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Multi-hazard risk assessment of rail infrastructure in India under local vulnerabilities towards adaptive pathways for disaster resilient infrastructure planning

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ABSTRACT

"Lifeline of the nation" is the motto of Indian Railways as it connects through a common thread, billion plus population in one way or the other. The National Rail Plan for India – 2030 focuses on creating a 'future ready' Railway system by 2030 by suitably integrating new railway systems like high-speed rails. However, rail infrastructure is exposed to multi-hazards and disasters sometimes disrupt safe rail operations. This study explores rail infrastructure risk assessment at a national scale utilizing the UNDRR framework and synthesized application of geospatial technologies with a focus on disentanglement of local vulnerabilities of the rail infrastructure assets utilizing factors of health of bridges, visibility obstruction to level crossings, labour wages & their regions and GSDP under multi-hazard scenarios. The results revealed that the NR and NFR were identified as high-risk routes under the risk analysis of physical and social vulnerability scenarios, followed by CR Railways. The average annual frequencies of emergency cases in each zone show a correlation r (17) = 0.4758 with the combined mean risk ranks for each zone. In comparison to socioeconomic factors, which contribute to indirect losses, physical factors directly affect safety and contribute to direct losses. Further, outcomes depict more accidents on Indian Railways during the monsoon (nearly 50%) and cold weather (29%) seasons. The study suggests that with the participation of key stakeholders, including urban and transport planners, an integrated approach is helpful in identifying critical rail routes towards risk-informed adaptive disaster-resilient infrastructure planning for providing safety, continuity and reliability of essential rail services.

1. Introduction

India is one of the rapidly urbanizing and economically prospering nations of Asia [1]. The establishment of transportation infrastructure such as railroads is commonly associated with rapid economic expansion [2,3]. Indian Railways continues to play an important part in the country's economy and integrating markets. It serves as a tool for political integration by connecting enormous territory. Since 2000, rail passenger travel has increased by about 200% and freight traffic by 150% in India, respectively. It demonstrates the country's social and economic success [1]. Increased urbanization will inevitably increase reliance on rail, with potential for investments in the metro, high-speed rails, and freight corridors, in addition to technological advancement and the urgent need to replace overdue assets of severely stressed existing rail infrastructure [4,5]. However, this spatially distributed network is exposed to multi-hazards causing risks in the contexts of disasters [6,7]. Of the 36 States and Union Territories in India, 27 are hazard-prone, with about 58.6% of the landmass being prone to earthquakes, 12% to flooding, and 15% to landslides, respectively [8–10]. Out of 7516 km of coast, 5700 km are vulnerable to cyclones and tsunamis [11]. The business continuity planning for rail infrastructure in India within the context of multi-hazard risk analysis was examined by Joshi, [12]. Emphasizing the significance of disaster-resilient infrastructure planning, it focuses on the primary passenger transport mode, including the newly planned High-Speed Rail. Farahani et al., [13] advance an integrated probabilistic model to assess seismic multi-hazard risk and restoration for railway systems, taking various factors into account. Chouhan, & Mukherjee, [14] unveil a survey form crafted for

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Indian Himalayan hill communities, assessing multi-hazards and emphasize the crucial role of resilient development planning for Himalayan communities in facing imminent disasters. The discussion also immersed into existing multi-hazard risk assessment survey forms utilized in India. As per Koks et al. [15], disruptions to secure train operations in India's rail infrastructure stem from the associated multi-hazard risks. This study, against this backdrop, evaluates the risk of current rail infrastructure facing natural hazards, considering local factors encompassing physical, social, and economic vulnerabilities [16]. Previous studies show that, compared to socioeconomic considerations, the physical factor significantly impacts safety [17–19]. This disentangled approach towards vulnerability is useful in the prioritization and allocation of limited resources. These finding add to the first-ever assessment of local compounding vulnerabilities using the UNDRR platform (https://www.undrr.org/) in the framework of multi-hazard risk assessment for Indian railway infrastructure zones. Risk is defined by UNDRR, formerly known as UNISDR, as the unfavorable effect of a hazard's interaction with an element's intrinsic vulnerability and exposure [20]. Risk is viewed by the UNDRR framework as a composite function that includes exposure, vulnerabilities, and hazards. Disruptions like disasters can interrupt the organization's entire operations and its ability to deliver timely services, preventing them from continuing normally. The Great East Japan Earthquake and tsunami of 2011 severely damaged the nation's infrastructure, including the railway infrastructure [21]. The transportation sector was the worst affected during the floods of 2015 in Tbilisi, Georgia; repair cost alone contributed 60% of the total damage cost [15]. These disruptions also expose the underlying vulnerabilities of a networked society, when due to Earthquake in Japan, 2011, there was a lowering of global supply of automotive vehicles. The resilience of infrastructures in the event of major disruptions is important to sustain the business, which is critical, especially in developing countries like India to keep the wheels of the economy running.

The rail transport network in India is extensive, carrying around 1160 billion passengers annually and over 22 million passengers daily, along with >3 million tons of daily freight movement. However, it is exposed to multi-hazards, posing risks in the context of disasters. The overstrained major routes further exacerbate these risks. Natural hazards magnify the challenges faced by the already severely stressed rail infrastructure, which is mainly due to overstrained networks [22]. Indian Railways Disaster Management Plan is based on the overarching framework of the National Disaster Management Plan as mandated by the Disaster Management Act, 2005. The plan is consistent with approaches promoted by the Sendai Framework for disaster risk reduction. As part of checks and balances to oversee the functioning of the various systems in place, Comptroller and Auditor CAG is the sole auditor under the Constitution of India and CAG DPC (Duties, Powers and Conditions of Service) Act, 1971 [23]. The current emphasis on disaster management over risk management in the Indian railways, as noted in the CAG Audit findings, poses challenges for infrastructure managers and policymakers, hindering informed decision-making and strategic planning for business continuity due to the absence of a comprehensive risk assessment framework. An important takeaway from the CAG audit findings is that handling disasters and responding to emergencies are prioritized more in India's railways than analyzing and controlling risks. Transport system reliability depends on increased funding and governance [22]. As reliable infrastructure is an asset and a lifeline for the country, more robust governance makes it easier to grasp the risk of disruption and plan for business continuity of the railway in the case of disasters.

The risk to rail infrastructure is dependent on the type of infrastructure itself as well as exposure to hazards and local vulnerabilities. Vulnerability is considered local in nature, it varies regionally, and the hazards cause immediate effects on the rail infrastructure. This makes infrastructure as critical or non-critical across regions, resulting in risks, which also differs across different zones in Indian Railways. In India, floods are the most severe hazards. There has been a three-fold rise in widespread extreme rainfall events across India from 1901 to 2015, which resulted in occasional surging with heavy rains and caused floodings [24]. In the last 100 years, floods have accounted for around 50% of the total disasters in India [25] and earthquake risk and vulnerability is evident from the fact that about 59% of India's land area could face moderate to severe earthquakes [26]. More than 23,000 people died due to six severe earthquakes in India between 1990 and 2006. Train accidents are significant emergency cases that can be expressed as a measure of risk, as evidenced in the study of Petrova E. [27]. Cyclones damage trees on the track, causing traffic to be suspended and heavy cyclones can also damage bridges. Fig. 1 illustrates the disruptions are the result of a disaster-management approach, and when these occur, these result in a disaster-management process, but business continuity planning approaches call for risk management prior to disasters in order to improve infrastructure resilience. The interaction between each component is grouped in two categories: (i) Proximate cause and (ii) Ultimate cause. The proximate factors cause immediate effects while the ultimate factors are considered either as root-cause or they vary regionally.

Overall, the study introduces an innovative approach by evaluating the risk of national rail infrastructure using the UNDRR framework and geospatial technologies. It meticulously examines local vulnerabilities of rail assets, factoring in elements such as bridge health, level crossing visibility, labor wages, and Gross State Domestic Product (GSDP) within a multi-hazard context. Specifically, the research delves into risk assessment for floods, seismic events, landslides with varying return periods, and severe rainfall hazards impacting visibility of level crossings. Moreover, it addresses a critical research gap by providing comprehensive risk assessments under local compounding vulnerabilities contributing to the advancement of business continuity planning.

