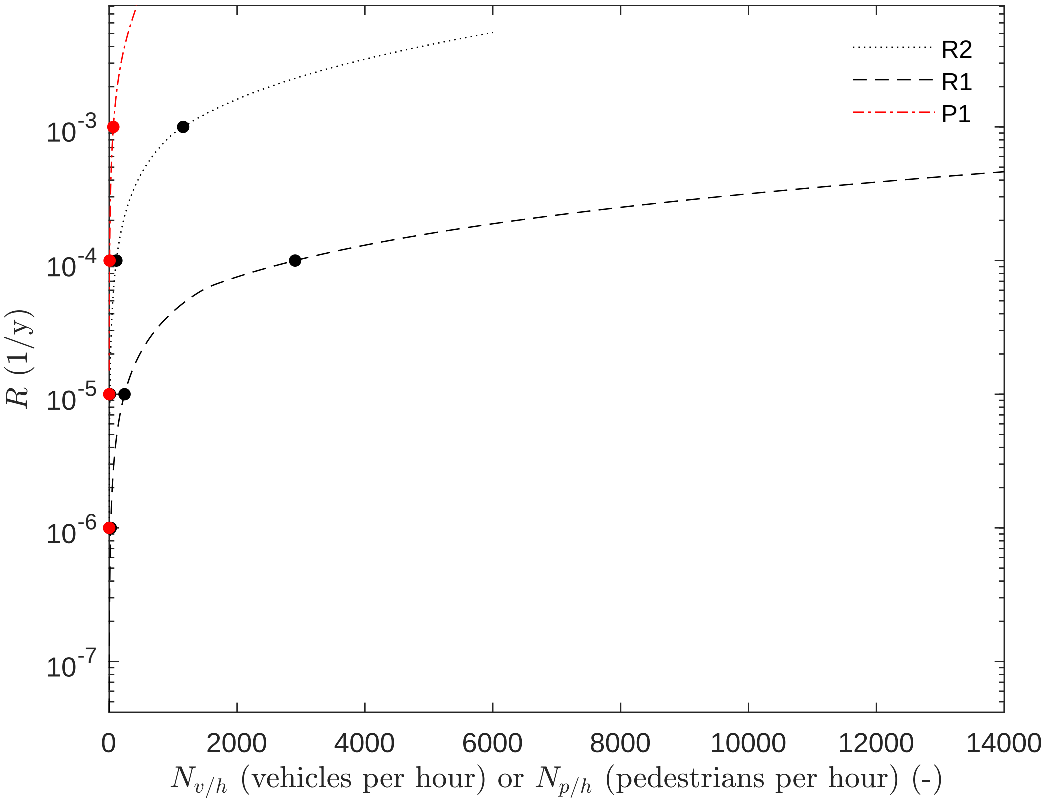

Figure 3. Allowable number of vehicles $N_{v/h}$ or pedestrians $N_{p/h}$ per hour for different value of annual probability of fatality R, for the roads R1 and R2 and for the pedestrian path P1. The circular markers refer to the values of R equal to 10^{-6}, 10^{-5}, 10^{-4}, reported in Table 3.

year.

The plots of the reaching probability $P_{S:B}$ (Figure 2.b) represent a profitable solution to understand the priority of intervention along the road or path for the decision makers.

4. Conclusions

The effects of rockfall hazard on transportation corridors both for car or pedestrian traffic influence the risk management policies of the Authorities and, consequently, the possibility of transit and access to mountain settlements. A quantitative assessment of the risk, in terms of number of fatalities per year, is often required by the stakeholders in order to define a priority list of interventions for risk mitigation. Among the quantitative methods, QRA and ETA are widely employed. Nevertheless, the former is more suitable for static element, i.e. with a unitary exposure, while ETA starts from the occurrence of an event, disregarding its frequency. An integrated QRA-ETA solution, tailored for vehicles and pedestrians, has been presented and discussed. All the possible scenarios and outcomes have been outlined. A unitary vulnerability is considered, with the precautionary assumption that any block of any size or velocity hitting a pedestrian or a vehicle causes damages. As the historical data on past events generally lack

Table 3. Different traffic conditions in terms of number vehicles or pedestrians per hour according to different threshold of acceptability in terms of annual probability of fatal accident R, for the roads R1 and R2 and for the pedestrian path P1.

R (1/y)	R1 ($N_{v/h}$)	R2 ($N_{v/h}$)	P1 ($N_{p/h}$)
10^{-6}	23	1	0
10^{-5}	239	11	0
10^{-4}	2908	112	6
10^{-3}	(-)*	1156	64

$*$ the maximum allowable number of vehicle passing hourly has been reached and the correspondent annual probability of fatal accident is less than 10^{-3}.

in accuracy, the proposed method allows to distribute the temporal occurrence probability also as function of the reaching probability defined through trajectory analyses. The method permits to quantify the annual risk for different levers of traffic of vehicles or pedestrians. For these latter, also the rest condition is considered. Vice versa, once defined the acceptable risk level, the maximum number of vehicles/pedestrians per hour (or per year) can be evaluated. Moreover, the method can be adapted considering passive protective measures to mitigate the risk. Performing new propagation analyses, through the variation in reaching probability of blocks on the road, it is possible to evaluate the risk reduction and thus, delineate the priority of intervention.

