



# A new rating system for hydrogeological risk management along railway infrastructures in Prealpine zone (northern Italy)

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## Abstract

Railway infrastructures in mountain areas often develop along hillslopes affected by geomorphological and hydrogeological processes which might lead hazardous events. Therefore, specific tools for risk analysis and management are required. This paper develops a new rating system (Railway Hydrogeological Management System, RHMS), based on a heuristic method which considers the susceptibility to different types of slope instabilities, as well as the peculiar features affecting the railway vulnerability. The proposed method introduces an iterative approach for the risk assessment, based on the definition of acceptability thresholds for the residual risk. The application of this method to a test area pointed out its feasibility, as well as its operational capability to identify the critical sections of the infrastructure, in which protection or mitigation measures are needed in order to reduce the risk.

**Keywords** Heuristic approach · Hydrogeological hazard · Intervention priority · Railway infrastructure · Risk assessment

## Introduction

At present days, effective maintenance procedures for transport linear infrastructures (i.e. highways and railways) have to be optimised in order to provide high levels of safety, with peculiar concern over the economic issues [1]. More specifically, the transport infrastructures belonging to mountain areas are often affected by hydrogeological hazards, arising from geomorphological processes, such as slope instabilities or river dynamics. These events can pose a serious danger for travellers, but they can also involve significant maintenance costs, as well as service and operation interruptions. Therefore, proper methods for hydrogeological risk analysis and management have to be defined in order to identify the critical situations and then to plan protection and mitigation measures.

A quantitative analysis for the geological and hydrogeological risk assessment [2] should be based on the statistical

assessment of both the geological hazard and the vulnerability of the infrastructure. Moreover, the economic value of the elements at risk should be considered.

Although quantitative risk analysis has become quite common in landslide risk management, for linear infrastructures these methods show some disadvantages, mainly connected to the lack of data, as well as to the high level of uncertainty usually affecting the available information [3]. Actually, linear infrastructures often cross environments which are very heterogeneous from a geological and geomorphological point of view, therefore involving different kinds of hazardous events, spanning from rock falls to soil slips, from floods to bank erosion. A quantitative hazard assessment for these events should be carried out at very large scale by using specific statistical tools [4]. This kind of quantitative assessment is quite time and data consuming; therefore, it is essential a prior identification of those sections in which the potential risk is higher than an acceptability threshold. The present technical note deals with this preliminary phase of qualitative risk analysis, and it is aimed at defining a rating method for identifying a relative scale of the hydrogeological risk along railways.

Over the last decades, many risk assessment systems have been proposed in order to identify hazardous slopes along highways and then prioritise the proper mitigation measures ([5, 6] and references therein). One of the most

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well known of these systems is the Rockfall Hazard Rating System (RHRS, [7]), which is a qualitative risk assessment system for rock fall risk management. The main advantage of this method is its ability to join both the geological and infrastructure features within a standard ranking system, in which the knowledge from different experts is exploited [8]. Unfortunately, at present no method has been proposed for considering all types of landslide which can affect linear infrastructure corridors, neither specific methods for hydrogeological risk management along railways. One of the very few examples refers to hazard assessment of rainfall-induced landslides [9].

Moreover, when dealing with railway infrastructures the vulnerability assessment should take into account for the transit frequency and the response time of the system to dangerous events, which on its turn depends on the infrastructure features, as well as on the train type and load. This latter should also take into account for the crowding conditions, that is a time dependant (daily, weekly and seasonally) parameter quite difficult to evaluate. Finally, the infrastructure management needs the definition of risk acceptability thresholds, which is often one of the most critical elements in the risk analysis. In the present study a first attempt was made in order to introduce these elements in the hydrogeological risk analysis along railways. Actually, this study develops a heuristic method for the hydrogeological risk management along railways in mountain areas; the proposed method takes into account for different kinds of geological and hydrogeological hazards and for the vulnerability of the infrastructure, with the definition of specific parameters describing the railway risk exposure. The method was applied to a 20 km long infrastructure belonging to FerrovieNord S.p.a., located in the Prealpine area of northern Italy.

## Methods and materials

### Methodological approach

The proposed approach is named Railway Hydrogeological Management System (RHMS) and it is a risk rating system aimed at providing a comparison of the hydrogeological risk conditions among different sections along a railway infrastructure, in order to facilitate a prioritisation of the follow-up actions. The method modifies the existing method RHRS for highways [6] in order to introduce different kinds of hydrogeological hazards, as well as to adapt the method to the typical characteristics of the railway infrastructures.

RHMS develops through the following main steps:

1. Creation of a database with technical, geological, hydrogeological and morphological data;
2. Assessment of the hydrogeological susceptibility (S), with the identification of 5 classes of potential hazard (from very low to very high);
3. Assessment of the infrastructure vulnerability (V), with the identification of 5 classes (from very low to very high);
4. Risk and residual risk assessment and management.

In order to apply this method, a georeferenced database is needed, containing all geological, morphological, hydrogeological and technical data of each section of the infrastructure. Table 1 summarises all the parameters useful for the assessment of both the hydrogeological susceptibility and the infrastructure vulnerability.

The assessment of the hydrogeological susceptibility takes into account for geological, geomorphological and

**Table 1** Parameters for the susceptibility (from  $x_1$  to  $x_7$ ) and vulnerability (from  $x_8$  to  $x_{10}$ ) with the corresponding normalised indexes

| Parameter              |   | Normalised index   |
|------------------------|---|--|
| Mapped hazards         | MH (Table 2a)   | $x_1 = \frac{MP - MP_{min}}{MP_{max} - MP_{min}} \log_3 100$     |
| Previous instabilities | PI (Table 2b)   | $x_2 = \frac{PI - PI_{min}}{PI_{max} - PI_{min}} \log_3 100$     |
| Geological conditions  | RMR [10] for rock masses  | $x_3 = \frac{RMR_{max} - RMR}{RMR_{max} - RMR_{min}} \log_3 100$ |
|                        | SC (Table 2c) for soils   | $x_3 = \frac{CG_{max} - CG}{CG_{max} - CG_{min}} \log_3 100$     |
| Slope height           | SH (m)  | $x_4 = \frac{SH - SH_{min}}{SH_{max} - SH_{min}} \log_3 100$     |
| Slope angle            | SA (°)  | $x_5 = \frac{SA - SA_{min}}{SA_{max} - SA_{min}} \log_3 100$     |
| Water                  | W (Table 2d)  | $x_6 = \frac{W - W_{min}}{W_{max} - W_{min}} \log_3 100$         |
| Vegetation cover       | VC (Table 2e)   | $x_7 = \frac{VC - VC_{min}}{VC_{max} - VC_{min}} \log_3 100$     |
| Transit frequency      | $TF = \frac{\text{no. trains/h}}{\text{speed}_{\frac{km}{h}}} \text{lenght}_{[km]}$ | $x_8 = \frac{TF - TF_{min}}{TF_{max} - TF_{min}} \log_3 100$     |
| Distance from signals  | DS (km)   | $x_9 = \frac{DS_{max} - DS}{DS_{max} - DS_{min}} \log_3 100$     |
| Slope distance         | SD (m)  | $x_{10} = \frac{SD_{max} - SD}{SD_{max} - SD_{min}} \log_3 100$  |

hydrogeological parameters, as well as for the presence of previous instabilities or mapped hazards. Actually, the first three parameters in Table 1 mainly have a geological relevance:

- Mapped hazard (MH) accounts for the geological and hydraulic processes (landslides, active fans, river erosion, flooding, etc.) identified and mapped by previous studies in a buffer 500 m wide around the railway axis (Table 2a);

- Previous instability (PI) refers to hazard events (such as rock falls and embankment failures) already occurred in the past, which may have directly affected the railway infrastructure (Table 2b);
- geological condition is a parameter depending on the geo-material characterising the ground on which the railway develops; if the ground is constituted by rock masses, the index is based on the Rock Mass Rating (RMR) by Bieniawski [10]; indeed, the international literature provides other more complete classification systems, such as

**Table 2** Classes of values for the qualitative parameters listed in Table 1: (a) mapped hazards (based on previous studies); (b) previous instability (PI) (based on on-site surveys); (c) size classification

(SC) for soils (based on American Standard for Testing and Materials ASTM [11]); (d) water (W) (based on on-site surveys); (e) vegetation cover (VC) (based on on-site surveys)

| (a) Degree of mapped hazard                                | MH           |         |
|--|--------------|---------|
| Very high hazard (active landslide, active fan, etc.)      | 3            |         |
| High hazard (suspended landslide, partly active fan, etc.) | 2            |         |
| Low hazard (stabilised landslide, not active fan, etc.)    | 1            |         |
| No hazard  | 0            |         |
| (b) Previous instabilities                                 | PI           |         |
| Embankment failure (with railway affected)                 | 3            |         |
| Embankment failure (with railway not affected)             | 1.5          |         |
| Rock fall (with railway affected)                          | 2            |         |
| Rock fall (with railway not affected)                      | 1            |         |
| Soil slide (with railway affected)                         | 2            |         |
| Soil slide (with railway not affected)                     | 1            |         |
| Fall of vegetation (with railway affected)                 | 1            |         |
| Fall of vegetation (with railway not affected)             | 0.5          |         |
| No previous instability                                    | 0            |         |
| (c) Soil classification                                    | SC           |         |
| Sands or gravels and pebbles                               | 4            |         |
| Sands and gravels  | 3.5          |         |
| Sands  | 3            |         |
| Silty or clayey sands                                      | 1.5          |         |
| Clays  | 0            |         |
| (d) Water  | W            |         |
| Run-off  | 3            |         |
| Spring   | 2            |         |
| Ponding  | 1            |         |
| Dry  | 0            |         |
| (e)  | VC           |         |
| Vegetation cover   | In rock mass | In soil |
| Trees with roots   | 3            | 0       |
| Dense shrubs   | 2.5          | 0.5     |
| Sparse shrubs  | 2            | 1       |
| Weed   | 1.5          | 1.5     |
| Lawn   | 0            | 2       |
| No vegetation  | 1            | 2.5     |

the Romana system [11], widespread used for landslide hazard assessment in rock masses [12]; yet, in the present study the simplest Bieniawski method was used in order to make the period for the on-site surveys compatible with the operational needs of the infrastructure; if the ground is composed by soil deposits, the index is based on the traditional grain size classification (SC) adopted by the American Standard for Testing and Materials [13] (Table 2c).

The two following parameters in Table 1 describe the geometrical and morphological conditions of the slope, specifically its height (SH) and its angle (SA); the values of these parameters correspond to those actually measured during the on-site surveys.

The last two indexes are relevant for the hydrogeological susceptibility to landslide; they are:

- the presence of water (W): it is detected and classified during the on-site surveys, by attributing a higher (unfavourable) value to those phenomena that involve water flowing and therefore possible erosion, which can trigger slope instabilities [14, 15] (Table 2d);
- the vegetation cover (VC): for this parameter it is necessary to distinguish its effects on rock masses from those on soil deposits (Table 2e); actually, in rock masses the growth of vegetation having a significant root system can bring about a widening of joints, unfavourable for the slope stability [16]; on the contrary, in soils the root system of plants can provide a cohesive effect, involving stabilising effects [17].

These seven parameters mainly refer to the geological and hydrogeological conditions of the area and they contribute to the assessment of the landslide hydrogeological susceptibility. The following three parameters listed in Table 1 are representative of some technical characteristics of the infrastructure, and they contribute in defining its vulnerability.

At this aim, the first index is the Transit Frequency (TF), that is a function of the number of trains and their speed; this parameter is borrowed from the Average Vehicle Risk used for assessing risk along roads [18], and it is representative for the probability that a train is passing through a section of the infrastructure at the time the dangerous event occurs.

Moreover, the distance from signals (DS) was considered as a parameter representative of the possibility of reporting a problem along the infrastructure: the greater the distance of a section from the signal that precedes it in the travel direction, the less the vulnerability of the infrastructure will be, both because there is sufficient space for stopping and because there is time to activate the signal system. Of course this possibility depends on the presence of a monitoring and

alert system, which can report in real time the presence of a problem along the route.

Finally, an index related to the railway ballast width was introduced; the Slope Distance (SD) is equal to the distance of the railway tracks from the adjacent slope edge, distinguishing the left and right side up to a maximum value of 15 m. Obviously, the greater the distance, the lower the vulnerability of the infrastructure to a hazard event.

As many of these parameters are qualitative, they have been divided into classes and a ranking has been assigned to each class based on its willingness to risk (Table 2). Actually, all these elements (even the qualitative ones) have to be quantified with a standard ranking system and afterwards summed up in order to obtain the risk index.