2. Study area

The Republic of India is taken for study with focus on regional States and Union Territories. India is lying entirely in the northern hemisphere, fringed by the Great Himalayas in the north it stretches southwards and the Tropic of Cancer (23°30′N) as shown in the Fig. 2, where it tapers off into the Indian Ocean to the south between Bay of Bengal on the east and Arabian Sea on the west [28]. The boundaries extend between latitudes 6°45′ N and 37°6′ N and longitudes 68°7′ E and 97°25′ E [29]. The foothills of the Himalayas dominate the north. Winter snowfalls with alpine characteristics occur at high altitudes. The monsoon system in India was associated with two types namely North-East (NE) and South-West (SW) monsoon types [30]. The major rainfall is acquired during the SW monsoon and during the summer time (June–September) with large areas of western and central India receiving >90% of their total annual precipitation [31,32]. The extreme humidity creates an unpleasant sticky environment. The Northeast monsoon, which lasts from October to April, is less well-known than the rainy summer monsoon. During the dry winter monsoon, northeast winds blow [33]. These winds emerge from the atmosphere above Mongolia and northwestern China. The summers are very hot with temperatures of up to 50 °C. In the years following 1990, the average annual temperature was around 26.9 °C, while in the years preceding 2022, it was around 27.4 °C (https://www.worlddata.info/asia/india/index.php/).

3. Datasets and methodology

The workflow of this study was related to assess the multi-hazard (landslide, flood and earthquake) risk of railways infrastructure under local vulnerability scenario based on methodologies employed from previous research [15,18,27,34]. This study includes remote sensing observations and geospatial techniques [35] (index-based qualitative study) utilizing state-of-the-art hazard mapping combined with innovative vulnerability analysis of the rail infrastructure.

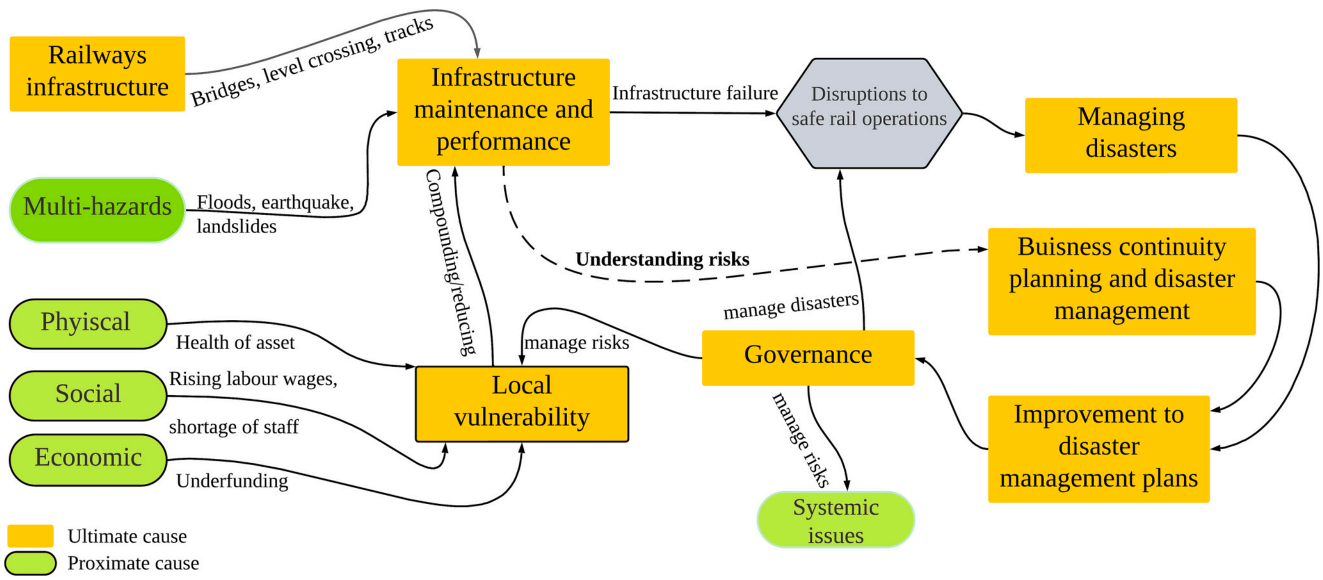

Fig. 1. The figure illustrates the mechanism of disruptions to safe rail operations, with the disruptions represented in hexagons. This representation highlights the various factors that can impact the safety and continuity of rail operations.

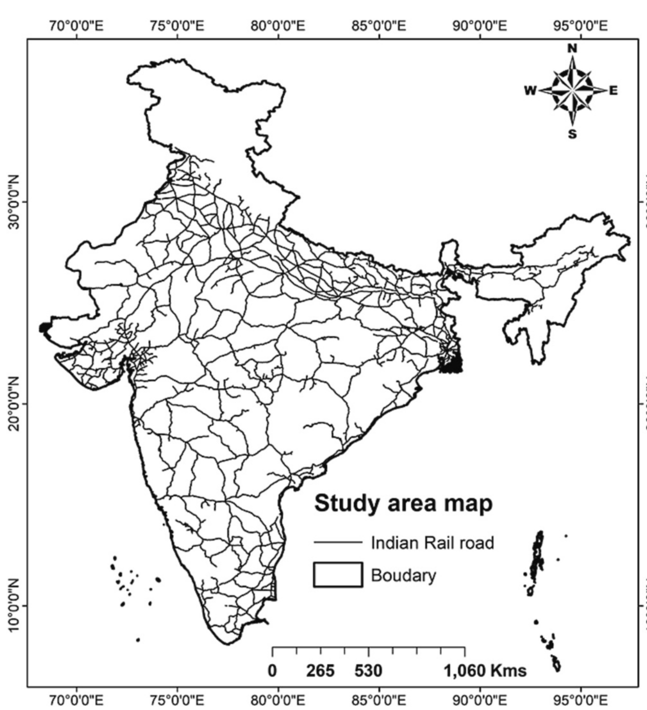

Fig. 2. The study area map shows the Indian Rail road and its boundary.

The datasets of specific needs related to multi-hazard can be acquired from the UNDRR [36,37]. We have used datasets such as peak ground acceleration (PGA), riverine flood, landslide triggered by rain for the parameters like hazard-earthquake, flood and landslide respectively from UNDRR (https://www.undrr.org/).

The liquefaction susceptibility dataset of 1Km resolution was taken for the Liquefaction hazard from Global liquefaction susceptibility by Zorn and Koks [38]. Bridges health, visibility of level crossing as a physical vulnerability dataset whereas labor wage regions, GSDP (constant prices) across the States/UTs as socio-economic vulnerability datasets were acquired from the Ministry of railways (Govt. of India) and Ministry of labor, Ministry of Statistics (Govt. of India) respectively. The datasets for the consequential emergency cases in railways was taken for the ground truth/emergency cases from the Ministry of Railways (Govt. of India), EM-DAT OSM, GitHub Creative Commons. The average annual rainfall of 0.25-degree resolution for the rainfall scenario was taken from the IMD (https://mausam.imd.gov.in/). The datasets utilized in the study for risk assessment of multi-hazards exposed rail infrastructure under local vulnerabilities are provided in Table 1.

The datasets like rail infrastructure routes exposed to multi-hazards are spatially identified and mapped for different return periods on GIS platform. The usage of hazard datasets like liquefaction susceptibility with the coarse resolution makes it convenient for countrywide spatial analysis. The liquefaction susceptibility maps provide nationwide coverage of hazard-exposed rail infrastructure, eliminating the need for the cumbersome approach of conducting soil tests at individual sites.

Table 1
Datasets utilized in the study for risk assessment of multi-hazards exposed rail infrastructure under local vulnerabilities.

Parameter	Data	Spatial Resolution	Source
Hazard-Earthquake, Flood, Landslide	PGA, riverine floods, landslide triggered by rains	7Km,1Km, 8Km	UNDRR (https://www.undrr.org/)
Liquefaction hazard	Liquefaction susceptibility	1Km	Zorn, & Koks, E [38] (https://research.vu.nl/en/datasets/global-liquefaction-susceptibility-map-2)
Physical	Bridges health, visibility of level crossing	N/A	Ministry of Railways (Govt. of India)
Socio-economic	Labour wage regions, GSDP (constant prices) across the States/UTs	N/A	Ministry of labour, Ministry of Statistics (Govt. of India)
Ground Truth/ Emergency cases	Consequential emergency cases in Railways	N/A	Ministry of Railways (Govt. of India), EM-DAT
Railways network	Railways lines, zones	N/A	OSM, GitHub Creative Commons (https://github.com/geohacker/railways)
Rainfall scenario	Annual average rainfall-across the States/UTs	N/A	IMD (Govt. of India) (https://mausam.imd.gov.in/)

