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RESEARCH

Risk assessment of national railway infrastructure due to sea-level rise: an application of a methodological framework in Italian coastal railways

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Abstract Nowadays, within the built environment, railway infrastructures play a key role to sustain national policies oriented toward promoting sustainable mobility. For this reason, national institutions and infrastructure managers need to increase their awareness in relation to the current and future climate risks on their representative systems. Among climate change impacts, preventing the effects of sea-level rise (SLR) on coastal railway infrastructures is a priority. The first step in the climate change adaptation policy cycle is the development of an ad hoc climate risk assessment. In this view, this research develops a vulnerability and a risk assessment metric to identify the hotspots within a national coastal railway due to the SLR impacts. The proposed methodology required different steps to quantify the SLR projections and the vulnerability characteristics of the assets, in terms of sensitivity and adaptive capacity. The investigated case study is the coastal railway infrastructure in Italy, thanks to an initial approach of co-design participative processes with the national Infrastructure Manager: Rete Ferroviaria Italiana (RFI). The results of this application, although not included in the paper due to confidential reasons imposed by the infrastructure manager — led to a clear identification of the areas and the coastal railway sections which are exposed to high levels of risks and of the places which require priority actions for urgent adaptation in a view of climate proof infrastructures.

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Introduction

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) stated with a high level of confidence that climate change caused by human activities has resulted in the melting of ice and the expansion of the oceans. This, in turn, leads to an elevation in sea levels. The projected sea level rise (SLR) in the future, together with severe weather events like storm surges and intense rainfall, would intensify the risk of urban and rural communities, assets, and people situated in coastal regions (Glavovic et al., 2022). According to Palin et al. (2021), sea level rise (SLR) may result in several types of flooding, including transitory coastal floods, permanent floods, and floods caused by alternating tides. While there is uncertainty in estimating sea-level rise (SLR) by 2100 (Shaw & Horton 2020), the scientific community is confident in predicting substantial impacts on infrastructure systems caused by this gradual process (European Commission, 2021a; Adams, 2021). The European Commission has released the European Strategy on Adaptation to Climate Change (European Commission, 2021b) in order to address the effects of climate change. Member states have chosen to adopt this strategy by developing their own National Adaptation Strategy and National Adaptation Plan. For years, academics, technology, politics, and society have been focusing on the flooding of public transport networks in low coastal regions, including trains and roads. Railways are a crucial component of infrastructure in regions experiencing worldwide expansion and a steady rise in yearly use (European Commission, 2021b). On a global scale, train lines carry over 3835 billion people per kilometer and move 9279.81 billion metric tons of products per kilometer (Koks et al., 2019; Statista, 2020). The coastal regions of Europe have approximately 228,000 km of rail lines. In recent decades, the railways sector in these regions has been significantly impacted by storm surges caused by extreme weather events (EUROSTAT, 2016) and gradual events like sea-level rise (Palin et al., 2021). The impact on the railway infrastructure may include the gradual wearing away and the inundation of essential components within the system, such as tunnels and tracks, leading to a significant amount of losses and damages (MIMS, 2022). By examining the scientific and gray literature pertaining to transnational, through an examination of scientific and gray literature, it was found that the impact of sea level rise (SLR) on rail assets and services is mainly caused by the flooding of rail tracks and stations, destruction of shoreline protection, and damage to other physical structures such as tracks or bridges. As a result, these consequences may cause service faults or interruptions, including the suspension of passenger services, the need for replacement, and/or increased maintenance costs (Quinn et al., 2017; TRaCCA, 2016; Capitol Corridor Joint Powers Authority, 2014). The European Commission (2021b) has analyzed the malfunctions or disruptions of rail services caused by extreme weather events and attempted to estimate the economic damages by considering future projections. However, the analysis has found that the consideration of climatic hazard has been insufficient thus far. It is necessary to evaluate the vulnerability, which consists of sensitivity and adaptability. In order to assess the vulnerability of coastal railway assets to the projected increase in sea level, it is recommended to examine their sensitivity and adaptive capacity for infrastructure investments financed by the Next Generation EU. The user is referring to the clear distinction between physical vulnerability and functional vulnerability. Physical vulnerability refers to the susceptibility of an infrastructure asset's physical components, such as the materials used in constructing a given piece, rather than the kind of building. Functional vulnerability, in parallel, pertains to the functional attributes of the network, such as its transportation capacity in terms of daily trips or number of passengers, rather than the speed of the infrastructure (Monte et al., 2021; Birkmann et al., 2013). Identifying these vulnerability factors is crucial for determining the primary risk factors, implementing appropriate adaptation measures, and ensuring a continuous process of monitoring and evaluation (Meyer et al., 2012; Kingsborough et al., 2017; Ryan et al., 2016; Ryan & Stewart, 2017).

On the other hand, while mathematically sophisticated methods are invaluable for addressing well-defined problems with precise data, their complexity can be a drawback during the participatory and politically sensitive stages of the planning process

(Fleming et al. 2023; Andrè et al., 2021; Te Boveldt et al., 2021). The state-of-the-art literature recommend to develop methods that support the incremental improvement of co-design options. Such methods should focus on iterative refinement and continuous feedback, allowing stakeholders to collaboratively enhance design solutions rather than simply ranking alternatives (Te Boveldt et al., 2021). Co-design, co-development, and co-delivery (collectively referred to as Co-3D) are indeed integral activities within the co-production research pathway, gaining increasing traction in climate change science and adaptation projects (Fleming et al. 2023; IPCC, 2022). All these approaches emphasize collaborative processes where researchers and stakeholders work together throughout the project's lifecycle to ensure that outcomes are relevant, practical, and effectively address local needs and conditions, but it also fosters a more inclusive and adaptive planning process, accommodating diverse perspectives and promoting consensus-building (Fleming et al. 2023; Te Boveldt 2021). In fact, infrastructure-effective adaptation measures are the result of a multiplicity of socio-economic processes acting on different scales, and they must be identified based on a hazard evaluation, a careful exposure assessment, and the quantification of the related vulnerabilities (European Commission, 2021b; Ranasinghe et al., 2021) along with a co-design approach to ensure that the resulting information is both relevant and usable (Andrè et al., 2021).