At this aim, all the parameters are normalised in between their maximum and minimum value (according to the equations in Table 1). Afterwards, to each normalised index  $x_i$  a ranking is assigned (in between 0 and 100) based on the following exponential equation:

$$y_i = x_i^3$$

Finally, the landslide hydrogeological susceptibility  $S$  (max value equal to 700) and the railway vulnerability  $V$  (max value equal to 300) are assessed through the two following equations:

$$S_{r,l} = \sum_1^7 y(x_i)$$

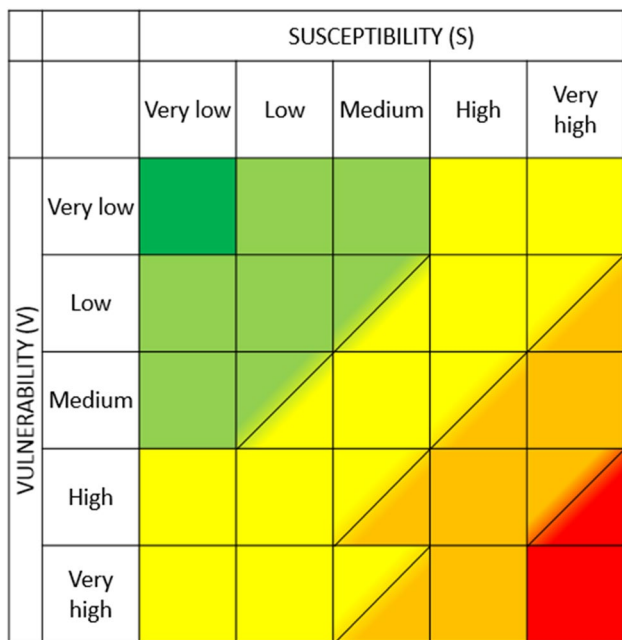
$$V_{r,l} = \sum_8^{10} y(x_i)$$

where  $x_i$  are the normalised indexes defined in Table 1 and  $y(x_i)$  are their rankings; the subscripts  $r$  and  $l$  identify the track of the railway based on the transit direction.

As a result, five classes of susceptibility and vulnerability are identified, based on which the risk ranking ( $R$ ) can be assessed, too. At this aim a matrix approach widespread used in heuristic methods for risk assessment was used [19] (Fig. 1).

By comparing the risk values in the different sections of the infrastructure, the critical situations can be identified in a relative scale. Actually, the risk ranking provides a relative evaluation which allows the identification along the route of those sections that are more critical than others. Within this relative scale, the manager of the infrastructure should define proper acceptability thresholds, based on economic and social issues. If the risk index exceeds the acceptability threshold ( $a_r$ ), protection or mitigation measures are needed as soon as possible in order to reduce the risk.

Moreover, a target threshold ( $o_r$ ) can be introduced as the goal to reach with long period planning (Fig. 2).



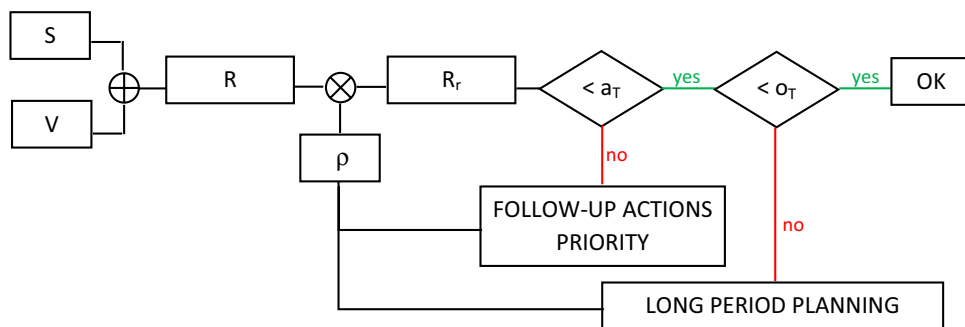
**Fig. 1** Matrix for risk assessment [19]: red colour corresponds to very high risk, whereas black green corresponds to very low risk

In order to introduce in the risk assessment tool the presence of protection and mitigation measures, the risk rating  $R$  can be corrected by multiplying it by a coefficient ( $\rho$ ) which takes into account for the presence, effectiveness and maintenance of protection (i.e. consolidation or draining systems) or mitigation (i.e. monitoring systems) measures (Table 3). In this way, a residual risk  $R_r$  can be pointed out.

The acceptability and target thresholds, as well as the values bounding the different susceptibility and vulnerability classes, have to be defined case by case, based on the distribution of the obtained values. At this aim, the following criteria are suggested for susceptibility and vulnerability:

- the median of the distribution should be in the 50% frequency class;

**Fig. 2** Iterative scheme for risk assessment, through test on the different thresholds of risk acceptability



**Table 3** Multiplier for the risk index correction in the presence of mitigation, protection or monitoring measures

| Mitigation or protection measures         | Multiplier $\rho$ |      |
|---|-------------------|------|
| Effectiveness                             | Maintenance       |      |
| Unfavourable (worsening the stability)    | Missing or poor   | 1.2  |
| Not present                               |                   | 1    |
| Partly effective                          | Missing or poor   | 0.83 |
| Partly effective                          | Good              | 0.66 |
| Favourable (well positioned and designed) | Missing or poor   | 0.5  |
| Favourable (well positioned and designed) | Good              | 0.33 |

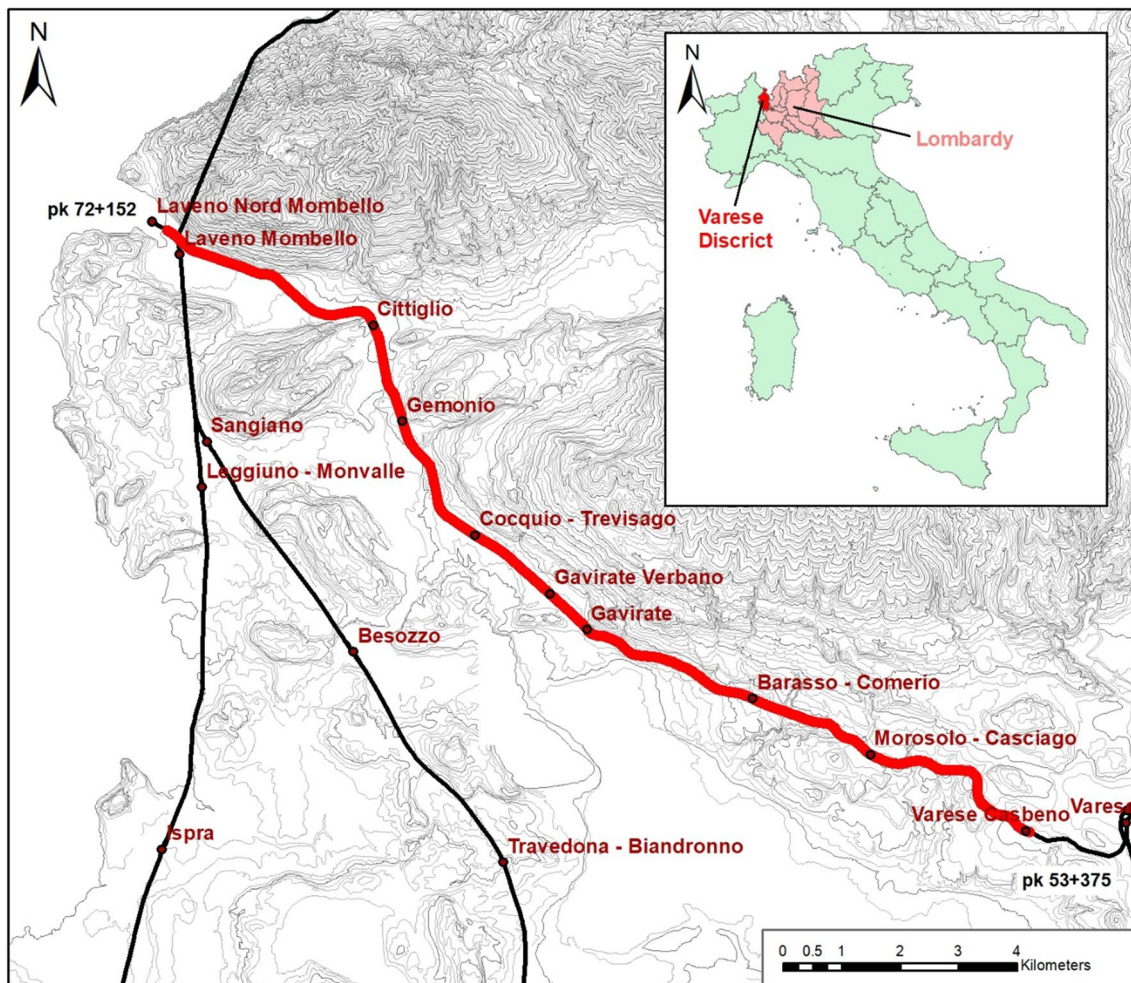
- the three classes identified as “high”, “moderate” and the sum of “low” and “very low” should have the same amplitude;
- the two extreme classes (“very high” and “very low”) should have a frequency equal to 5%.