The exposure of railway infrastructure to hazards does not automatically result in risks, as consideration of local vulnerability factors is critical for risk understanding and assessment. Primarily the actual health of railway assets like bridges and tracks play a critical role in understanding the physical vulnerability of the system. This study assesses the physical vulnerability factor for the bridge health reported as ORN numbers in railways. ORN 1, 2 and 3 bridges requiring special repairs on priority (ORN 1 being the most critical). For the social vulnerability factor, labor wages have a critical impact on the construction and maintenance cost of railway infrastructure and is important to consider for setting priorities for repairs to exposed critical railway infrastructure under the multi-hazard scenario. The GSDP is taken as an economic factor due to underfunding by respective States to Railways. It is an apt parameter to assess economic vulnerability across regions for level crossings (with TVU $\geq$ 100,000) having constraints of visibility (which can be there due to various reasons like the presence of permanent obstructions, steep gradients etc.) under the heavy rainfall hazard scenario. Then, the physical, social, and economic vulnerability indicators, namely ORN signifying health of bridges, visibility obstruction of level crossings, labor wages and their regions and GSDP were analyzed to prepare vulnerability maps. This study used the risk assessment methodology which is considered as function of hazard, exposure and vulnerabilities and a framework adopted by UNDRR (https://www.undrr.org/) which is as follow;

$$\text{Risk} = f(\text{Hazard}, \text{Exposure}, \text{Vulnerability})$$

Since, risk assessment involves either a qualitative or a quantitative evaluation to determine the nature and extent of risks in the context of hazards, exposure, and vulnerabilities. Therefore, integrating the direct and indirect losses, a qualitatively study based on hazard, exposure, and vulnerabilities is carried out in this study towards risk assessment of the rail infrastructure in India. An index-based modelling using ranking criteria method is used to assess the vulnerabilities of existing local rail infrastructure, along with multi-hazard as illustrated in Fig. 3.

The study further attempts to validate the risks obtained under the physical, social, and economic vulnerabilities of existing infrastructure by analyzing the consequential emergency cases recorded in the system, which serve as ground truth cases and also serve as the comprehensive indicator of risk assessment as it combines all the factors of risk: hazard by its physical parameters, exposure of facilities in a hazard area and vulnerability that links intensity of hazard to undesirable consequences [27]. The risk level is estimated for each Zonal Railway by the average annual number of emergency situations (accidents) since the year 2005 to 2020 as recorded in the safety system of the Ministry of Railways. Petrova E. [27] qualitatively assesses transport infrastructure risk using historical case records, aligning with the UNDRR framework. Understanding the UNDRR framework involves defining its building blocks. Qualitative and quantitative risk profiles aid advocacy in adopting strategies [39]. Quantitative risk assessment gauges asset damage value and estimates business losses under specific risk conditions. Qualitative processes, including ranking criteria and index-based models, assess risk and indicate resilience characteristics against disasters. These processes rely on ranking criteria tied to threshold paradigms for risk drivers like hazard scenarios, exposure, and vulnerability [18,34]. Direct losses correlate with ranks in the physical vulnerability driver of risk, while indirect losses are ranked under the socio-economic-environmental vulnerability driver. However, a significant constraint is the limited availability of vulnerability information, particularly for direct loss estimation. Vulnerability analysis, especially for diverse elements like bridges with varying fragility across types and components, can be intensive [39,40]. Additionally, fragility curves differ across assets, health conditions, regional variations, and lack specificity for Indian Railways.

4. Results

The results of the study are presented by analyzing risks for hazard-exposed existing rail infrastructure regions under physical, and socio-economic vulnerability scenarios and further validation using ground truth consequential emergency cases with mapped risks for regions.

4.1. Risks to existing rail infrastructure under local vulnerabilities

Vulnerability is a defining local component in the risk assessment

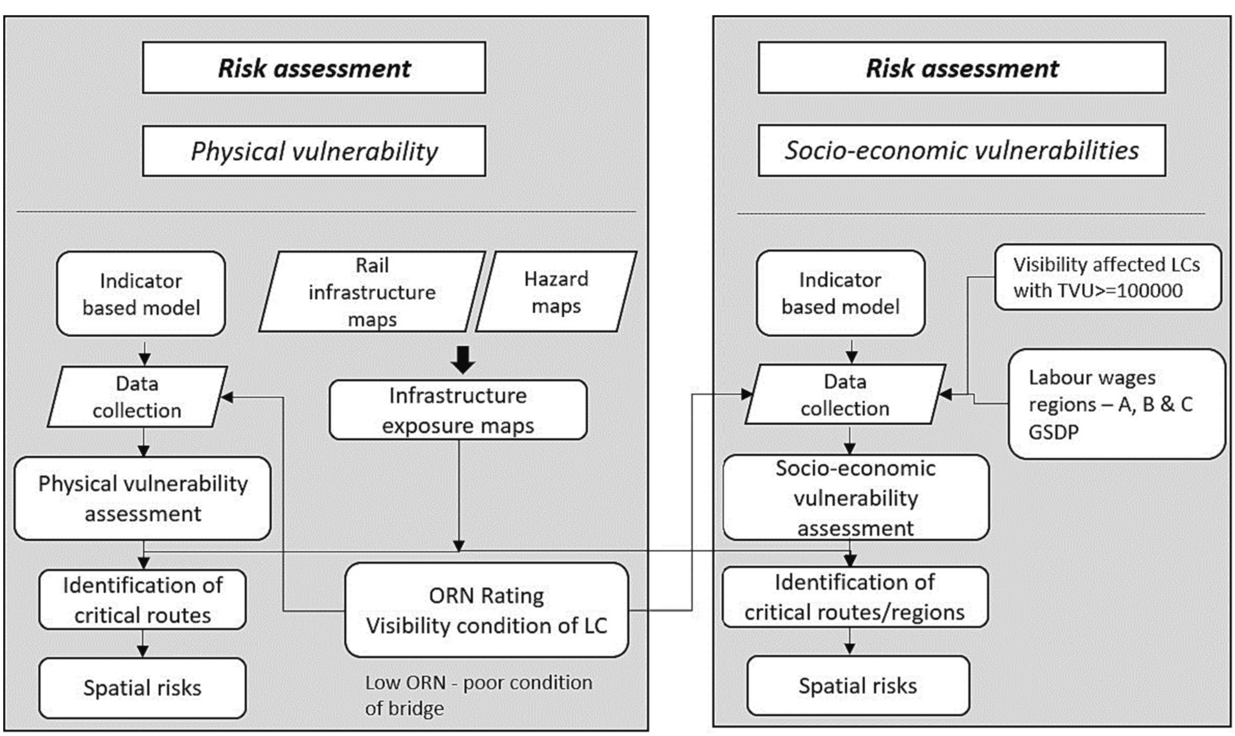

Fig. 3. The methodology figure illustrates the study's detailed steps for analyzing local vulnerabilities in the existing rail infrastructure.

framework as it increases the disruption susceptibility of assets or systems to the impacts of hazards and most of the global risk assessment studies have little information regarding this aspect. The levels of vulnerability help to explain why some non-extreme hazardous events can lead to extreme impacts to existing infrastructures while some extreme events do not.

Vulnerability is the physical, social, economic, and environmental susceptibility of assets to suffer loss and damage under a hazard of given severity and is indicative of the adaptive or coping capacity of the infrastructure under hazard scenario. As the environmental vulnerability require spatial assessment on finer scale and owing to limited scope, in this study only physical, social and economic aspects of vulnerabilities are considered for multi-hazard risk assessment of rail infrastructure. Koks et al. [15] put a global analysis built around transport infrastructure as part of their risk estimate. These factors in general relate to infrastructure and talking about Railways in Indian context contribute to regional variations and the key to understanding local vulnerabilities. The critical local compounding vulnerabilities are attached to the underfunding, rising labour costs resulting in high cost of maintenance, and physical condition of the assets.

4.1.1. Risk exposed rail infrastructure regions under physical vulnerability

The physical factors are related to the design, construction and maintenance and is reflective of the health condition of the asset.

(a) The results of the risk analysis of physical vulnerable rail infrastructure under landslide hazard scenario is shown in Fig. 4. The critical railway routes exposed to landslide hazard were ranked into five railways zones from low to extreme (rank 1 to rank 5). The four different maps of railways zones were created namely railways zone: under landslide susceptibility, railways zone: exposure of rail infrastructure under hazard (rank 3, 4 and 5), railways zone: physical vulnerability ranking (vulnerable zones) and railways zone: risk to rail infrastructure respectively. The outcomes depicted that railway zones under land slide susceptibility were NR, NFR, SWR under low to medium ranking. The railway zones under the exposure of rail infrastructure showed the rank 3 to 5 for NR, NFR, SWR. Further, the railway zones under the physical vulnerability ranking showed the NR, SER and WR railways (3 to 5 ranking). Therefore, the results highlight critical routes having risks in the zones of NR, NFR, CR, SER and WR under physical vulnerable of landslide hazard scenario. The risk analysis under landslide hazard scenarios was performed over Nilgiri district, India for selecting appropriate landslide risk reduction strategies to control risk over the infrastructure [41]. Bil et al. [42] and Schlögl et al. [43] also assessed the landslide hazard, one among the natural hazards responsible for, disruption in the infrastructure and showed the impacts of interruptions caused by landslide hazard scenarios.