To date, although few studies relate to railway climate vulnerability and risks in relation to SLR impacts (Adams & Heidarzadeh, 2021; Dawson et al., 2015; Hawchar et al., 2020; Hong et al., 2015; Paulik et al., 2020; Rizzi et al., 2017; Zhu et al., 2021), none of these apply the theoretical framework proposed by the IPCC with the objective of identifying the different levels of risk propensity (Emanuelsson et al., 2014; O'Neill et al., 2022; Oppenheimer et al., 2014; Ranasinghe et al., 2021). Most of the applied methods are indeed based on mathematical models that consider the historical trends of the impact and the observed damages (Adams & Heidarzadeh, 2021; Zhu et al., 2021). The updated studies underline the importance of a vulnerability and risk assessment based on an integration of mathematical GIS tools together with a co-designed approach, but a few of them make use of these instruments to support risk management monitoring systems (Capitol Corridor Joint Powers Authority, 2014; Hawchar et al., 2020; Hong et al., 2015). This is also because although vulnerability and risk indicators/metrics are in common use today, the latter are categorized differently due to the lack of a common and recognized taxonomy concerning the factors that compose the risk (UNFCCC, 2022): climate hazard, exposure, and vulnerability (Ferranti et al., 2021; European Commission, 2021b). This gap, however, showed that the different types of vulnerabilities that projects look at are related to the network's physical and geographical features, its functionality and performance, security and governance aspects, and finally management information, such as early warning systems (Birkmann et al., 2013; Monte et al., 2021). The European Commission (EC) recently published a report to give technical guidance on the climate proofing of investments in infrastructure (European Commission, 2021b). Based on lessons learned from major climate-proofing projects, the EC guidance integrates climate-proofing with project cycle management, environmental impact assessments, and strategic environmental assessment processes, as well as recommendations to support national climate-proofing processes in relation to infrastructure. Based on the two climate change pillars (i.e., mitigation and adaptation), the proposed process divides into two distinct phases: screening and detailed analysis. The detailed analysis is dependent on the screening phase's outcome, which helps reduce administrative burdens. In this context, vulnerability and climate risk assessment remain the basis for identifying, appraising, and implementing climate change adaptation measures (European Commission, 2021b). To overcome the challenges of climate information for policymaking and action in the railway infrastructural system, this study proposes and discusses Co-3d risk assessment metrics associated with SLR on a national coastal railway using distinct Representative Concentration Pathways (RCPs) (RCP4.5, RCP8.5), different return periods (T2, T100), and two different Digital Elevation Models (DEM) at a resolution of, respectively, 2 and 20 m (DEM2 and DEM20) over the Italian territory. The IPCC (2022) presents future projections of changes in global surface temperature from 2021 to 2100, categorized into low (RCP-2.6), intermediate (SSP2-4.5), and very high (SSP5-8.5) GHG emissions scenarios. For this work, RCP 4.5 has been considered the more plausible scenario for risk assessment due to the efforts made in the last few years, as suggested by Hausfather et al. (2020), and RCP 8.5 represents the worst case. We have used the DEM at 20 m for the

Friuli-Venezia Giulia region. The Italian Ministry of the Environment and Protection of Land and Sea has made the DEM available through the web portal (MATTM, 2022). The outputs of the proposed approach refer to the expected future SLR impacts, the identification of the most vulnerable coastal tracks at the national level, and the categorization of the risks for railway infrastructure. Based on international guidelines for climate change risk assessment, the proposed method aims to provide decision-makers with geospatial information on the impacts of future expected SLR, highlighting the most critical hotspots for future prioritization in a more detailed study to implement adaptation actions. In reality, moving from a theoretical framework to a practical evaluation means: (i) picking out parts of the railway system to be used as exposed samples; (ii) figuring out the weaknesses that go with them; (iii) giving each indicator a weight; and (iv) figuring out the overall risk and putting it into the right category by using the planned method. The application of a well-structured protocol to an infrastructure network provides a key tool for public and private policy makers and railway infrastructure managers to identify the most critical railway sections in terms of SLR in the medium- and long-term. This paper organizes itself as follows, drawing from previous insights: In the "Material and methods" section, we present the hazard, exposure, and vulnerability indicators, along with the methodology we applied to the Italian national coastal railway infrastructure to evaluate the risks of SLR. "Results and discussion" section focuses on the discussion of the results based on the different scenarios and elements under analysis, taking into account the restrictions related to confidential reasons imposed by the infrastructure manager, Rete Ferroviaria Italiana (RFI), as well as the strengths and limitations of the applied approach. Finally, the "Conclusions" section summarizes the study's conclusions.

Material and methods

Case study description and unit of analysis

RFI is the Ferrovie dello Stato Italiane Group's company in charge of managing the Italian railway network. As the national infrastructure manager, RFI, according to national policies on growth and financing of infrastructure, develops and upgrades the network, maintains the efficiency of assets and technologies, allocates transport capacity to railway undertakings (RUs), ensuring accessibility of lines, stations, and yards, and defines track access charges. It also manages railway traffic and operations, ensuring the safety of operations themselves. In addition, RFI conducts research and innovation activities in the fields of its interest.

In December 2022, RFI manages about 16,829 km of railway lines, including 1467 high-speed lines (referred to as ERTMS-equipped sections powered at 25 kV, including their connections to service locations), c.a. 2200 passenger stations, and 199 freight plants (facilities with intermodal hubs, freight yards, junctions, etc.), ensuring the daily operation of more than 9000 trains operated by 37 RUs. In terms of coastal lines, a rough estimation of their extension is around 3800 km. The study uses the coastal railway section from one station to another (i.e., units from station A to station B, from station B to station C, from C to D, etc.) as an analytical unit to analyze the network at the highest possible resolution. We conducted the risk analysis on a national basis to provide a clear and complete overview of the SLR risks to the Italian coastal railway infrastructure.

Risk assessment step-by-step methodology due to the impacts of SLR on the national coastal railway infrastructure

The research utilizes the latest guidelines and employs a comprehensive, reproducible, and adaptable approach to assess the risk level of each segment of the coastal railway infrastructure. The methodology takes into account various emission scenarios, return periods, and high-resolution digital elevation models (DEMs). The sources referenced include the works of Emanuelson et al. (2014), IPCC (2021), and Palin et al. (2021). The return period of an event is defined as the average time between two consecutive occurrences of the event. Alternatively, the return level is the predicted value that is surpassed, on average, once during each return period (Vezzoli et al., 2012). Risk is defined as the outcome of combining hazard (H), exposure (E), and vulnerability (V), which are further split into sensitivity (S) and adaptive capacity (AC). Thus, these studies determine the climate risk (H) by simulating the sea level rise (SLR) based on several scenarios (RCP4.5 and RCP8.5) and different timeframes. The dataset titled

"Water level change indicators for the European coast from 1977 to 2100 derived from climate projections" may be accessed on the Copernicus C3S platform. This dataset contains climate projections for sea level rise, as shown in the study by Yan et al. (2020). We assessed the exposed sample (E) by overlaying the SLR projection shapefile from different scenarios with the coastal railway polyline shapefile from RFI. Next, we selected vulnerability indicators (V) as the tangible and operational attributes of the coastal railway network that have the potential to either heighten or diminish the degree of risk (Ellena et al., 2023; Master Adapt, 2018; MATTM, 2018). We organized each stage of the process using a continuous of sharing vision and expertise, the initial stage of co-design approach (Fig. 1).

