JOWRM

Journal of Water Resources Management

Journal homepage: https://journal.water.gov.my

e-ISSN: 2811-3578

Mapping Global Research on Railway Flood Impacts: A Bibliometric Review

Surachai Airak[1,a*], Sitti Asmah Hassan[1,b], Nor Eliza Alias[1,c], Nordiana Mashros[1,d]

[1]Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

**Corresponding author: sasmah@utm.my*

Email: [a]surachai@graduate.utm.my, [b]sasmah@utm.my, [c]noreliza@utm.my, [d]mnordiana@utm.my

Received 15 June 2026;
Accepted 16 Oct 2026;
Available online 21 Oct 2026

Abstract: Flooding is one of the most disruptive climate-induced hazards affecting railway and wider transport systems across the globe. However, the trends and thematic priorities of research in this domain remain scarce. Although research on railway flood risk is expanding, its global scope and focus areas are still not well understood. This paper uses a bibliometric approach to examine how the field has developed and where the main knowledge clusters lie. A total of 2,608 peer-reviewed journal articles indexed in Scopus up to 23 June 2025 were retrieved, cleaned, and standardised before being analysed using VOSviewer. Co-authorship and keyword co-occurrence networks were analysed to their thematic patterns. Results show that research output has increased significantly since 2010, with the United States and China contributing the largest volumes, followed by an expanding Asia-Pacific cluster and limited input from low-income regions. Three dominant thematic areas emerge: climate risk and resilience, geospatial or hydraulic flood modelling, and infrastructure performance analysis, particularly those employing machine learning and remote sensing techniques. Nonetheless, indirect service disruptions, tropical railways, and equity-based adaptation remain underexplored. These findings provide a transparent evidence base to inform collaborative agendas, direct funding toward neglected regions and topics, and promote integrated models linking hydrological extremes to network-level economic disruption.

Keywords: Climate change, Flood vulnerability, Transport network, Railway infrastructure, Risk assessment

1. Introduction

Railways transport transfer large volumes of passengers and freight while having carbon emissions that are lower than road or air transport. However, their fixed routes, reliance on electricity and telecommunications, and the continuous nature of tracks, bridges, and signalling systems make them highly exposed to disruption, where a single flood event can bring entire corridors to a standstill (Pant et al., 2018). System-wide reviews now rank fluvial and pluvial flooding as the dominating climate hazard for rail, accounting for roughly two-thirds of all weather-related service disruptions worldwide (Haghighi et al., 2025; Koks et al., 2019).

Recent European data place average direct flood losses to railways at ~ €581 million yr^{-1}, with ensemble projections indicating possible increases of 255–310 % under a 3 °C warming pathway (Bubeck et al., 2019). Empirical flood-damage modelling shows that the 2006 Morava/March-River event in Austria destroyed c. 10 km of track and generated €41 million in repair costs; large-scale application of the same model across the Mur catchment suggests annual losses could rise four- to six-fold under mid-century climate scenarios (Kellermann et al., 2015).

Coastal railways face an additional hazard: gradual submergence by sea-level rise. A national assessment for Italy identified > 250 km of coastal tracks requiring priority adaptation by 2100 under RCP 8.5 (Ricciardi et al., 2024), while high-resolution case studies such as the Dawlish (UK) main line highlight recurrent closure risks even under present-day extremes (Pregnolato & Dawson, 2017).

The Asian monsoon domain is projected to experience the world's largest increases in short-duration extreme rainfall. Bias-corrected CMIP6 experiments report robust intensification of wet-day totals over Mainland South-East Asia by mid-century (Liu et al., 2023), corroborating observed upward trends in summer extremes (Xu, 2022). Multi-model ensembles further indicate a 10–20 % rise in annual precipitation and a marked shift toward heavier 95th-percentile events (Supharatid et al., 2022; Supari et al., 2020). Such changes will interact with rapid urban expansion and poorly drained alluvial soils, amplifying track-bed saturation, scour and embankment failure risks (Zhu et al., 2022).

Adaptation research is beginning to translate these projections into operational guidance. In China, hourly precipitation thresholds for speed restriction, inspection and closure have been recalibrated using CMIP6-driven risk hours, showing 175–647 % increases in alert exceedances by late-century (Jiang et al., 2024). Network-science stress-tests for the London Underground found that optimised recovery scheduling could halve passenger delays under a once-in-30-year flood scenario (Bi et al., 2024), while Swedish studies recommend temperature-specific maintenance regimes to mitigate buckling and frost-heave on mixed-traffic lines (Garmabaki et al., 2024). Comparative reviews across Canada, Sweden and China also emphasise the value of nature-based

**Corresponding author: sasmah@utm.my*
2026 JPS Publishing. All right reserved.

solutions, such as vegetated swales and green revetments, for dual benefits of drainage and lateral track stability (Kostianaia & Kostianoy, 2023).