(b) The result of the risk analysis of physical vulnerable rail infrastructure regions under earthquake hazard scenario is shown in Fig. 5. The outcome of the study has shown the risk under earthquake hazard for five different return periods namely 250 years, 475 years, 975 years, 1500 years, 2475 years and ranking from low to extreme (rank 1 to rank 5). The earthquake hazard exposed rail infrastructure under return periods showed the critical routes having risks in the zones of NR, CR, WR, ECR, SER and NFR. According to Wang et al. [44] the assessment of the risk of current and proposed railway assets with regard to two major natural disasters, earthquakes and flood across 50 nations

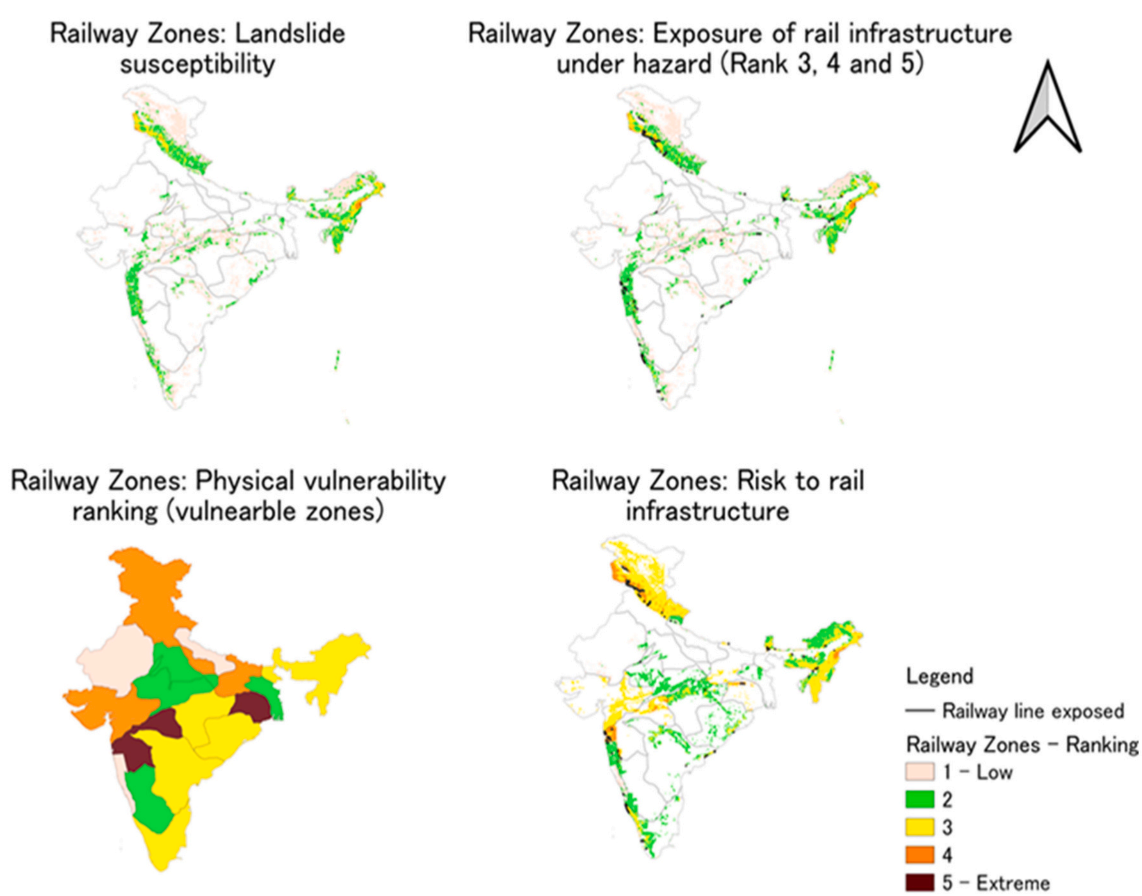

Fig. 4. Identification of critical railway routes exposed to landslide hazard under physical vulnerability of railway bridges.

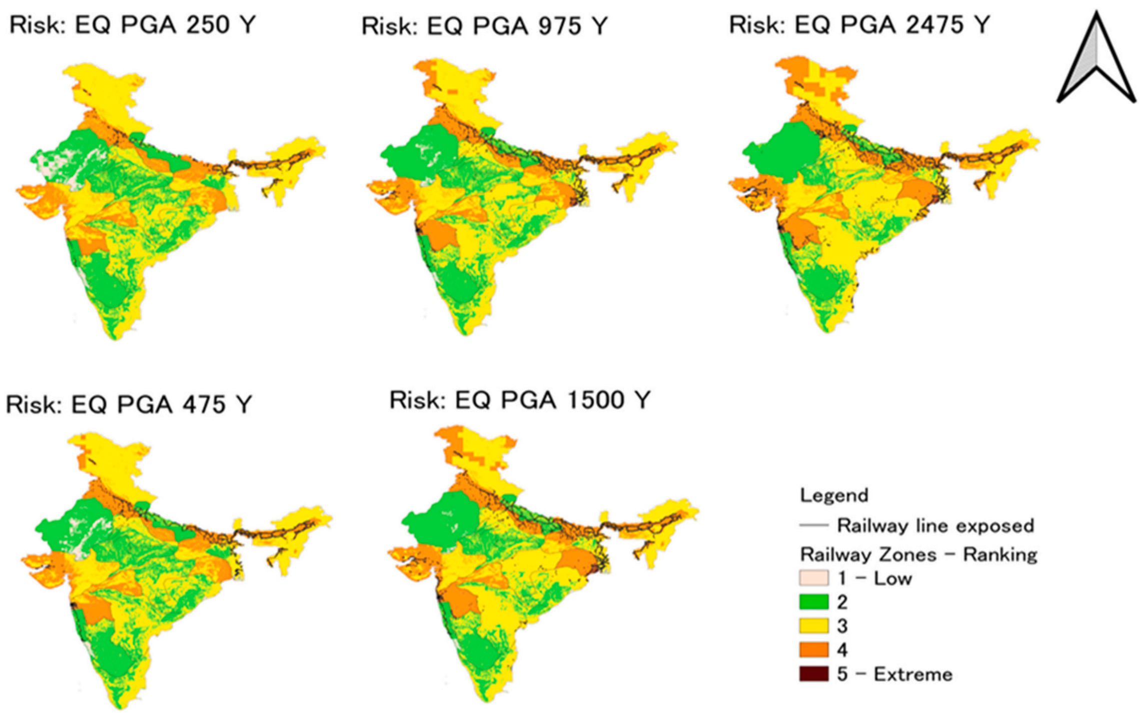

Fig. 5. Identification of critical railway routes exposed to earthquake hazard under physical vulnerability of railway bridges. Here EQ denotes the earthquake and PGA depicts the peak ground acceleration during the earthquake shaking a location.

including Indochina, 22.3% are vulnerable to an earthquake event that happens once every 475 years.