Step 1: Identification of future expected SLR on Italian's coastal areas

"The bathtub model" (Yunus et al., 2016) is the most widely used approach in the literature for coastal flooding assessment, especially over large areas. By comparing the water level with the DEM of the territory under analysis and selecting all areas below the considered sea level, this method identifies the area of potential submersion. To ensure greater reliability of the results, hydrological connectivity between flooded areas and the sea was required (Van de Sande et al., 2012). Overall, the resolution of the DEM determines the limitation of the bathtub method. If the resolution is low, the identification of submerged pixels can be incorrect since the attribution of the elevation

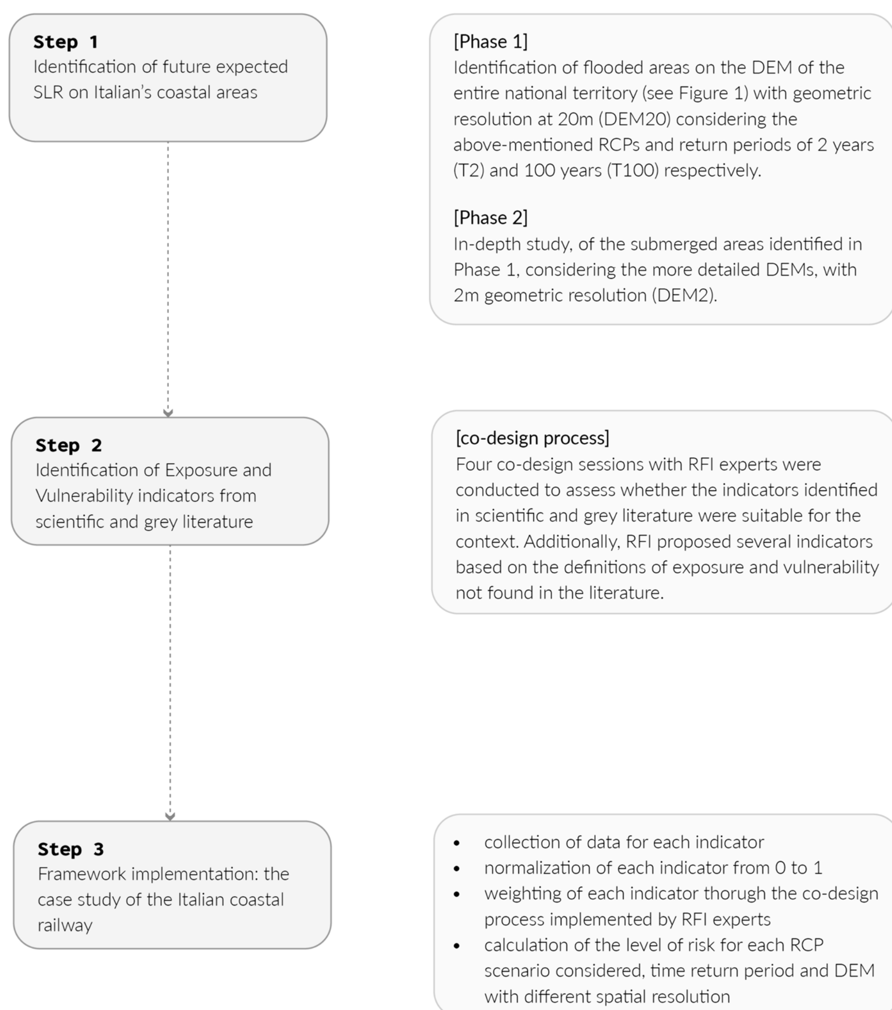


Fig. 1 Summary diagram outlining the three main steps adopted for the development of the methodology

mean value to a large area could hide a high variation in the terrain morphology. The bathtub approach can provide different results compared to other more complex hydraulic modeling methods (Didier et al., 2019), but it remains the most used option today. Higher-resolution DEMs can enhance the accuracy of the outcomes. In this study, we decided to proceed in two phases, as described below, to reduce computational times and ensure reliable results.

[Phase 1]: We identify the flooded areas on the DEM of the entire national territory (see Fig. 2) with a geometric resolution of 20 m (DEM20), taking into account the previously mentioned RCPs and return periods of 2 years (T2) and 100 years (T100). We were able to identify the sections of railway lines (i.e., shapefiles of lines) within the perimeter of these areas, which are susceptible to the impacts of submersion due to SLR.

[Phase 2] We conducted an in-depth analysis of the submerged areas identified in Phase 1, taking into account the more detailed DEMs with a geometric resolution of 2 m (DEM2). Particularly, the preliminary study permitted the analysis of only the detailed DEMs, which include the sections of the considered railway lines. We first needed to harmonize the SLR and DEMs in both cases, as they referred to different reference systems (altimetric datums). Next, we obtained a DEM of the differences (DEMD) by subtracting the SLR values from the DEM. Therefore, we isolated the areas potentially subject to submersion with values of the DEMD equal to or lower than zero. Finally, we identified the sections of the railway line that could potentially face flooding in the future by intersecting the layer corresponding to the flooded areas with the layer of the entire national railway network. Elaborations related to DEM 2 have considered those areas identified by the worst-case scenario obtained from DEM 20. We grouped the DEM 2 s by region and distinguished the area of interest with an identification code. The union framework, in vector format, accompanies the DEMs and easily identifies this area with its consistent extension of

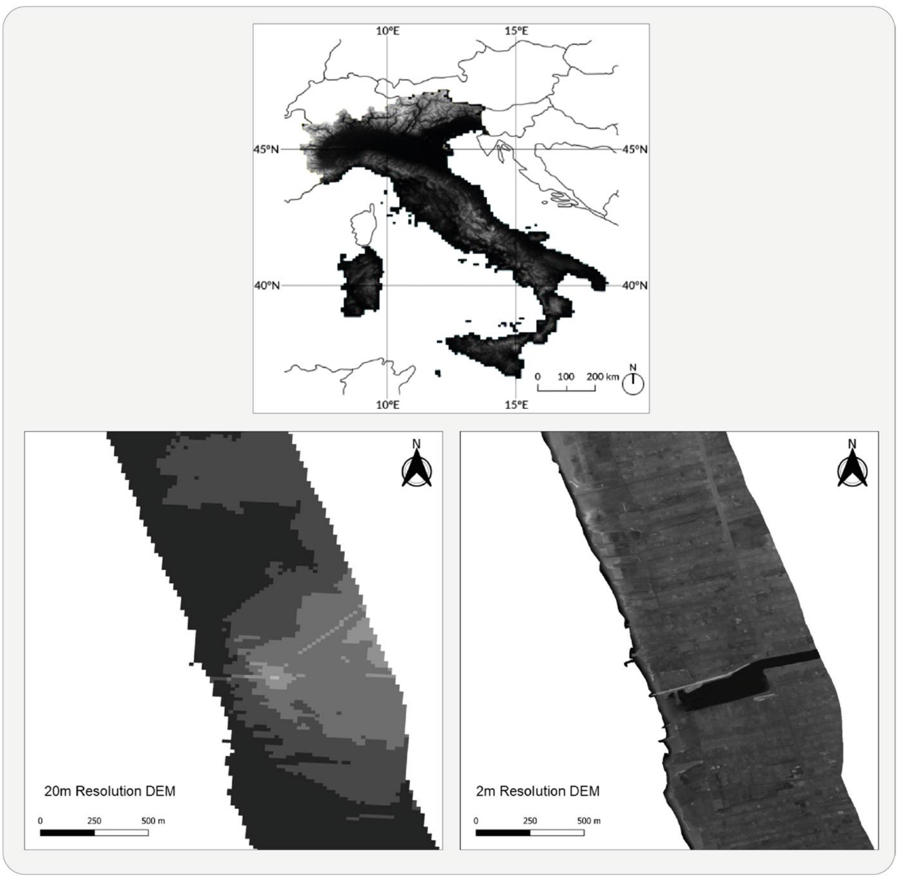


Fig. 2 The top image shows the visualization within QGIS software of the DEM with a 20-m spatial resolution for the entire Italian territory, with equirectangular coordinates. The bottom image illustrates a local frame of the difference in resolution between the 2-m DEM and the 20-m DEM