Instead, the bounding values of the risk index should be defined by the sum of the bounding values of susceptibility and vulnerability, and they should be kept equal for both the initial and residual risk.

**The study area**

The study area is located in the Prealpine zone of northern Italy and more specifically in the Lombardy region. The railway infrastructure 19.780 km long and it develops with a SE-NW direction connecting the Varese Casbeno station (on the Varese Lake, pk 53 + 375) to the Laveno station (on the Maggiore Lake, pk 72 + 152), with an altitude ranging from 374 to 199 m a.s.l. (Fig. 3).

In the test area, the railway route spans over 10 municipalities and it passes through 7 stations (in addition to the departing and arriving ones); the infrastructure is mainly single rail, with rail switches and two or three platforms only nearby the stations. The railway route is straight for more



**Fig. 3** Location map of the railway infrastructure. In black the whole railway network is shown, whereas in red the studied route is highlighted (based on the DTM of the Lombardy Region <http://www.geoportale.regione.lombardia.it>)

than its half, with about 20% in trench and 20% in embankment. Moreover, 32 bridges and 19 water pipes are present. 39 trains run this route in a day (from 5:30 am to 11:00 pm), corresponding to an average frequency of 2.15 train/h. The type of train is always the same and the route speed is 70 km/h, corresponding to a quite low transit frequency.

From a geological point of view, the study area belongs to the Subalpine structural domain of Southern Alps [20], which is characterised by south-trending overthrusts and folds. It is mainly constituted by Triassic carbonate rocks (mainly dolomites and limestones, with marl intercalations) having a dip direction towards the South with a dip ranging in between 20° and 40°. The bedrock is locally covered by quaternary deposits, having glacial, fluvio-glacial or alluvial origin. These deposits are mainly constituted by sands and gravels in silty or clayey matrix [21]. Moraine hills are mainly W-NW ÷ E-SE trending. From pk 52 + 376 and pk 61 + 105 the infrastructure develops along the southern slope

of the Campo dei Fiori Massif, which is a carbonate massif characterised by an important karsts aquifer which supplies many springs.

From a hydrological point of view, the infrastructure crosses many rivers. They have mainly a N-S direction, and they are often responsible for local erosive phenomena, bringing about the bedrock outcropping, as well as slope instabilities.

### Data collection and on-site surveys

The available topographic, geological and geomorphological data were collected from several public agencies; then, these data were made homogeneous in order to create a proper database for the following risk analysis.

At this aim, the photogrammetric data of the infrastructure were overlaid on the topographic database (scale 1:1000) in a 500 m wide strip. Afterwards, the geological

map (scale 1:5000) was also overlaid, as well as data about geomorphological processes. These latter arise from studies previously carried out for land planning at the municipality scale (1:5000), as well as for the hydraulic risk management at the basin scale (1:10,000).

In addition to these data, detailed on-site surveys were carried out along the railway infrastructure. Field data were initially collected on Sects. 5 m long; afterwards, in order to optimise the size of the database with respect to its ability in describing the system heterogeneity, data were aggregated on homogeneous stretches, obtaining sections having a length ranging from 25 to 35 m, for a total number of 486 sections. For each section, a form was filled (Fig. 4), containing parameters related to both the infrastructure (i.e. wideness, type and shape, train speed, etc.) and the geological (i.e. lithology, rock orientation and strength, joint spacing, etc.), geomorphological (i.e. slope angle and height, slope distance, etc.) and hydrogeological (i.e. the presence of water with the corresponding characteristics) data, as well as information on previous instability phenomena (i.e. landslides, rock falls, erosive phenomena, etc.) and existing protection measures (i.e. nets, walls, draining devices, etc., with their conditions). Geometrical information (such as infrastructure wideness or slope height) was simply measured during the on-site surveys; other parameters are qualitative (such as the shape or kind of track, as well as the presence and type of water or vegetation) and they were recorded on the schedule by selecting the proper item in the form (see Fig. 4 for reference). Finally, the geological information was collected by means of traditional geological–technical surveys [22]; more specifically geo-structural and geomechanical surveys were carried out on rock slopes [23], whereas in soil deposits grain size analyses [13] were carried out in order to characterise the soil composition.

Data arising from the on-site surveys populated a geo-referenced database, useful for the following risk analysis and management.

## Results

### Database

Based on the data arising from the on-site surveys, the infrastructure mainly develops on soils (less than 2 km of the route develops on rock masses, corresponding to about the 10% of the total), and specifically on sands with pebbles (less than 1 km of the route develops on silty sands). Slopes have an average height of few metres (Fig. 5a), with very different dip angles (Fig. 5b): lower than 20° for natural and soil slopes and higher than 60° for rock slopes or slopes with engineering works, such as bridges or retain walls.

As far as previous instabilities, an active landslide affects the infrastructure, involving relevant protection measures. In addition, several rock falls (mainly on the right track) and embankment failures (mainly on the left track) were identified during the on-site surveys, as well as many troubles involving the vegetation cover (Fig. 5c). Water was locally detected, mainly as an outcropping of groundwater (Fig. 5d). In order to face previous instabilities, some protection systems are still present along the infrastructure, such as walls, rockfall nets and draining systems (Fig. 6a), which are generally characterised by a quite good effectiveness (Fig. 6b).