(c) The result of the risk analysis of physical vulnerable rail infrastructure regions under flood hazard scenario is shown in Fig. 6. The outcome of the study has shown the risk under flood hazard for different return periods namely 25 years, 50 years, 100 years, 200 years, 500 years,1000 years and ranking from low to extreme (rank 1 to rank 5). The risk for flood hazard, the rail infrastructure was found critical in the following zones during different periods of 25, 50 years: ECR, SER, ER, NFR; 100, 200 years: ECR, SER, NR, ER, NFR; 500, 1000 years: ECR, NR, CR, SER and NFR. The outcomes demonstrated that larger portions the study region are affected with risk due to flood hazard under different return

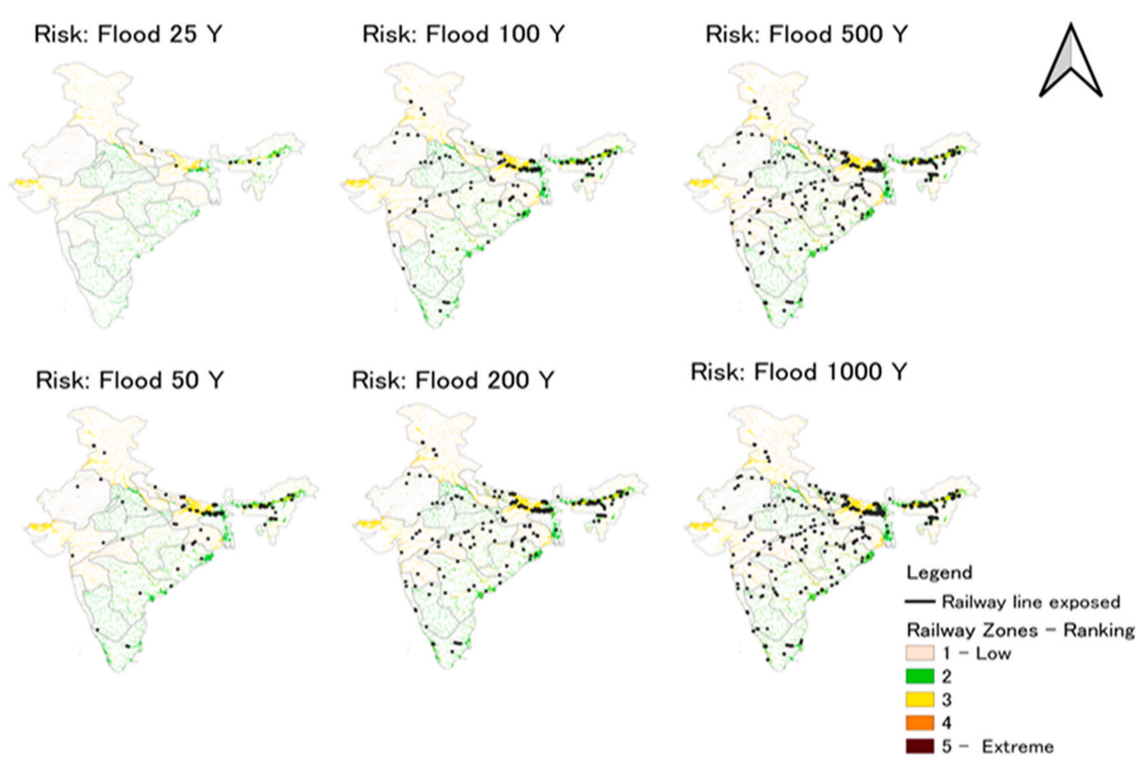

Fig. 6. Identification of critical railway routes exposed to flood hazard (different return periods) under physical vulnerability of railway bridges.

period. The root causes of many sorts of travel accidents and delays, including those involving road, rail, air, and waterways are revealed, as are the contributions of various natural hazards. Among them, studies showed the meteorological hazards namely flood and rains as largest contributors to transport accident and disruptions [27,45–47].

4.1.2. Risk exposed rail infrastructure regions under social vulnerability

The social factors include social status reflective of income profile, age profiles and literacy rate.

(a) The results of the risk analysis of rail infrastructure regions exposed to landslide hazard under social vulnerability scenario is shown in Fig. 7. Similar to physical vulnerability, the critical railway routes exposed to landslide hazard were ranked into five railways zones from low to extreme (rank 1 to rank 5) and four different maps of railways zones were created for detailed analysis. The NR, NFR followed by NER were found as more critical railways routes under land slide susceptibility. The ER, SWR followed by the NR and SR were also found as critical railways routes under the social vulnerability ranking (labour wages regions). Overall, the results highlight critical routes having risks in the zones of NR, SR and CR.

(b) The results of the risk analysis of rail infrastructure regions exposed to earthquake hazard under social vulnerability scenario is shown in Fig. 8. Under the social vulnerability, the risk for risk for earthquake hazard, during different return periods of 250 years, 475 years, 975 years, 1500 years, 2475 years, the rail infrastructure was found critical in the zones of NR, NER, WR, CR and ER.

(c) The results of the risk analysis of rail infrastructure regions exposed to flood hazard under social vulnerability scenario is shown in Fig. 9. The results of this study revealed the risk of flooding hazard over multiple return periods, including 25 years, 50 years, 100 years, 200 years, 500 years, and 1000 years, and ranked from low to extreme (rank 1 to rank 5). The risk for flood hazard, the rail infrastructure was found critical in the following zones during different periods of 25, 50 years: NER, ER; 100, 200 years: NER, ER, ECOR and NFR; 500, 1000 years: NER, ER, NFR, SCR and SR. Other zones start reaching moderate level of risks under increasing return periods.

4.1.3. Risk exposed rail infrastructure regions under economic vulnerability

The economic factor includes GDP health, supply chains including materials supply. The results of risk analysis of economically vulnerable rail infrastructure regions of level crossings combined with rainfall hazard scenarios is shown in Fig. 10. The results show that States which have high economic vulnerability their corresponding railway zones also have high risks under economic vulnerability. Still, State like Kerala in spite of having good economic situation has very high risk owing to high presence of rainfall hazard exposed visibility affected level crossings.

Therefore, the critical rail infrastructure routes exposed to multi-hazards (landslide, flood and earthquake) are identified and mapped through risk assessment under each vulnerability scenarios (physical, social and economic) and the results showed zones of NR and CR are having extreme risks while the zone of NWR has the lowest risk.

Plotting risks across IR: The risk obtained under each vulnerability scenario is useful for identifying the approaches for vulnerability reduction. Further, the combined risk scenarios are further explored in this section under the assumption of similar damage occurring under the same risk and the results are shown in the box-plot form for mean individual risks for the whole of Indian Railways along with combined risks for each hazard and vulnerability scenario are also plotted as shown in Fig. 11(A to D).

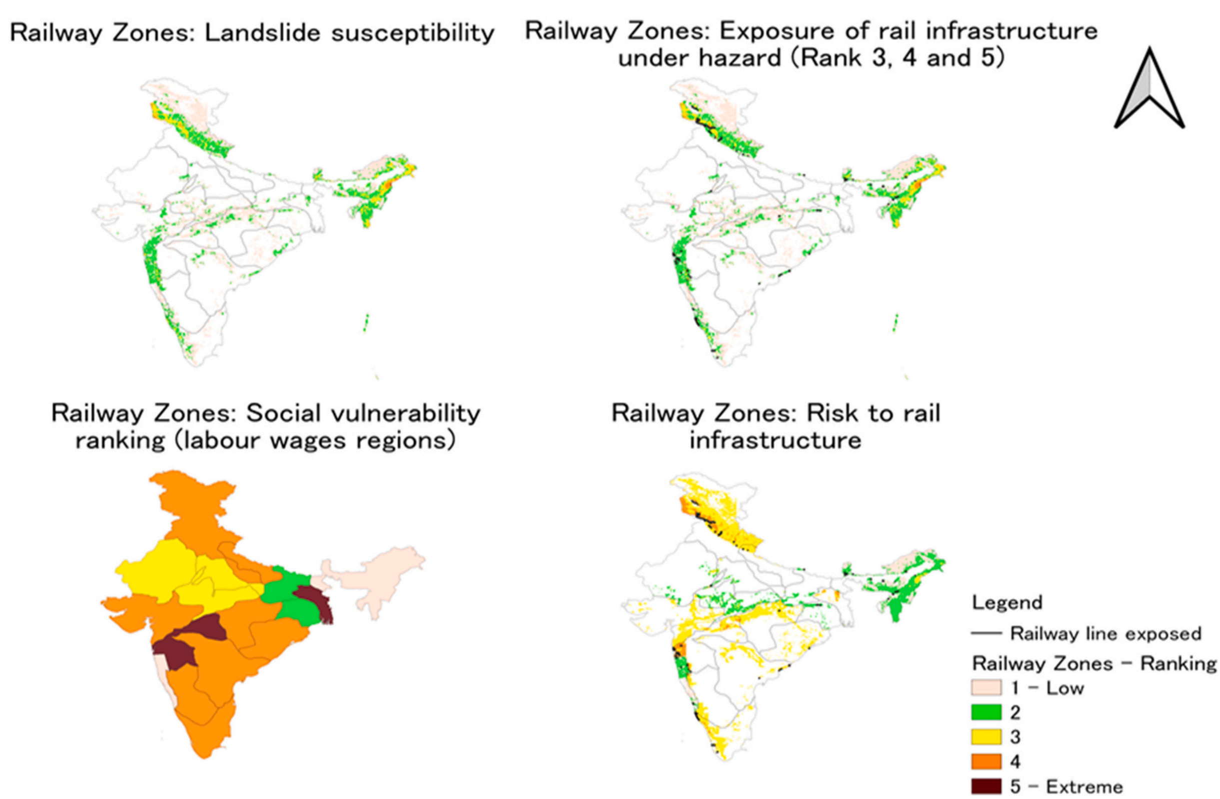

Fig. 7. Identification of critical railway routes exposed to landslide hazard under social vulnerability of differential regional labour wages.