Despite these advances, most vulnerability tools were conceived for temperate soils, uniform-gauge tracks and legacy drainage. Nevertheless, the literature rarely incorporates the distinctive environmental and infrastructural conditions of ASEAN railway corridors, such as tropical lateritic subgrades, mixed narrow- and standard-gauge systems, and the compound effects of tidal surges and monsoon rainfall (Samela et al., 2023). Developing probabilistic, multi-hazard models that integrate extreme rainfall, fluvial backwater, and sea-level rise, while accounting for the operational knock-on costs captured by depth–disruption functions (Pregnolato et al., 2017), remains an urgent research frontier. This review therefore synthesises current evidence and highlights methodological gaps most pertinent to the rapidly expanding rail networks of South-East Asia.

2. Background

Understanding how floods harm railways start with the idea of vulnerability, which is commonly divided into three parts: exposure (Adger, 2006; Turner et al., 2003; Koks et al., 2019; Zhu et al., 2022), sensitivity (Adger, 2006; Turner et al., 2003; Ricciardi et al., 2024) and adaptive capacity (Füssel & Klein, 2006; Smit & Wandel, 2006; Ricciardi et al., 2024). In this context, exposure refers to where the track sits in relation to the flood; sensitivity refers to how easily the rails, ballast and signals can be damaged; and adaptive capacity refers to how well the operator can prepare, respond and rebuild. These systems view also reminds us that rail services rely on power lines, telecoms and road access for emergency repairs, so a break in one lifeline can magnify the damage to the others (Pant et al., 2018). Yet data on these three parts are still lacking for South-East Asian networks with mixed gauges, older drainage and monsoon climates.

Floods reach railways in several ways. Deep, slow-moving river floods can overtop or weaken embankments; short, fast flash floods can wash out ballast or smash debris into bridges; and heavy rainfall in hilly areas can destabilized slopes, sending landslides onto the track. A practical GIS method now sorts each track segment into likely failure modes so engineers can screen large corridors quickly (Samela et al., 2023). However, the soil strength and rainfall intensity parameters used to define these thresholds are mainly derived from temperate European regions, rendering their direct application to tropical soils uncertain.

To quantify flood impacts in economic terms, researchers construct depth–damage curves linking flood-water depth to infrastructure repair costs. The best-known curves were calibrated after Austria's 2006 March-River flood and later scaled up in the network-wide RAIL model (Kellermann et al., 2015). When these curves feed into climate scenarios, annual losses across Europe could still triple under a 3 °C warming future (Bubeck et al., 2019). Yet no curves have yet been built for timber sleepers, slab track or the high-sediment rivers common in ASEAN countries.

Recent studies increasingly integrate expert judgement with machine-learning techniques to improve the accuracy and reliability of flood-risk assessments. For example, weighting many small factors in a multi-criteria system cut false "high-risk" flags by about 80 %, while pairing an analytic hierarchy process (AHP) with machine-learning rainfall generators pushed the accuracy of run-off forecasts close to perfection in Brazilian trials (Samela et al., 2023). However, such approaches remain limited in Southeast Asia, primarily due to the scarcity of long-term and reliable damage records. Finally, the allocation of limited adaptation funding is increasingly becoming an equity concern. In the United Kingdom, Pregnolato and Dawson (2018) showed that transport-infrastructure investment can favour high-demand corridors, while regions with high flood risk but lower transport demand may receive less resilience investment, potentially widening spatial inequalities in mobility and economic opportunity. In Southeast Asia, railway-related flood studies have mainly examined climate exposure, operational vulnerability, and infrastructure disruption, rather than the spatial equity of adaptation-funding allocation (Binti Sa'adin et al., 2016; Binti Sa'adin et al., 2017; Ochsner et al., 2023). In Malaysia, broader flood-resilience funding has increased in recent years, but available assessments still emphasise national flood-mitigation expenditure rather than railway-specific distributional audits across regions or corridors (Rosli et al., 2025). Without such assessment, flood-prone rural railway segments may continue to receive weaker protection even as climate-related risks intensify. These findings indicate that although the concepts and tools used to assess railway flood risk are relatively well established, many existing approaches remain heavily dependent on European datasets and environmental conditions. Consequently, Southeast Asian railway systems require locally derived flood thresholds, region-specific damage functions, and funding frameworks that appropriately balance flood risk, passenger demand, and broader social value.