A study case in the North Western Italian Alps is introduced, and, for different annual probabilities of fatality, the maximum allowable traffic is computed. As the definition of an acceptable threshold for the risk is difficult to achieve, the maps of the reaching probability, together with the number of block reaching the road, derived from recorded past events, are fundamental to define a priorities in a list of interventions. Further development can account for the possibility of mutual interference between pedestrians and vehicles, e.g. in case of a farm road. Additionally, for each different context a precise estimation of the probabilities or other input parameters, i.e. stopping sight distance, can be performed.

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Authors’ contribution

M. Marchelli (M.M.) and V. De Biagi (V.D.B.) developed the theory and D. Bertolo (D.B.) and M. Paganone (M.P.) provided critical feedback and supported for the study case; M.M. performed the numerical analyses and wrote the final version of the manuscript with the help of V.D.B.; D. Peila (D.P.) supervised the project.

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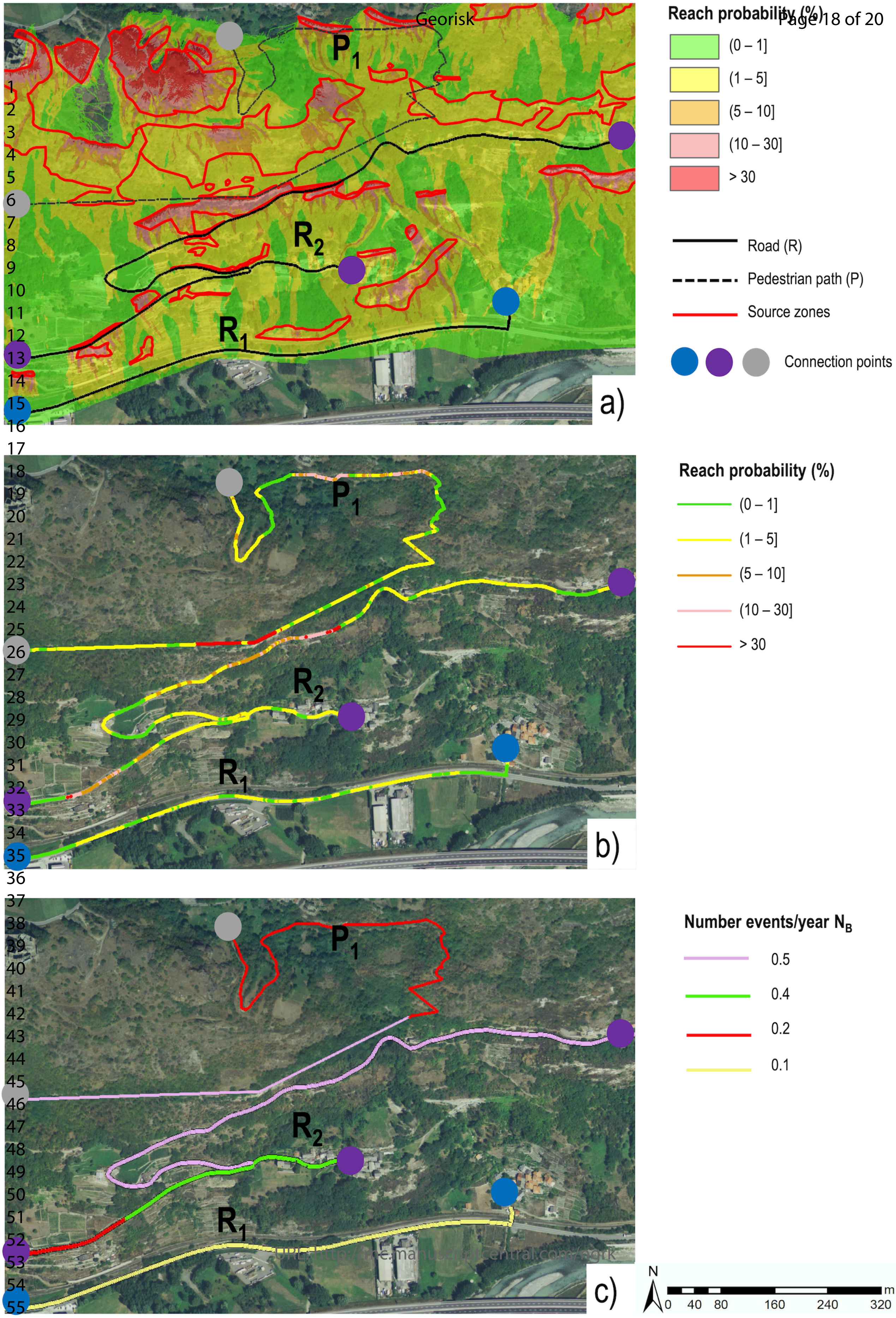
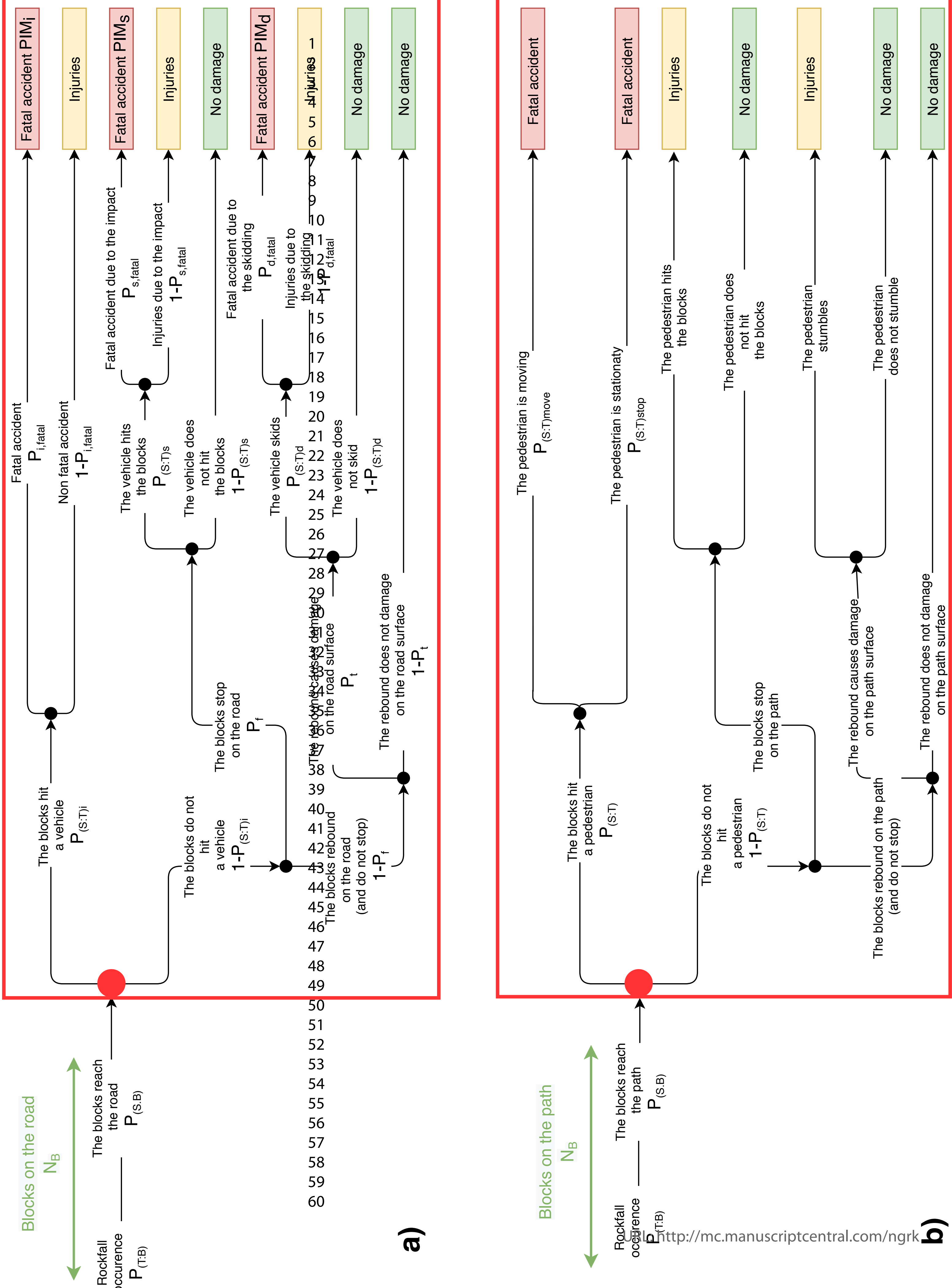
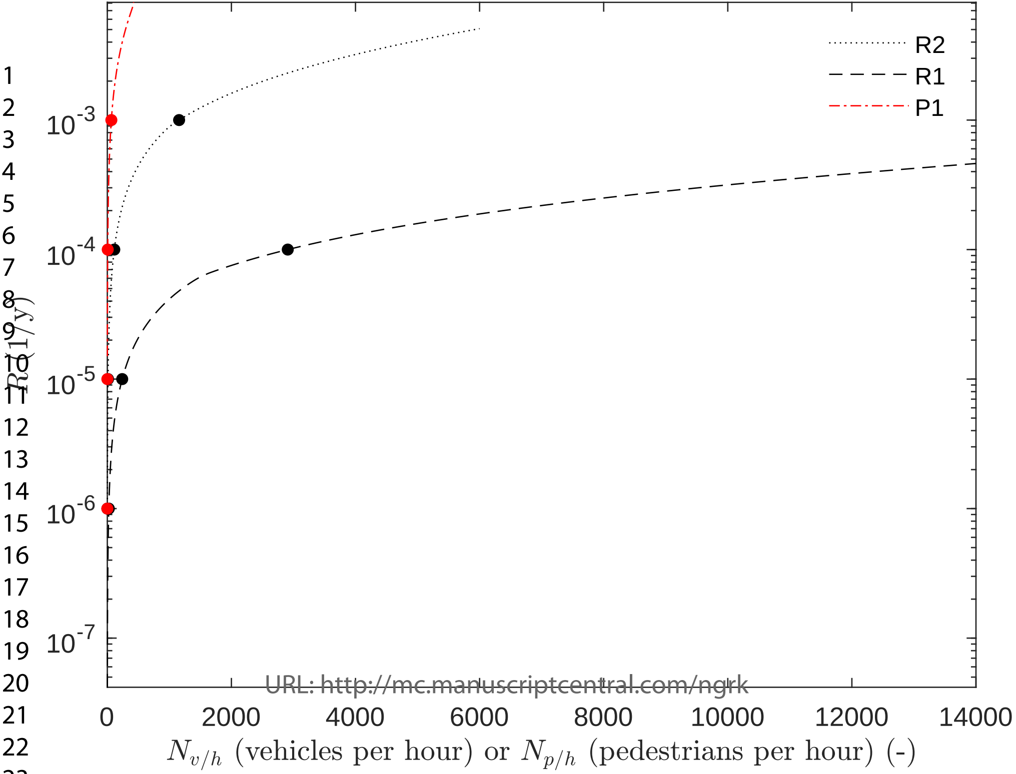