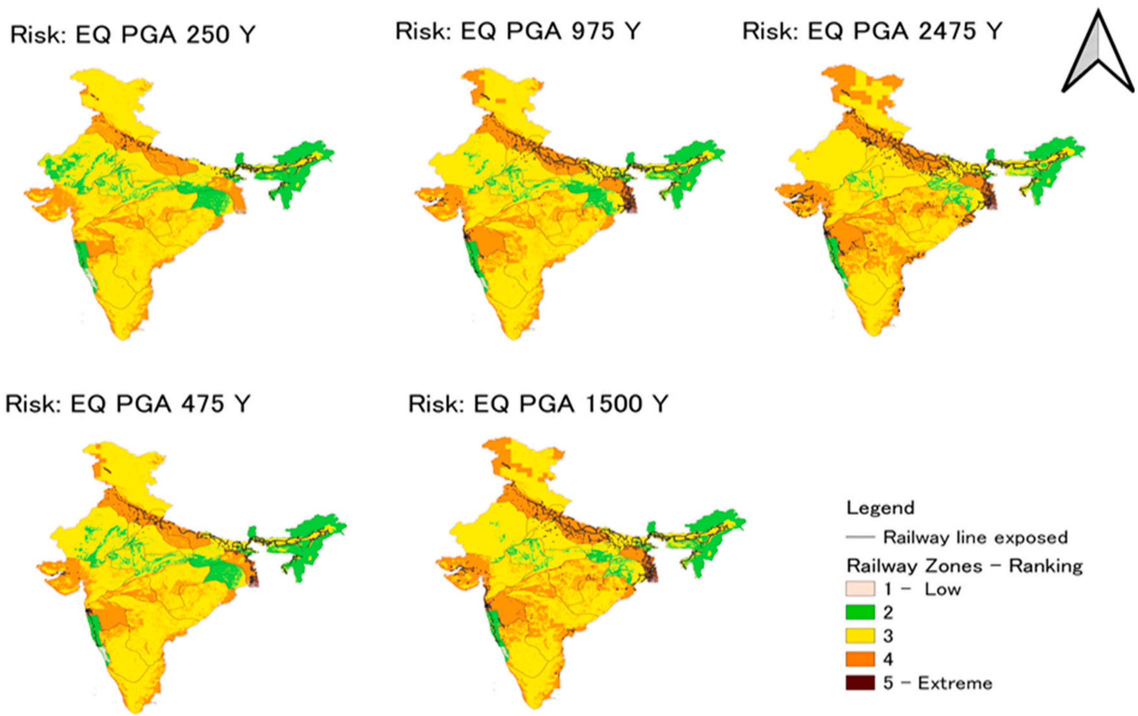

Fig. 8. Identification of critical railway routes exposed to earthquake hazard under social vulnerability of differential regional labour wages.

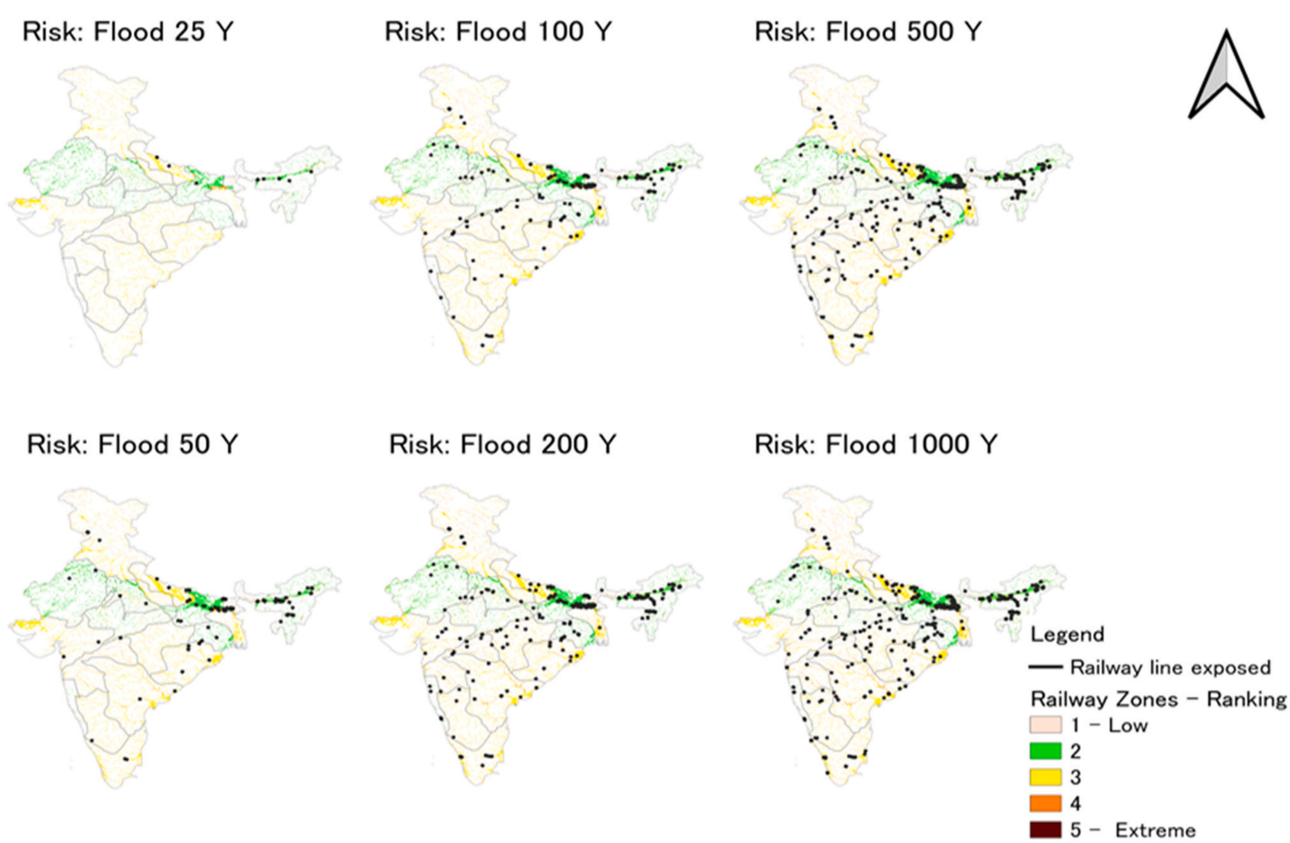

Fig. 9. Identification of critical railway routes exposed to flood hazard under social vulnerability of differential regional labour wages.

4.2. Validation of risks of existing rail infrastructure regions with consequential emergency cases

The average annual number of emergency situations recorded in the system from the year 2005 to the year 2020 is normalized and the risk profile of each Zone in Indian Railways is then mapped as shown in Fig. 12 along with the season-wise profile of emergency cases [48].