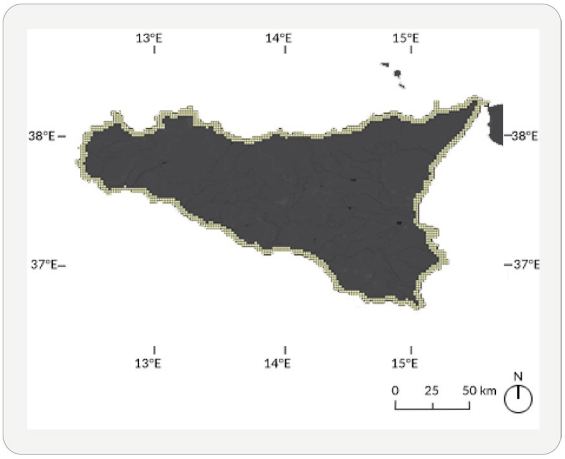
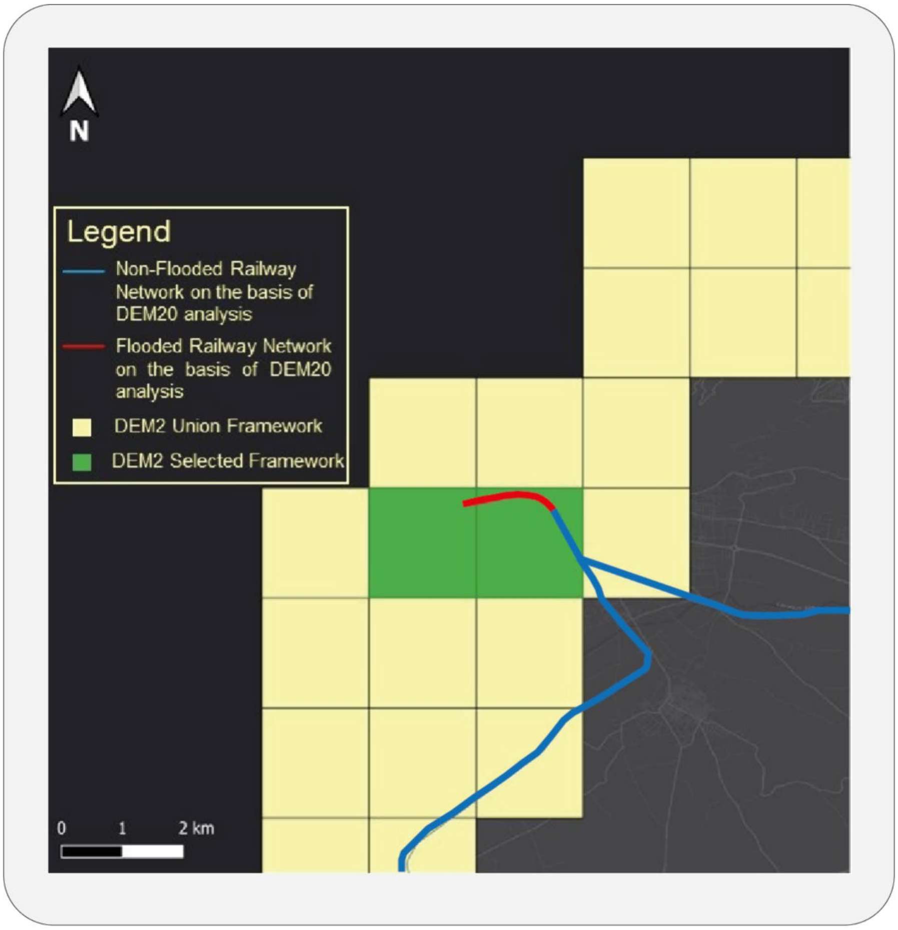


Fig. 3 DEM2 Union Framework for the Sicily region and squares (described in Fig. 3)

0.02°×0.02°. The flooded railway lines' layers were also in vector format. It was therefore possible to select the elements of the union framework on which the flooded railway network sections fall according to the scenario RCP 4.5 T100 on the DEM20 using a spatial query (ISO, 2018). As an example, Fig. 3 shows the union framework of DEM 2 s in Sicily (i.e., the largest region in Italy), while Fig. 4 shows a more detailed perspective.

Figure 4 is an example of the procedure applied to select the areas to be investigated: from the original railway network (in light blue), the sections at risk of flooding were identified according to the RCP4.5 scenario, with a return period of 100 years (in red). Using the Union Framework (in yellow) as a guide, we identified and selected the boxes in green that correspond to the aforementioned

Fig. 4 Detail of the Union Framework relating to the DEM2, and the flooded railway sections identified based on DEM20



sections, enabling us to conduct a comprehensive study using the 2 m DEM data. We repeated the same processes on the 2 m DEM. Since the accuracy of the submerged railway depended on the DEM resolution, the DEM 20 usage precluded the identification of useful details. However, it facilitated a more accurate initial selection of the areas for investigation. In addition, due to the lower resolution, both false and missed alarms could occur, although these cases are generally rare.

Step 2: Identification of exposure and vulnerability indicators from scientific and gray literature

We have analyzed the scientific and gray literature on the effects of SLR on coastal railway infrastructure with the aim of selecting and adopting the most valuable indicators for exposure and vulnerability factors. We have collected 120 indicators for this purpose. Table 1 enumerates these indicators, providing specific details about their geographical context of use, the corresponding scale of resolution, the risk factor they pertain to, and the source from which the indicator originated.

Following an initial phase of preliminary screening, the relevant key stakeholders of the case study under investigation jointly undertook several exchanges to identify which indicators were more coherent and significant for the SLR analysis of the Italian railway coastal infrastructure. We proposed additional indicators after scrutinizing the information and existing datasets from the RFI repository. Stakeholders in the case study, the national scientific community, and the state-of-the-art literature have thoroughly evaluated these new indicators. Ultimately, we selected a total of 22 indicators, 5 for the exposure (E) factor and 17 for vulnerability (V), with 15 corresponding to sensitivity and 2 to the adaptive capacity subfactors. Table 2 displays the final selected exposure indicators with the corresponding description. We divided the listed indicators into quantitative (QN) and qualitative (QL), highlighting the associated unit of measurement, for clarity.

Tables 3 and 4 refer to indicators of sensitivity and adaptive capacity, which are the two subfactors that compose vulnerability (Glavovic et al., 2022). In this case, we have divided the listed indicators into quantitative (QN) and qualitative (QL) categories, emphasizing not only the unit of measurement but also the type of vulnerability they pertain to: (i) functional/performance or (ii) physical. While physical vulnerability metrics assess the vulnerability of an asset or asset category based on its design or construction, functional or performance vulnerability metrics assess the vulnerability of an asset or asset category based on its functions and relationships with other assets and asset categories.