The database contains all the parameters listed in Table 1, divided for track right and left, and it was used for evaluating all the indexes  $x_i$  and the related scores  $y(x_i)$ . Many of them (i.e. mapped hazards, vegetation cover, etc.) have a typical stepped behaviour, as they are based on qualitative classes (Fig. 7a). On the contrary, for quantitative parameters, such as slope height and angle, the trend is continuous (Fig. 7b).

### Susceptibility, vulnerability and risk

Based on the score of the different indexes, the landslide hydrogeological susceptibility (S) and the infrastructure vulnerability (V) were assessed along the route of the case study, as well as the initial and residual risk (respectively,  $R$  and  $R_r$ ). The frequency distribution (Fig. 8) is very asymmetric for susceptibility, whereas for vulnerability and risk it assumes a quite typical bell shape, showing higher values for the left track.

In order to divide the railway infrastructure into sections having different risk level, the values bounding the different classes have been defined with reference to the present case study (Table 4), according to the rules listed in Sect. 2.1.

Figure 9 shows the distribution along the railway infrastructure of the different classes of susceptibility, vulnerability and risk. Results point out that:

- in the NW sector there are some sections with high susceptibility, mainly arising from fluvial dynamics and active landslides affecting the slope; the presence of high slope angle and water locally increases the susceptibility. The vulnerability is quite high, too, because of the short distance between the rail and the edge of slopes, especially along the left track. As a consequence, the risk index is from moderate to high for long distances, even if the presence of mitigation measures locally reduces the residual risk;
- in the central sector the sections having high susceptibility correspond to zones characterised by silty loose soils with water or rock slopes affected by block fall. The vulnerability is also high, bringing about high values of the risk index, especially along the left track. The presence of mitigation measures partly reduces the residual risk;


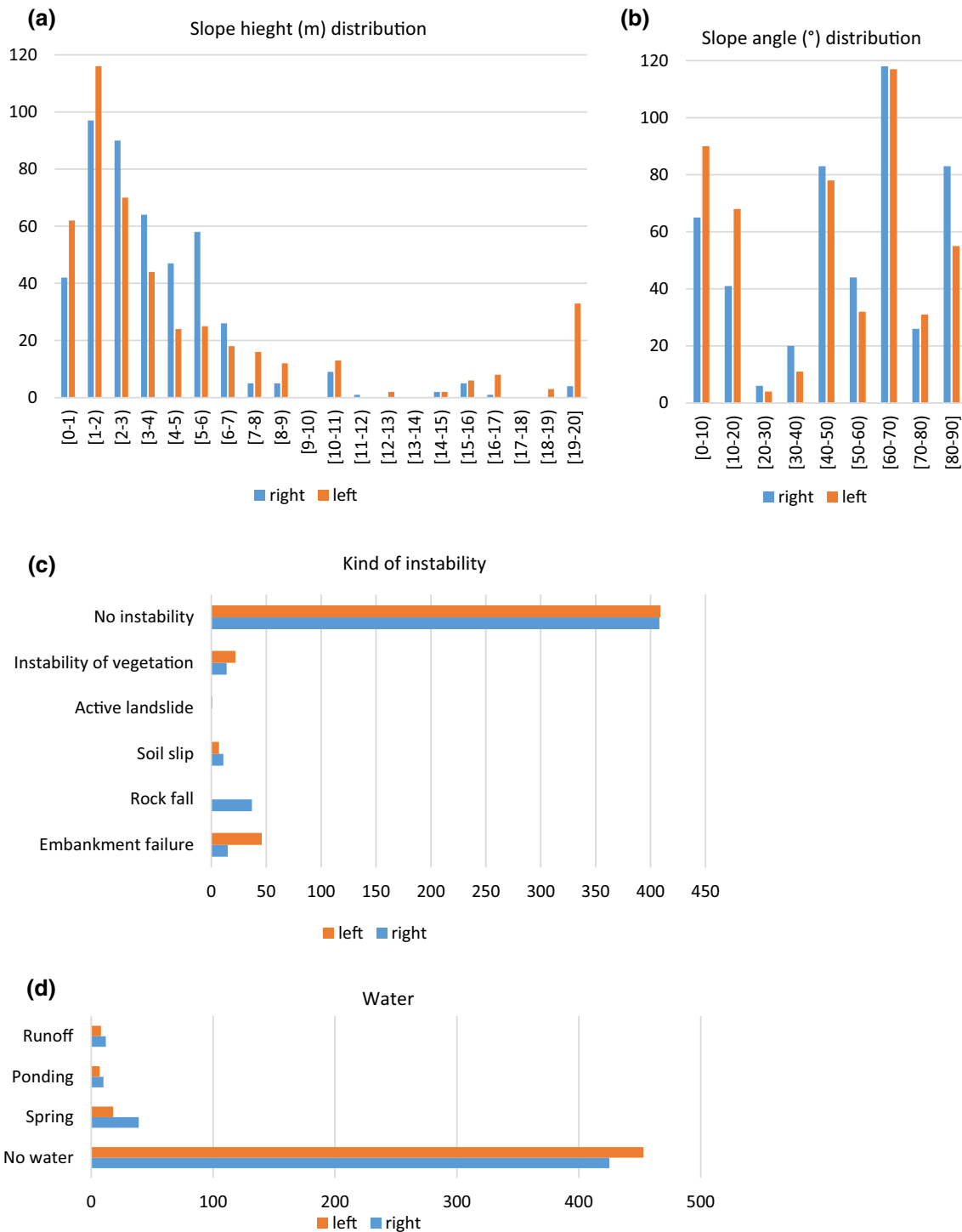
|   |  |                   |                   |                                 |                   |               |              |               |
|---|--|-------------------|-------------------|---------------------------------|-------------------|---------------|--------------|---------------|
| <b>FORM n.</b>  | <b>20</b>  | <b>Date</b>       | <b>14/06/2019</b> |                                 | <b>Location</b>   | <b>Varese</b> |              |               |
| <b>Coordinates</b>  | N  | 5073781           | E                 | 484909                          | <b>From pk</b>    | <b>53+400</b> | <b>to pk</b> | <b>53+425</b> |
| <b>Technical features of the infrastructure</b>                                     |  |                   |                   |                                 |                   |               |              |               |
| Wideness of the railway ballast (m)   |  | 5                 | N. rail           | 1                               | Speed (km/h)      | 60            |              |               |
| Shape of the track  | (straight, slightly turning, turning)                | straight          |                   |                                 |                   |               |              |               |
| Kind of track   | (ground level, trench, embankment, tunnel or bridge) | ground level      |                   |                                 |                   |               |              |               |
| <b>Morphological and geological features</b>  |  |                   |                   |                                 |                   |               |              |               |
|   |  |                   | <i>right</i>      |                                 |                   | <i>left</i>   |              |               |
| Distance of rail from slope (m)   |  | 2                 |                   |                                 | 9                 |               |              |               |
| Slope height (m)  |  | 4                 |                   |                                 | 5                 |               |              |               |
| Slope angle (°)   |  | 45                |                   |                                 | 55                |               |              |               |
| Slope lithology   |  | glacial deposits  |                   |                                 | glacial deposits  |               |              |               |
| <b>for SOIL slope</b>   |  |                   |                   |                                 |                   |               |              |               |
| Grain size composition (sand, gravel and sand, silty sand,...)                      |  | sands and pebbles |                   |                                 | sands and pebbles |               |              |               |
| <b>for ROCK slope</b>   |  |                   |                   |                                 |                   |               |              |               |
| Kind of layers  | (thin, thick, interbedded,...)                       |                   |                   |                                 |                   |               |              |               |
| Dip direction (upstream, downstream more or less than slope)                        |  |                   |                   |                                 |                   |               |              |               |
| Average joint spacing (m)   |  |                   |                   |                                 |                   |               |              |               |
| N. of joint sets  |  |                   |                   |                                 |                   |               |              |               |
| Compressive strength (R from Smidth Hammer)   |  |                   |                   |                                 |                   |               |              |               |
| <b>Other features</b>   |  |                   |                   |                                 |                   |               |              |               |
| Kind of previous instability (if any)   |  | none              |                   |                                 | none              |               |              |               |
| Rail affected (yes or no)   |  |                   |                   |                                 |                   |               |              |               |
| Kind of water (if any: spring, runoff, ponding)                                     |  | none              |                   |                                 | none              |               |              |               |
| Vegetation (trees, dense or sparse shrub, weed, lawn)                               |  | none              |                   |                                 | lawn              |               |              |               |
| Kind of protection measures (if any)  |  | none              |                   |                                 | draining systems  |               |              |               |
| Effectiveness (good, fairly good, sufficient, not sufficient)                       |  |                   |                   |                                 | fairly good       |               |              |               |
| <b>PHOTO</b>  |  |                   |                   | <b>NOTE</b>                     |                   |               |              |               |
|  |  |                   |                   | <p>5 draining pipes in 10 m</p> |                   |               |              |               |