The zone of NR has the highest risk and the zone of NWR is among

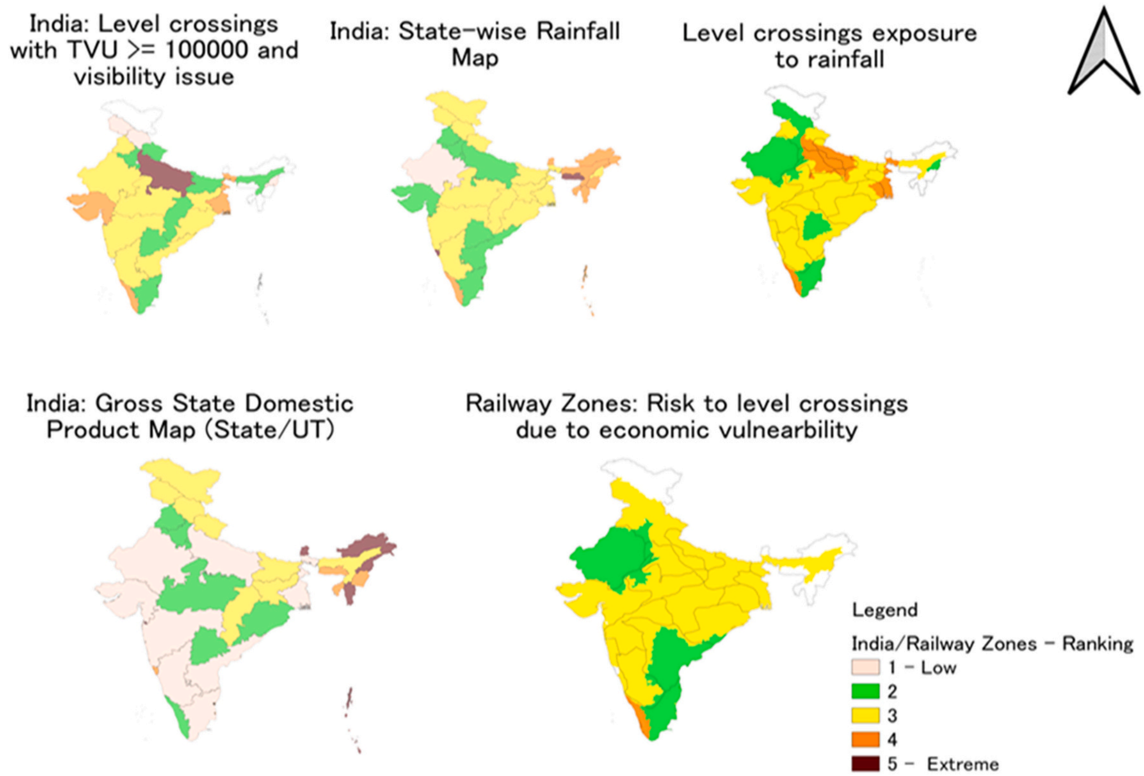

Fig. 10. Identification of critical railway zones having level crossing infrastructure exposed to heavy rainfall hazard under economic vulnerability of differential GSDP.

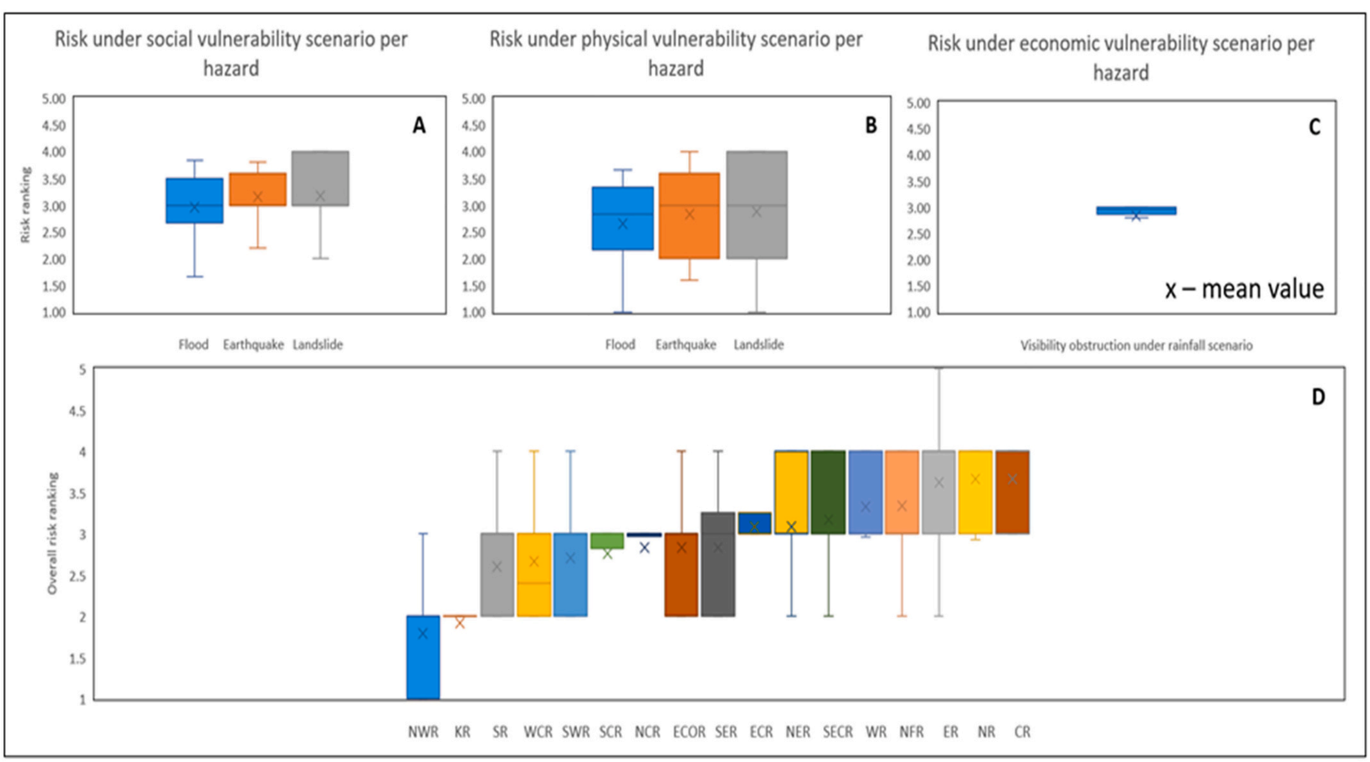

Fig. 11. Plotting risks for vulnerable railway zones in IR exposed to multi-hazards.

the lowest risk affected zones after analyzing consequential emergency cases scenario vide Fig. 12, which is validating with the mean risk rank in box plot for each zone in Indian Railways in Fig. 11 (image D). The coefficient of correlation of average annual frequencies (AAF) of emergency cases in each zone with combined mean risk ranks for each zone, is found as, r (17) = 0.4758 and is found moderately correlated

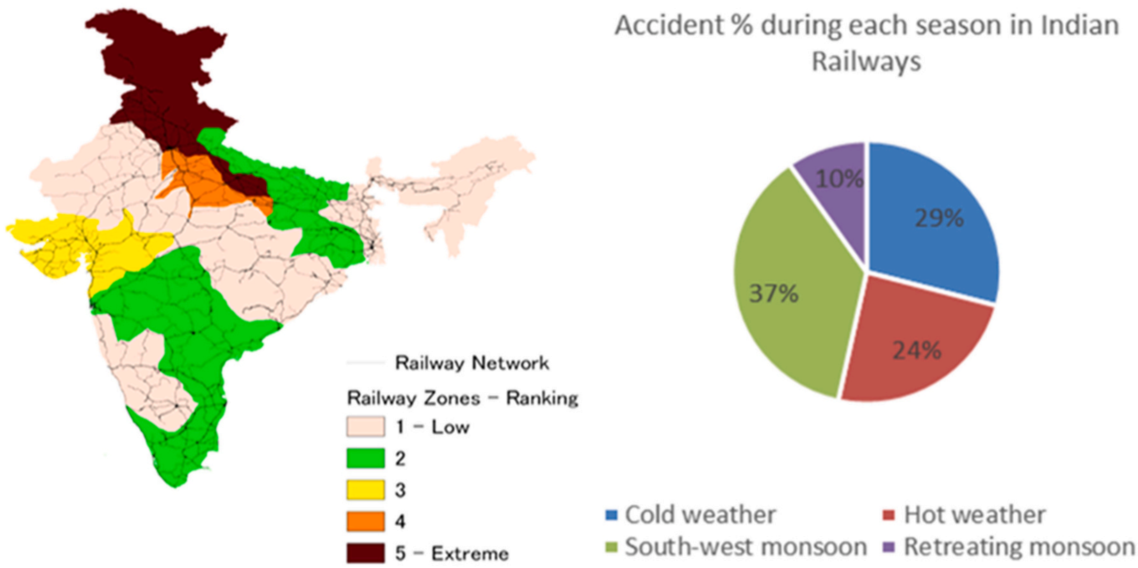

Fig. 12. Risks across IR as per consequential emergency cases with seasonal profiling of emergency cases in IR (right image).

(significant at $p < 0.1$). Similarly, for individual correlation of emergency cases with risk under physical, social, and economic vulnerabilities, the results are obtained as r (17) =0.4605 (significant at $p < 0.1$), 0.2946 and 0.0512 respectively. Significant at $p < 0.1$, the correlation was found moderately correlated and the results were indicative of the fact that consequential emergency cases not only include natural disasters but systemic issues as well besides estimated risk ranks were qualitative in nature. The results were indicative of the fact that the physical factors contribute to direct losses as they affect safety directly in comparison to socio-economic factors which contribute to indirect losses as was observed in the study of [18] and most of the emergency situations in Indian Railways are mainly registered in monsoon season (nearly 50%) as per Fig. 12 (right image) followed by cold weather season [12,49,50].