The active and continuous engagement of key system stakeholders enabled the establishment of indicators that precisely captured the unique features of the Italian coastal railway system. According to the data supplied by RFI, several indicators need further calculations to determine their ultimate value. A measure of exposure, known as the "percentage of submerged section/segment length," was determined by calculating the ratio between the potential length of the railway line that might be submerged in the future and the entire length of the railway section now under investigation. The precise length of the potential submerged railway segment was determined by using the railway geometry provided in the RFI shapefile railway layer. This provides the planimetric length of the vector associated with a certain segment. Corresponds. The "Commercial Classification of the Line" assigns values from 0 to 1 to quantify different types of lines. The classification is as follows: shuttle lines (diesel) in complementary networks (0.1); shuttle lines (electrified) in complementary networks (0.2); low-traffic lines (diesel) in complementary networks (0.3); low-traffic lines (electrified) in complementary networks (0.4); secondary lines (diesel) in complementary networks (0.5); secondary lines (electrified) in complementary networks (0.6); basic network lines (diesel) (0.7); basic network lines (electrified) (0.8); knot lines (diesel) (0.9); and line nodes (electrified) (1.0). Specific vulnerability indicators were carefully considered in the final calculations. We reversed the sign of the civil components values for the "period of construction of the civil works" indication compared to the other sensitivity indicators. This means that a lower value indicates a worse condition, while a higher value indicates a better state. We carefully evaluated and revised this feature at every stage of the standardization process. Ultimately, given that the railway segment encompasses an initial location (referred to as hypothetical station A) and a terminal point (referred to as hypothetical station B),

Table 1 Systemic summary of the Exposure and the Vulnerability indicators discovered in the up-to-date literature

Geographical and Spatial scale	Risk assessment factors under analysis	Indicators	Reference
China (National)	Vulnerability Capitol Corridor Joint Powers Authority, 2014)	Daily railway services affected by the interruption of the service	Zhu et al. (2021)
		Number of daily passengers affected by the interruption of the service	
		Daily rail services diverted to an event that results in a service interruption	
		Increase in time taken by trips diverted by the interruption of service	
		Average time in increase of the runs diverted from the interruption of the service	
		Quantities of cancelled daily trains and their passengers that will not use the trains due to the interruption of service	
UK (Local: Dawlish)	Exposure Adams and Heidarzadeh, (2021)	Broken sections of the network for the suspension of service due to weather events	Adams and Heidarzadeh, (2021)
	Vulnerability Didier et al., 2019)	Instability of the slopes	
		Occurrence of landslides	
		Flooding of the rails	
		Damage to the walls of parapets	
		Ballast washout	
		Subsidence of the foundations of the embankments	
		Damage to masonry elements	
		Leakage of infill material from embankments	
		Failure of the upper parts of the wall	
New Zealand (National)	Exposure Benavente et al., 2006)	Buildings	Paulik et al. (2020)
		Roads and railways	
		Water distribution infrastructures	
		Electric distribution infrastructures	

Table 1 (continued)

Geographical and Spatial scale	Risk assessment factors under analysis	Indicators	Reference
Ireland (National)	Exposure Didier et al., 2019)	Airports of national importance	Hawchar et al. (2020)
		Ports	
		Train stations	
		Railway lines	
		Roads	
		Bridges	
		Electricity production station	
		Wind energy production plants	
		Gas distribution system	
		Wastewater treatment plants	
		Key sites of interest of the telecommunications entity	
UK (Local: Dawlish)	Vulnerability Adams and Heidarzadeh, (2021)	Days with restriction of movement on the railway line in the observed period (DLR)	Dawson et al. (2016)
China (National)	Exposure André et al., 2021)	Number of trains interrupted by flooding events	Hong et al. (2015)
		Duration of interruption of train service due to flooding events	
	VulnerabilityArup TRaCCA Phase 2 Consortium, 2016)	Number of passengers affected by the interruption	
		Waiting time of passengers due to interruption	
		The sum of the number of trains interrupted (which is defined as the decrease in the number of trains in relation to a day of the typical week) calculated for each day that characterises the duration of the service interruption	

which may correspond to distinct localities. The estimates for the indicators "county value-added," "synthetic index of tourist density per municipality," and "inhabitants for each municipality" all indicated the value mentioned at the conclusion of the section. The process of continuous system stakeholder engagement facilitated our ability to reach a choice that was in line with the RFI and appropriately represented the actual situation.

Step 3: Framework implementation: The case study of the Italian coastal railway

In accordance with the up-to-date literature (Glavovic et al., 2022; European Commission 2021b), the risk assessment was structured based on the indicators listed above and pertaining to hazard (H), exposure (E) and vulnerability (V). The applied risk assessment equation is the following (Ellena et al., 2023; European

Table 2 List, descriptions, and references of applied Exposure indicators in the risk assessment methodology

Risk assessment factor	Type	Name	Description	Unit	Reference	Source of data	Open source
Exposure	QN	Number of boarded/descended passengers	Annual sum of passengers boarded and disembarked at the start and end stations (data referred to 2019)	number	Proposed in accordance with RFI expertise	RFI data archive	No
		Percentage submerged section/length of the section	Ratio between the kilometres of the railway sections that in future could be potentially submerged on the total kilometres of the section under investigation. *	%	Adams and Heidarzadeh, (2021)	Geometry of national railway infrastructure and SLR projections	Yes
		Passengers' trains per day	Number of total trains scheduled on a typical working day that would not be able to run on the section. The value is understood as the sum of the services in both directions, and it is estimated based on 2021–2022 scheduled timetable	number/day	Zhu et al. (2021)	RFI data archive	No
		Freight trains per year	Number of total freight trains that would not be able to run on the section. The value is understood as the sum of the services in both directions, and it is estimated based on 2021–2022 scheduled timetable	number/year		RFI data archive	No

Table 2 (continued)

Risk assessment factor	Type	Name	Description	Unit	Reference	Source of data	Open source
	QL	Classification of railway line	Contains information on the commercial classification of the line to which each section belongs: 1. node line (electric) 2. node line (diesel) 3. fundamental network (electric) 4. fundamental network (diesel) 5. complementary network—secondary lines (electric) 6. complementary network—secondary lines (diesel) 7. complementary network—low traffic lines (electric) 8. complementary network—low traffic lines (diesel) 9. complementary network—shuttle lines (electric) 10. complementary network—shuttle lines (diesel)	Classification from 1 to 10 based on the importance	TRaCCA (2016)	RFI data archive	No

* [In the case of double-track rail, the section kilometers and submerged kilometers were doubled]

Commission 2021b; GIZ, 2017; Master Adapt, 2018; Palin et al., 2021; Ranasinghe et al. 2021; Emanuelson et al. 2014):

$$R = H * E * V \quad (1)$$

Considering that H (i.e., SLR in this case) represents the probability of occurrence of a given potential phenomenon (e.g., exceeding a threshold value) in a specific period and in each area, its value is closely related to the return period, which expresses the interval of time elapsed (on average) between two successive exceedances (i.e., T2 and T100). Equation (2) was therefore applied to provide for the return period equal to 2 years a probability of exceeding of 50% and for the return period equal to 100 years a probability of exceeding of 1%.