Fig. 4 Example of the schedule filled during the on-site survey in order to collect data for the RHMS application



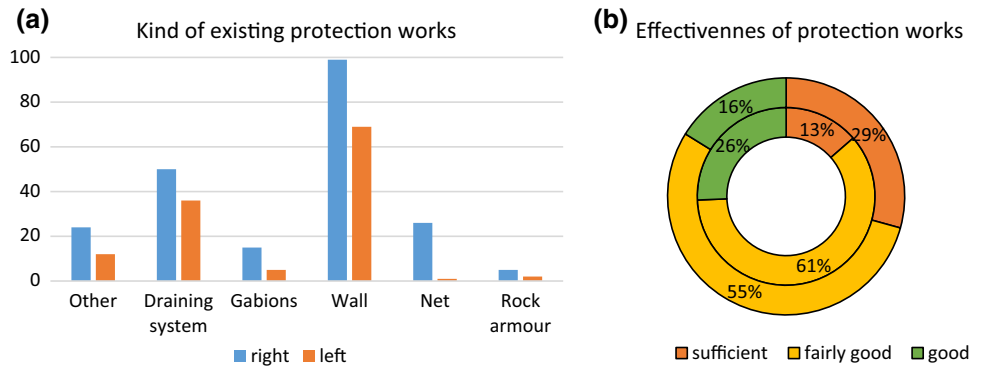


**Fig. 5** Example of data stored in the database: class distribution of **a** slope height, **b** slope angle, **c** previous instability, and **d** water. The number refers to the sections (the total number of sections is equal to 486 for each direction, right and left) for which the survey was carried out

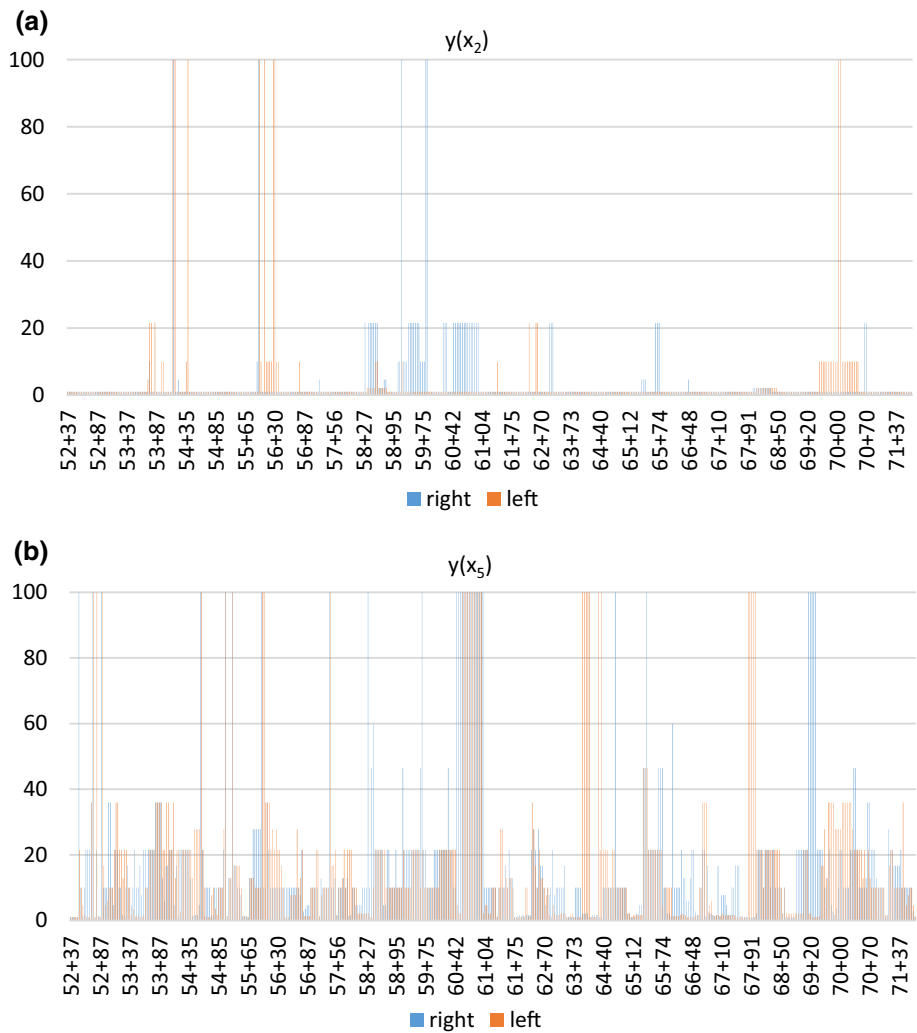
– in the SE sector there are no relevant hydrogeological problems; the susceptibility is high only on very short distances (i.e. where the slope angles are higher). The

vulnerability is quite low; therefore, the risk is generally low, too.