Reach probability (%)
(0 – 1]
(1 – 5]
(5 – 10]
(10 – 30]
> 30
Road (R)
Pedestrian path (P)
Source zones
Connection points
P1
R1
R2
a)
Reach probability (%)
(0 – 1]
(1 – 5]
(5 – 10]
(10 – 30]
> 30
b)
Number events/year NB
0.5
0.4
0.2
0.1
c)
N
0 40 80 160 240 320
m



Blocks on the road
N_B
Rockfall occurence
$P_{(T:B)}$
The blocks reach the road
$P_{(S.B)}$
The blocks hit a vehicle
$P_{(S:T)i}$
Fatal accident
$P_{i,fatal}$
Fatal accident PIM_i
Non fatal accident
$1-P_{i,fatal}$
Injuries
The blocks do not hit a vehicle
$1-P_{(S:T)i}$
The blocks stop on the road
P_f
The vehicle hits the blocks
$P_{(S:T)s}$
Fatal accident due to the impact
$P_{s,fatal}$
Fatal accident PIM_S
Injuries due to the impact
$1-P_{s,fatal}$
Injuries
The vehicle does not hit the blocks
$1-P_{(S:T)s}$
No damage
The blocks rebound on the road (and do not stop)
$1-P_f$
The rebound causes damage on the road surface
P_t
The vehicle skids
$P_{(S:T)d}$
Fatal accident due to the skidding
$P_{d,fatal}$
Fatal accident PIM_d
Injuries due to the skidding
$1-P_{d,fatal}$
Injuries
The vehicle does not skid
$1-P_{(S:T)d}$
No damage
The rebound does not damage on the road surface
$1-P_t$
No damage
a)
Blocks on the path
N_B
Rockfall occurence
$P_{(T:B)}$
The blocks reach the path
$P_{(S.B)}$
The blocks hit a pedestrian
$P_{(S:T)}$
The pedestrian is moving
$P_{(S:T)move}$
Fatal accident
The pedestrian is stationaty
$P_{(S:T)stop}$
Fatal accident
The blocks do not hit a pedestrian
$1-P_{(S:T)}$
The blocks stop on the path
The pedestrian hits the blocks
Injuries
The pedestrian does not hit the blocks
No damage
The blocks rebound on the path (and do not stop)
The rebound causes damage on the path surface
The pedestrian stumbles
Injuries
The pedestrian does not stumble
No damage
The rebound does not damage on the path surface
No damage
b)


R2
R1
P1
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
R (1/y)
0
2000
4000
6000
8000
10000
12000
14000
$N_{v/h}$ (vehicles per hour) or $N_{p/h}$ (pedestrians per hour) (-)