Table 3 List, descriptions, and references of applied Sensitivity indicators (Vulnerability) in the risk assessment methodology

Risk assessment factors	Type	Vulnerability type	Name	Description	Unit	Reference	Source of data	Open source
Sensitivity (Vulnerability)	QN	functional/ performance	Average mission length of passenger trains	Sum of daily trains/ km from origin to destination of passenger services on the section divided by the total number of passenger services on the section, based on the scheduled timetable 2021–2022	km	Proposed in accordance with RFI expertise	RFI data archive	No
			Average mission length of freight trains	Sum of annual trains/ km from origin to destination of freight services on the section divided by the total number of freight services on the section, based on the scheduled timetable 2021–2022			RFI data archive	No
			Inhabitants for each municipality	Number of inhabitants per municipality of the section affected by flooding	number		Italian National Statistic Institute (ISTAT)	Yes
			Workers for each municipality	Number of workers per municipality of the section affected by flooding			Italian National Statistic Institute (ISTAT)	Yes

Table 3 (continued)

Risk assessment factors	Type	Vulnerability type	Name	Description	Unit	Reference	Source of data	Open source
			County value added	Provincial value added by province of the sections under analysis	€/county		Italian National Statistic Institute (ISTAT)	Yes
		physical	Percentage of viaduct length /total section length	Complement to 1 of the ratio between the sum of the length of viaducts on the section and the length of the section itself	1-%		RFI data archive	No
			Railway sidings	Number of industrial plan and logistic hubs connected to the railway infrastructure that would be compromised by the flooding of the section in question	number		RFI data archive	No
			Railway sections subject to slope instability and landslides	Singular points present on railway sections that have been interested in the past by instability of the slopes phenomena and by demand for special maintenance policies		Adams and Heidarzadeh, (2021)	Risks of the municipal territory represented in the general urban plan	Yes

Table 3 (continued)

Risk assessment factors	Type	Vulnerability type	Name	Description	Unit	Reference	Source of data	Open source
			Railway sections subject to floods	Singular points present on railway sections that have been interested in the past by floods phenomena and by demand for special maintenance policies		Capitol Corridor (2014)	Risks of the municipal territory represented in the general urban plan	Yes
			Railway sections subject to marine and pluvial erosion	Singular points present for railway sections that have been interested in the past by marine and pluvial erosion and by demand for special maintenance policies			Risks of the municipal territory represented in the general urban plan	Yes
			Presence of asset components	Presence of bridges, viaducts, tunnels, overpasses, subways			RFI data archive	No
			Presence of water and saltwater sensitive asset components in flood potential area	Number of water-sensitive components (i.e., central seats, technology cabins, substations, TLC cabins, passenger buildings, potentially exposed station equipment)			RFI data archive	No

Table 3 (continued)

Risk assessment factors	Type	Vulnerability type	Name	Description	Unit	Reference	Source of data	Open source
			Period of construction of asset components	Year of construction of the oldest civil work of the section under consideration among all the works of art of the asset (i.e., bridges, viaducts, tunnels, overpasses, subways)	year of construction		RFI data archive	No
	QL	functional/ performance	Synthetic tourist density index by municipality	Municipal classification of tourist density	Categorization: 5 classes by 0 to 1	Proposed in accordance with RFI expertise	Italian National Statistic Institute (ISTAT)	Yes
			Interconnection with other transport systems (c.a. 1 km)	Degree of interconnection with airports, commercial ports, tram, and subway near to the stations on the railway section	Categorization: from 0 (no interconnection) 1 (1 interconnection) or 2 (2 interconnections)	Capitol Corridor (2014)	RFI data archive	No

Table 4 List, descriptions, and references of applied Adaptive Capacity indicators (Vulnerability) in the risk assessment methodology

Risk assessment factors	Type	Vulnerability type	Name	Description	Unit	Reference	Source of data	Open source
Adaptive capacity (Vulnerability)	QL	functional/performance	% passenger trains/km referred to a long-haul connection related to passenger trains/km	Share of services that are more likely to be preserved in their mission through intermediate limitations (cancellation between B and C on a longer route from A to D) or to be rerouted on alternative paths. It is calculated as the ratio between the trains/passenger km from origin to destination related to a long-haul connection passing on the section in question and the total passenger trains/km of interest	%	Capitol Corridor (2014)	RFI data archive	No
		physical	Protection of coastal area by cliff system	Complement to 1 of the ratios between the sum of the lengths of the coast protection cliffs to the marine erosion present on the section and the length of the section itself.		Proposed in accordance with RFI expertise	Satellite imagery	Yes

$$T = 1/Ps \quad (2)$$

In the equation, T refers to the return period, and Ps refers to the probability of exceeding. For such analysis, H is assumed to be equal to Ps. As expressed in previous chapters, for this paper RCP 4.5 (for the period 2071–2100) and RCP 8.5 (for the period 2041–2070) were considered, with return periods of 2 and 100 years, at a resolution of the DEM of 2 m and 20 m. Therefore, the single probability was determined by fixing the IPCC scenario, the corresponding period of analysis and the return period (and the probabilities was aggregated). After collecting and analyzing the data, min–max normalization was applied using the following formula (Ellena et al., 2023; GIZ, 2017):

$$\mathrm{Xi} = \mathrm{xi} - \mathrm{xmin}/\mathrm{xmax} - \mathrm{xmin} \quad (3)$$

where x_i represented the individual data to be transformed, x_{max} corresponded to the highest value, and $\mathrm{x}_{\mathrm{min}}$ to the lowest value for each indicator. In this way, each X_i parameter was identified by a numerical value from 0 to 1, where the highest value corresponded to the highest contribution to each indicator, considered separately from the others. This procedure allowed all indicators of each coastal railway section to be transformed into a range from 0 to 1, facilitating cross-comparability and their evaluation across all the railway network on the coast (as described, among others, in Ellena et al. 2023). Then, we characterized the final phase of the risk index calculation by applying Eq. (1), which involves the hazard factor, the exposure (resulting from the projection of the impact of the climate hazard SLR), and the associated vulnerabilities. Ellena et al. (2023) and Pede et al. (2022) proposed a methodology for the final risk classification, using four classes to categorize the risk level: "moderate," "medium," "high," and "very high." To obtain a range of values between 0 and 1, we further normalized the final risk value in this context. We adopted this operation to create a homogeneous class breakdown, specifically ranging from 0 to 0.25, from 0.251 to 0.50, from 0.51 to 0.75, and from 0.751 to 1.00, as suggested by several studies that have applied similar techniques (GIZ, 2017; Rizzi et al., 2017). This categorization made it possible to investigate how to focus future priorities in terms of adaptation actions for coastal railway infrastructure to cope with rising sea levels. Overall, the here-applied methodology follows an existing and peer-validated process already proposed in the literature (Ellena et al., 2023; Pede et al., 2022; De Vivo et al., 2022; ISO, 2019a; ISO, 2019b; ISO, n.d.; Master Adapt, 2018; ISO, 2018; GIZ, 2017; Emanuelson et al., 2014). However, the authors of this research were able to assign a specific weight to each exposure and vulnerability indicator (OECD & JRC, 2008) by using a continuum key stakeholder engagement approach, as a base for the co-design approach. This process was conducted with the help of RFI employers, who are experienced in the management of railway infrastructure. The "swing weighting" approach was specifically used to weight the indicators of exposure and vulnerability (Ministry of Housing, Communities and Local Government, 2009). This approach uses the comparison of differences to explicitly assess how the shift from 0 to 100 on one preference scale compares to the identical shift on another scale. When making these comparisons, evaluators are advised to consider both the disparity between the least and most favored choices and the level of importance they attach to that disparity.