**Fig. 6** Existing protection measures along the railway infrastructure (a), with their effectiveness (b)



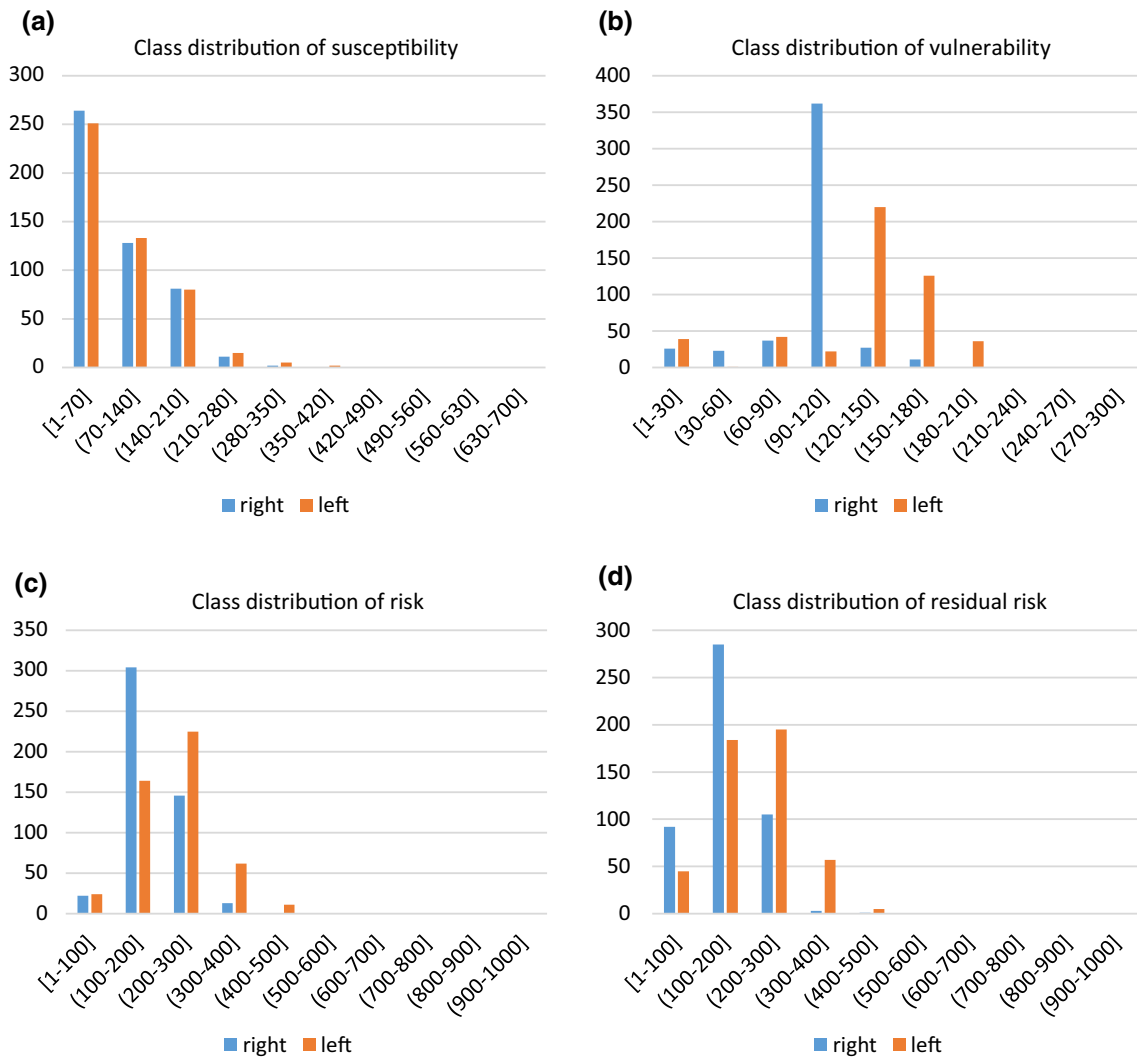
**Fig. 7** Examples of the score  $y(x_i)$  along the infrastructure for a qualitative parameter (previous instabilities) and b a quantitative parameter (slope angle)



**Risk management**

In order to prioritise the follow-up actions along the railway infrastructure, for the case study an acceptability threshold for the risk index equal to 260 was adopted,

which means that “high” and “very high” classes are not acceptable. In order to exclude very local situations, “high” risk values were considered only if the two adjoining sections had values higher than 195 (corresponding to the intermediate value of the “moderate” class).



**Fig. 8** Frequency distribution of the values of susceptibility (a), vulnerability (b), risk (c) and residual risk (d) for the 486 sections of the railway infrastructure

In this way, for the case study the intervention priorities with the corresponding protection or mitigation measures were identified (Table 5).

The risk assessment should be updated yearly or after the realisation of new protection and mitigation works, in order to reach an acceptable level of risk along the whole

infrastructure. Eventually, based on socio-economic issues, a target threshold can be defined in addition to the acceptability one: it will be the value to which aim in the long term.