5. Discussion and policy implications

The study is the first to demonstrate the applicability of the UNDRR framework for the rail infrastructure in India wherein, the risk assessment is carried out for rail infrastructure regions in India exposed to different scenarios of natural hazards under disentangled approach to address each local compounding vulnerability. This research used a ranking criterion-based assessment approach. Five groups of low to extreme patterns are identified for identifying risk-affected critical rail infrastructure and railway routes and subsequently mapped. The study enables movement towards the key aspect of "understanding risks" which is a common link among various frameworks such as Sendai Framework, National Disaster Management Plan and Business Continuity Planning and is useful in identifying critical rail infrastructure regions in India (extreme risks) and strengthening spatial planning for building resilience and system adaptiveness. The consequential emergency cases represented by average annual frequency values are inclusive of not only natural disasters but other accidents involving technical issues besides the risk ranks themselves being qualitative indicators and is the reason for moderate correlation with the proposed methodology of the study. While analyzing the seasonal variations, it is observed most of the emergency situations in Indian Railways are mainly registered in the monsoon season (nearly 50%) owing to washout or flooding of railway tracks due to heavy rains or floods, accidents at level crossings due to poor visibility in heavy rains, other processes contributing such as landslides, debris flows, and rockfalls across Indian Railways. However, the quantitative outputs for multi-hazards processes can be explored further by utilizing advances in remote sensing-based disaster monitoring and assessment, as suggested by Im et al., [51] and utilizing Synthetic Aperture Radar (SAR) technology, as suggested by Aditiya A. et al., [52]. Such approaches allowing finer spatial scale, should be integrated for other hazards like cyclones, subsidence etc. Duly incorporating other vulnerability factors like vacancies of maintenance staffs, health of assets like embankments, tunnels etc., towards comprehensive risk analysis. The hazard maps utilized in the study are based on empirical modelling results which have inherited uncertainties and errors and results should be carefully used. The results of this study can be directly utilized for setting the priority of critical rail infrastructure damage reduction projects, including priority elimination of overaged assets with high risks and better plan spatially new rail infrastructure for safe rail operations either through high-quality quantitative risk analysis or heuristic approach by infrastructure managers in assessing damage costs (Fig. 13). Thereby through identifying regions of physical, social and economic vulnerability separately under the hazard exposure, the risk assessment study provides a platform to work towards addressing those vulnerabilities. Addressing the identified vulnerabilities requires the participation of numerous stakeholders, including urban and transport planners, as hazards like floods, earthquakes cannot be dealt in isolation but requires an integrated systems approach. This will help in identifying key routes towards risk-informed adaptive disaster-resistant infrastructure planning for providing safety and reliability of essential rail services.

6. Conclusion

This study deals with multi-hazard risk assessment of rail infrastructure in India under local vulnerabilities towards adaptive pathways for disaster-resilient infrastructure planning. A qualitative study based on a ranking criterion for the hazard, exposure, and vulnerabilities is carried out towards risk assessment of the rail infrastructure in India. The existing rail infrastructure exposure maps are created by overlapping the railway infrastructure with natural hazard maps of the UNDRR project under different return periods utilizing advanced GIS techniques. The spatial infrastructure of railways is studied under multi-hazards like landslides, seismic coupled with liquefaction susceptibility, and flood scenarios of different return periods, including heavy rainfall hazards considering the average annual rainfall of India. Therefore, this study can be used to better understand risks and further plan, develop and manage risk-informed adaptive disaster-resilient rail infrastructure

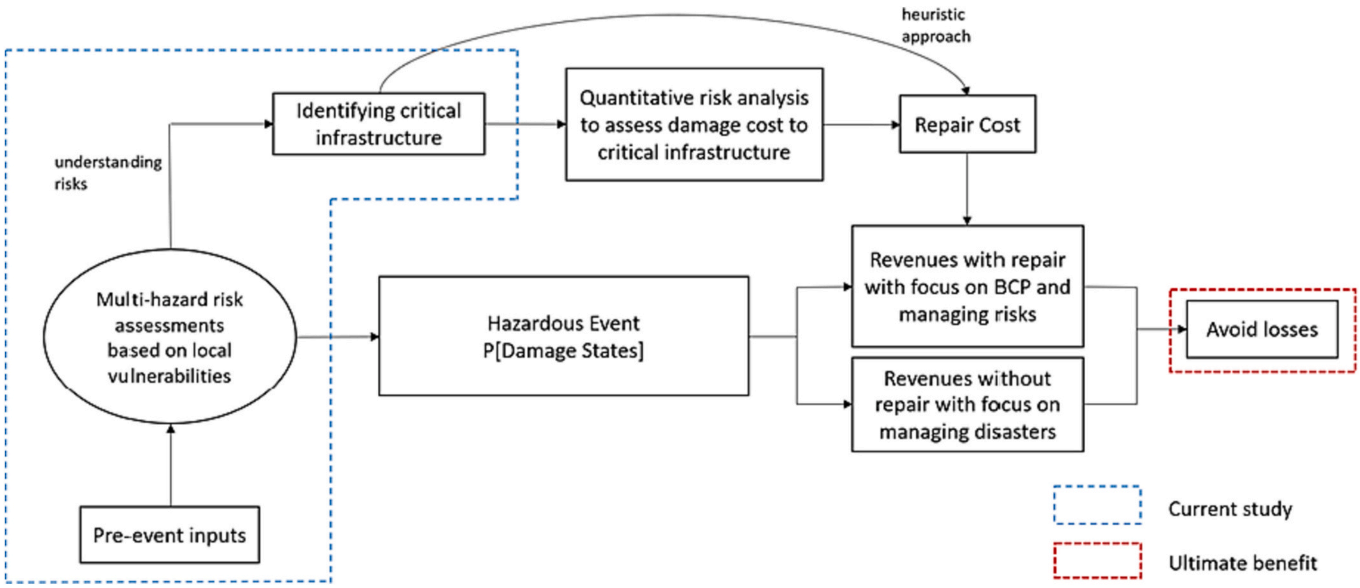

Fig. 13. Benefits of risk assessment under UNDRR framework for IR infrastructure.

in India in the near future to work towards business continuity planning.

(i) The Zones of NR, and NFR, followed by CR, were found as critical routes having risks under risk analysis of physical and social vulnerability scenarios, while the zone of NWR has the lowest risk.
(ii) Despite having a good economic situation, a state like Kerala has very high risk owing to the high presence of rainfall hazard exposed visibility affected level crossings.
(iii) The study further attempts to validate the risks obtained under the physical, social, and economic vulnerabilities of existing infrastructure by analyzing the consequential emergency cases recorded in the system that serve as ground truth cases. The coefficient of correlation of emergency cases with combined mean risk ranks is found as 0.4758 and is found to be moderately correlated.
(iv) Individual correlation of emergency cases with risk under physical vulnerability (0.4605) was higher than social and economic vulnerability (0.2946 and 0.0512, respectively), demonstrating that physical factors have contributed to direct losses as they affect safety directly compared to socio-economic.

Since this study is an attempt to provide a risk assessment to fill in the existing research gaps towards understanding risks under local compounding vulnerabilities and is the right first step towards high-quality risk analysis for rail infrastructure in India. Therefore, this study can be used to better develop railways infrastructure and management plans in the near future towards business continuity planning in Indian Railways.

Author contributions

D.J. and W.T. designed the study. D.J. collected all the data and underlying information and further carried out the hazard, exposure, vulnerability and risk analysis. D.J., R.A., N.K. and W.T. contributed to conceptualizing the paper, draft preparation and review. All authors contributed to the paper and gave final approval for the publication.

CRediT authorship contribution statement

Dheeraj Joshi: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Project Administration, Validation, Visualisation, Writing - original draft, Writing - review & editing. **Wataru Takeuchi:** Conceptualization, Software, Project Administration, Supervision, Validation, Writing – original draft, Writing – review & editing. **Nirmal Kumar:** Resources, Validation, Writing – original draft, Writing – review & editing. **Ram Avtar:** Software, Project Administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Railways and their abbreviation

Railways	Abbreviation
Central Railway	CR
East Central Railway	ECR
Eastern Railway	ER
North Central Railway	NCR
North Eastern Railway	NER
North Western Railway	NWR
Northeast Frontier Railway	NFR
Northern Railway	NR
South Central Railway	SCR
South Eastern Railway	SER
South Western Railway	SWR
Southeast Central Railway	SECR
Southern Railway	SR
West Central Railway	WCR
Western Railway	WR
Konkan Railway	KR
Gross State Domestic Product	GSDP
United Nations Office for Disaster Risk Reduction	UNDRR
Peak ground acceleration	PGA
General of India Office	CAG
India meteorological department	IMD
Overall Rating Numbers	ORN
Train Vehicle Units	TVUs

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