RFI experts were engaged in an initial stage of co-design with the aim to determine and develop specific indicators and their corresponding weights based on the following fields:

- Research and development to explore initiatives that have the potential to provide substantial benefits to the environment, society, and economy, in particular focusing on improving the infrastructure, technology, and organization of the transportation system.
- Mobility analysis and traffic studies in relation to investments in the national railway system, with a specific emphasis on conducting cost–benefit analyses.
- Research and experiments to assess the susceptibility and flexibility of railway assets to long-term climate-induced impacts. These experts are also testing novel methodologies for analyzing climate-related risks.

In this scenario, weights were assigned to each indicator, with the sum equating to 1 for each risk factor (exposure, sensitivity, and adaptive capacity).

Results and discussion

As previously stated, the findings of the applied methodology have not been included in the paper due to confidentiality reasons. Data protection is a crucial aspect that both private and public companies must manage in their risk assessment process to safeguard sensitive information related to their assets. That is why this section mainly focus on highlights, strengths, and limitations related to the methodological risk assessment framework and to the computational processes. The purpose of these analyses is to assist national and local authorities in identifying areas of high risk associated with coastal railway infrastructure. This will enable the authorities to determine suitable adaptation measures in collaboration with all relevant stakeholders. It is important to consider that SLR not only affects railway infrastructure, but also impacts other aspects of the surrounding landscape, such as roads, transportation systems, energy and communication networks, and urban areas. Therefore, it is crucial to involve these factors when planning and designing measures to safeguard the infrastructure.

In this study, the authors had the opportunity to assign a specific weight to each exposure and vulnerability indicator, which represents the most innovative methodological improvement compared to previous research in the field of risk assessment. Through an initial phase of co-design, RFI assigned a specific weight for each indicator of exposure and vulnerability based on the inner expert judgment of the different departments of competence, as reported in the "Material and methods" section. In Table 5, the exposure indicator assigns the maximum weight to "passengers' trains per day" (0.29), and the lowest weight to "percentage submerged section/length of the section" (0.11). In terms of sensitivity, "Interconnection with other transport systems (c.a. 1 km)" has achieved the highest weight (0,15), while "railway sections subject to slope instability and landslides" has been the lowest (0.02). When considering the adaptive capacity indicator weighting process, "Protection of coastal area by cliff system" (0.72) received more attention than "% passenger trains/km referred to a long-haul connection related to passenger trains/km" (0.28).

In addition, the identification of potentially submerged areas is vital to evaluating proper actions (e.g., route relocation) and adaptation measures in the design phase of new lines and infrastructure development projects. Figure 5 shows the analyzed scenarios (8 in total) as a product of hazards, exposures, and vulnerability, providing information at the regional and very high-resolution scales (from station to station). Therefore, the risk ranking from "moderate" (in yellow) to "very high" (in purple) may change based on the scenario considered, the return time under consideration, and the DEM taken into consideration. In terms of climate adaptation policy development, it is fundamental to underline that if the railway units potentially exposed to the risk of submersion in the future due to SLR have "moderate" and "medium" values of risk, they do not have to be excluded from the adaptation strategies and plans. Instead, they need to be considerate, with less priority given to intervention than those who appeared to be at "high" and/or "very high" risks. In the future, for the planning of adaptation measures, it is suggested that priority be given to those tracks for which the analysis has highlighted greater criticality. In addition, to support and guide future decisions in terms of adaptation policies, it will be necessary to consider that the cases characterized by RCP scenario 8.5 have reported results with a shorter time horizon (2041–2070) and are nearest to the time that the study was carried out.

In terms of computational processes, some critical issues emerged and required some clarification. Data availability is a fundamental aspect of conducting risk assessment analyses. This methodology substitutes the lack of high-resolution DEM with other available DEM resolutions, such as the Friuli-Venezia Giulia region. In parallel, when looking at future trends, the calculation of submerged sections could lead to some errors. For example, from the calculation of the length of the submerged section using open-source software QGIS 3.22.1-Białowieża, it emerged that some sections had a value equal to "0" or null (""). The potential flooding from SLR in this case led to many estimates of extremely short lengths (in the order of centimeters), but because the study used kilometers as the unit of measurement, the software did not account for this factor. For computational purposes, we considered stations and sections as points and lines, respectively, with a proper size, space, and specific extension. The study's already complex nature led to this choice, but future steps in the development of the proposed methodology

Table 5 List of weights obtained through the system stakeholder engagement process conducted with RFI experts

Risk assessment factor	Name	Weight
Exposure	Number of boarded/descended passengers	0.23
	Percentage submerged section/length of the section	0.11
	Passengers' trains per day	0.29
	Freight trains per year	0.20
	Classification of railway line	0.17
Sensitivity	Average mission length of passenger trains	0.17
	Average mission length of freight trains	0.07
	Inhabitants for each municipality	0.04
	Workers for each municipality	0.04
	County value added	0.03
	Percentage of viaduct length /total section length	0.05
	Railway sidings	0.07
	Railway sections subject to slope instability and landslides	0.02
	Railway sections subject to floods	0.04
	Railway sections subject to marine and pluvial erosion	0.09
	Presence of asset components	0.07
	Presence of water and saltwater sensitive asset components in flood potential area	0.10
	Period of construction of asset components	0.05
	Synthetic tourist density index by municipality	0.04
	Interconnection with other transport systems (c.a. 1 km)	0.15
Adaptive capacity	% passenger trains/km referred to a long-haul connection related to passenger trains/km	0.28
	Protection of coastal area by cliff system	0.72

will take these characteristics into account. Furthermore, the complexity of the analyzed infrastructure has prevented us from considering the construction characteristics of the line, related infrastructure, and civil structures as they truly are. This implies that if we consider the construction characteristics, potential submersions from these analyses may not pose a problem. Considering this aspect, each section identified as medium or high risk requires a detailed analysis and timely inspection, based on priority, to account for the construction characteristics in subsequent adaptation actions. Finally, the study's general assumption, which considers a section exposed only if water touches the railway infrastructure and assumes ground elevation without considering civil works or the height of the railway infrastructure, has not integrated the phenomenon of railway embankment erosion into the risk assessment process. The risk analysis has yielded valuable insights to steer future sea level adaptation policies for railway sections near RFI's coastal strip. Suckall et al. (2018) reported that coastal and delta regions could adopt various adaptation solutions to counteract the effects of sea level rise (SLR), safeguarding the asset components and service safety. These solutions could include managing the retreat of infrastructure from the coast, integrating wetland protection into infrastructure planning, considering the impacts of climate change and SLR, combining "green" and "gray" infrastructure, and enforcing municipal regulations for modified infrastructure in urban areas. Through the exploration of technical and scientific literature on railway infrastructure adaptation measures to storm surges and flooding, some "hard" adaptation measures have been implemented to safeguard the Copenhagen metro system (in Denmark) from flooding. For instance, we have designed the area around the underground station entrances to divert rainwater away from these openings. Furthermore, some underground stations have incorporated a step at their entrance. In 2020, Network Rail, the national infrastructure railway