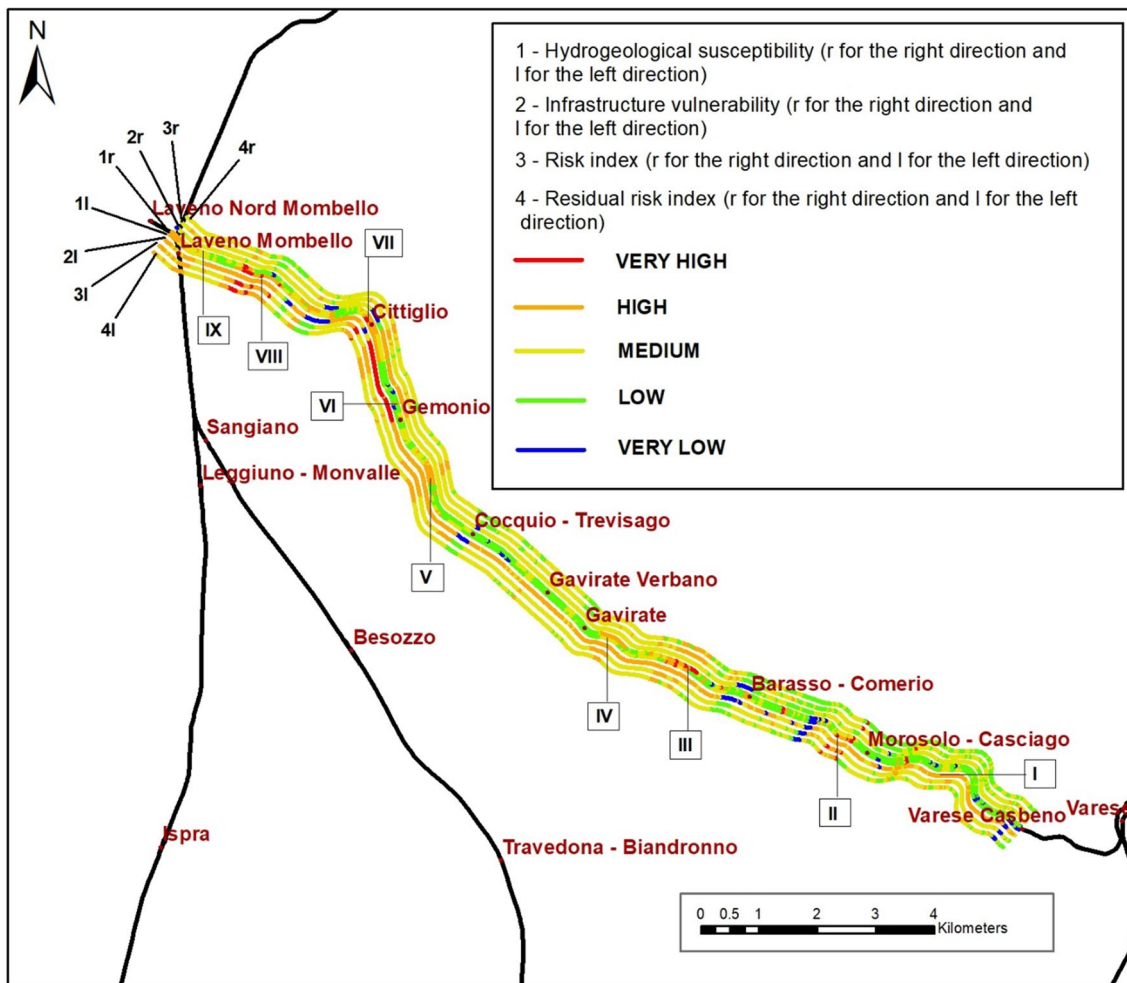
### Discussion

The proposed heuristic method provides a useful tool for hydrogeological risk management along railway, as it allows to compare the relative values of hazard, vulnerability and risk in the different sections of an infrastructure; therefore, it gives a priority scale for the follow-up actions.

Based on the application to the case study, the method constitutes a good compromise between the desire to fully describe the complexity of the phenomena and the need to

**Table 4** Classes of landslide hydrogeological susceptibility (S), infrastructure vulnerability (V) and risk (R) for the case study

|           | Susceptibility     | Vulnerability      | Risk               |
|-----------|--------------------|--------------------|--------------------|
| Very high | $S > 210$          | $V > 180$          | $R > 390$          |
| High      | $140 < S \leq 210$ | $120 < V \leq 180$ | $260 < R \leq 390$ |
| Moderate  | $70 < S \leq 140$  | $60 < V \leq 120$  | $130 < R \leq 260$ |
| Low       | $21 < S \leq 70$   | $9 < V \leq 60$    | $30 < R \leq 130$  |
| Very low  | $S \leq 21$        | $V \leq 9$         | $R \leq 30$        |



**Fig. 9** Susceptibility, vulnerability, risk and residual risk for the case study, based on the ranking defined in Table 4. The Roman numbers show the location of the priority actions listed in Table 5

**Table 5** Follow-up priority actions for the case study and the corresponding protection/mitigation measures

| ID   | Problem  | Measure   |
|------|--|---|
| I    | High slope angle with embankment failure and weed vegetation | Structural measures along the slope and vegetation removal                      |
| II   | Erosive phenomena  | Maintenance and reinforcing works   |
| III  | Active landslide (left track)                                | Structural protection measures  |
| IV   | Rock subvertical slopes with block fall (right track)        | Structural protection and draining measures                                     |
| V    | Loose soils in the presence of water and high slope angle    | Monitoring of the existing draining system effectiveness                        |
| VI   | Water run-off  | Realisation of draining systems   |
| VII  | High hydraulic hazard (fluvial dynamics)                     | Vegetation removal and monitoring of the existing draining system effectiveness |
| VIII | Embankment failure (left track)                              | Structural protection measures  |
| IX   | Active landslide on the slope above the infrastructure       | Monitoring system for block impact along the tracks                             |

Their location is shown in Fig. 9

simplify the problem in order to supply a tool easy to apply and update, even by unskilled users.

Actually, the data can be collected and updated with on-site surveys in time intervals compatible with the functional needs of the infrastructure, with no service interruptions.

For example, even if the geological conditions described by the corresponding parameters (see Table 1 for reference) is not complete, the application to the case study demonstrated that a reliable identification of the geological critical issues in rock masses can still be achieved. Moreover, the exponential ranking system used in the present study demonstrated to be able to emphasise the most critical situations.

One of the main differences of the proposed method with respect to other methods usually applied for geological hazard assessment along highways is related to the braking distance. Braking distance expresses the possibility that a driver can stop his vehicle before impacting an obstacle. The value of this parameter is usually obtained as the ratio between the actual view and the braking distance of the vehicle. For a train that run at a speed of 70 km/h the braking distance is at least 500 m and therefore well above the driver's actual view. For this reason, in the present study a different parameter was considered as representative of the possibility of reporting any problems along the infrastructure; at this aim the distance from the signalling systems was taken into account (see Sect. 2.1 for the definition of the parameter). This parameter is relevant only whether a monitoring and early warning system is present along the route. One of the few examples of real-time monitoring for geological risk management along railway concerns rock falls detection in central Italy, where a prototype of artificial intelligence camera is used [24]. Unfortunately, no monitoring system is still present in the case study; therefore, this parameter could not be considered in the method application and its weight was equally distributed to the other two parameters describing the vulnerability.

## Conclusions

Although railway infrastructures in mountain areas are often affected by relevant geological and hydrogeological hazards, in the technical international literature this topic is overlooked and therefore it is necessary to refer to methods already developed for the risk assessment along highways.

The present study aims at filling this gap, by pointing out a heuristic method for hydrogeological risk assessment and management along railway infrastructures, with specific reference to geomorphological conditions typical of the Pre-alpine zone (northern Italy). The proposed method allows:

- to assess the hydrogeological susceptibility, vulnerability, risk and residual risk along any railway infrastructure having geomorphological features typical of mountain areas;
- to identify a priority scale in the follow-up measures, based on the definition of acceptability thresholds specific for each case study.

One of the main advantages of the proposed method is its ability to combine a reasonable degree of complexity in describing the problem with a user-friendly approach, which is not much time consuming in data collection and processing. Moreover, the method can be applied with an iterative approach, updating the evaluation and eventually the thresholds, depending on the evolution of the political and socio-economic conditions.

The main disadvantage of the proposed method is the relative scale in which the results are expressed. Actually, the obtained results cannot be looked as an absolute risk rating, as the method is based on a heuristic approach. As a consequence, the resulting risk rating has a relative validity, which only allows to identify some sections as more critical than other ones.

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## Compliance with ethical standards

**Conflict of interest** The authors declare no conflict of interest.

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