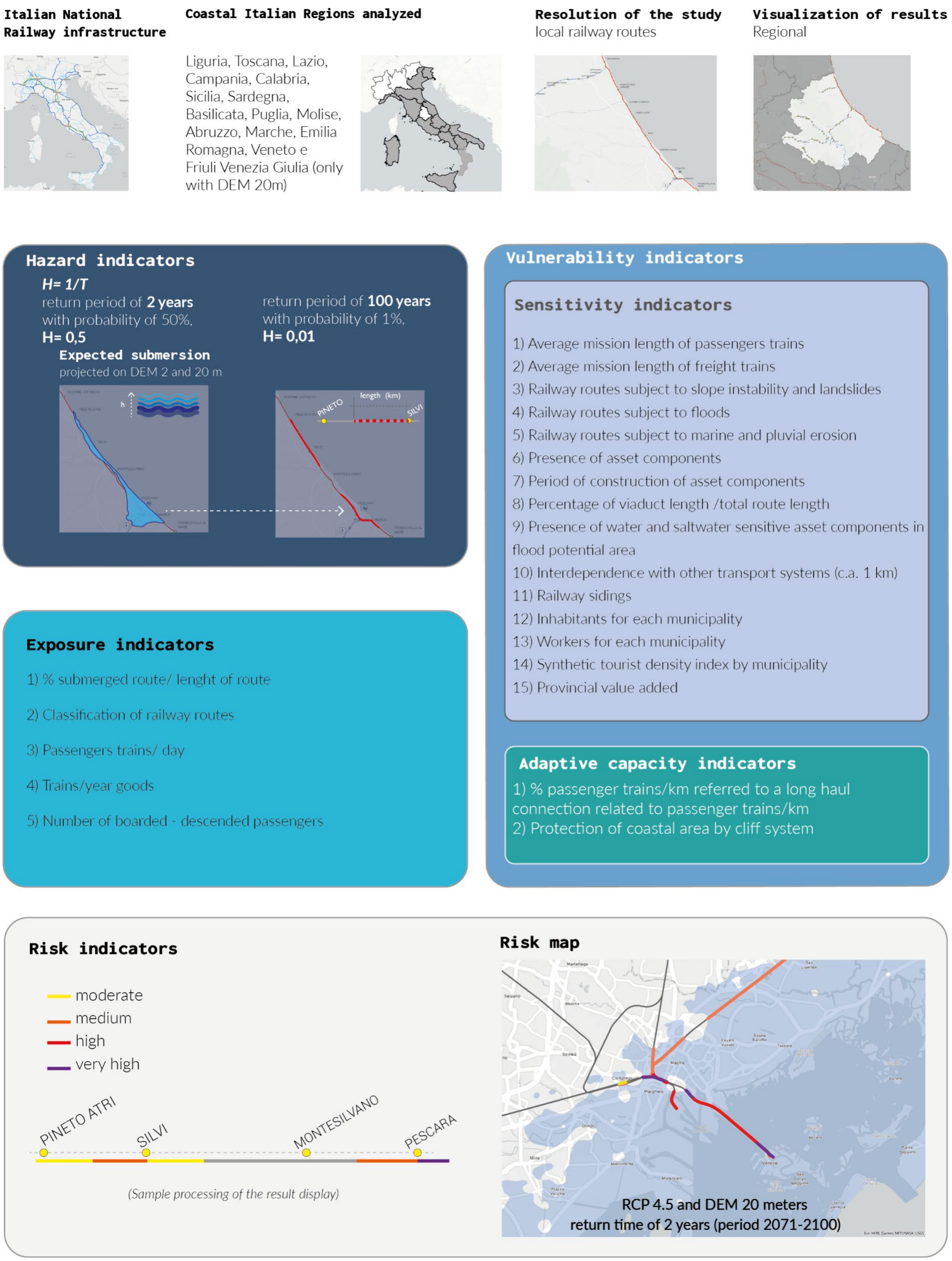


Fig. 5 Overall description of the analysed indicators and of the risk categorization

manager of the UK, implemented climate change allowances in drainage standards across railway networks to restore some submerged sites. Additionally, the same entity completed the refurbishment and reinforcement of the sea wall in Dawlish (UK) in the same year, following its destruction by an extreme weather event in 2016. The goal of the new wall was to protect the coastal railway and town from sea level rise and extreme weather events. After examining neighboring countries, the Austrian Federal Railways (BB Infra AG) made the decision to invest in climate change issues in response to numerous extreme meteorological events that had consistently damaged the railway system. The company has achieved this by introducing crisis and disaster management systems and plans, developing monitoring, modeling, and forecasting systems, and establishing early warning systems.

Conclusions

The approach proposed in this paper has been previously discussed and demonstrated in earlier research and publications (Ellena et al., 2023; De Vivo et al., 2022; European Commission, 2021b; GIZ, 2017). However, this paper is the first to employ this method in a comprehensive manner to assess the distribution of SLR risks along a national coastal railway. Currently, a widely used measure for recognizing potential risks and vulnerabilities is currently a central focus of the efforts to adjust to climate change within the climate talks (specifically, the Conference of the Parties, COP). Hence, the flexible and replicable systematic approach proposed for the Italian coastal railway infrastructure case study can serve as a foundation for conducting similar risk assessments in other nations and on various types of network infrastructure, such as roads, water distribution, and electrical distribution, at national, regional, or local levels. As research progresses, it is essential to enhance the development of risk assessment models that include multiple hazards. These models may include the effects of severe temperatures, river floods, wind, droughts, and sea level rise. They also consider the vulnerability of assets such as stations, poles, and pylons that are exposed to these hazards. Future endeavors should also include the impacts of storm surges and waves during severe occurrences. Furthermore, it is essential to take into account the interconnection with other modes of transportation and the potential ripple effects when establishing a more organized and comprehensive approach. However, although not presenting the accomplished outcomes in detail, this research establishes the foundation for future development and integration of additional systems and impacts.

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Author contribution Guglielmo Ricciardi: Conceptualization; methodology; writing-original draft; writing-review & editing. Marta Ellena: Conceptualization; methodology; writing-original draft; writing-review & editing. Giuliana Barbato: Conceptualization; methodology; writing-original draft; writing-review & editing. Emanuele Alcaras: Conceptualization; methodology; writing-original draft; writing-review & editing. Claudio Parente: writing-original draft; writing-review & editing. Giuseppe Carcasi: writing-original draft; writing-review & editing. Cristiano Zarelli: writing-original draft; writing-review & editing. Alberto Franciosi: writing-original draft; writing-review & editing. Paola Mercogliano: Conceptualization; methodology; review & editing.

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Alberto Franciosi: Writing—original draft; Writing—review & editing.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors. The authors declare that they are in compliance with the Ethical and Standards required by the Journal.

Competing interests The authors declare no competing interests.

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