3 Methodology

Figure 1 summarises the integrated workflow, from data acquisition and screening through network construction and interpretation, providing the methodological scaffold for the subsequent results and discussion sections. This study was guided by the following research question: What are the major research trends in the assessment of climate-induced flood vulnerability in railway and transport networks? To address this question, a systematic keyword-search strategy was developed to capture three main dimensions of the literature: flood-related hazards (e.g., "flood risk" and "flood impact"), railway and transport infrastructure systems (e.g., "rail infrastructure" and "railway network"), and analytical approaches used in vulnerability studies (e.g., "vulnerability assessment" and "hydraulic modelling").

Boolean operators were applied to article titles and abstracts to maximise retrieval coverage while maintaining conceptual relevance. In addition, wildcard and proximity operators were carefully configured to reduce duplication and minimise distortion in keyword-frequency analysis caused by synonymous terms. The resulting dataset was subsequently analysed using bibliometric mapping and thematic interpretation techniques to identify publication trends, collaboration structures, and dominant research themes within the field. Network visualisation methods were further employed to examine relationships among authors, keywords, countries, and institutional affiliations, thereby revealing the intellectual structure and developmental trajectory of the literature over time. Several regional gaps were also identified, highlighting the need for broader geographical representation.

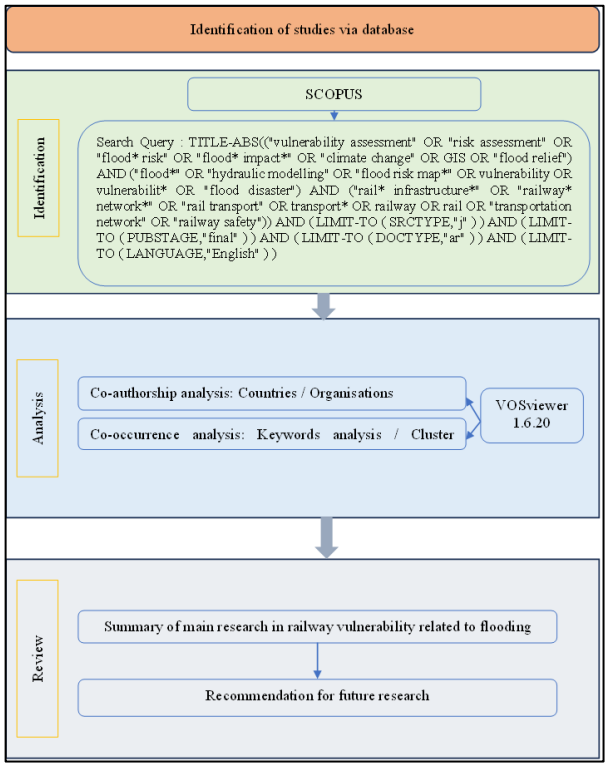

Fig. 1 – The flowchart of methodology for this study

Scopus was selected as the sole data source because recent comparative studies show that it indexes a broader spectrum of open-access and engineering journals than Web of Science, giving fuller international coverage without sacrificing quality controls (Maddi et al., 2025). The search was limited to English-language, peer-reviewed journal articles in their final publication stage, thereby excluding conference papers and in-press items. Implementing these filters up to the 23rd of June 2025 yielded 2 608 records that constitute the raw corpus; the complete Boolean string and retrieval statistics appear in Table 1.

Table 1 – Full Search String used for this study

Search String (Refined)	No. of Articles
TITLE-ABS(("vulnerability assessment" OR "risk assessment" OR "flood* risk" OR "flood* impact*" OR "climate change" OR GIS OR "flood relief") AND ("flood*" OR "hydraulic modelling" OR "flood risk map*" OR vulnerability OR vulnerabilit* OR "flood disaster") AND ("rail* infrastructure*" OR "railway* network*" OR "rail transport" OR transport* OR railway OR rail OR "transportation network" OR "railway safety")) AND (LIMIT-TO (SRCTYPE,"j")) AND (LIMIT-TO (PUBSTAGE,"final")) AND (LIMIT-TO (DOCTYPE,"ar")) AND (LIMIT-TO (LANGUAGE,"English"))	2608

To improve transparency in record identification and screening, the selection process was reported with reference to the PRISMA 2020 approach, which provides guidance for documenting the identification, screening, eligibility assessment, and inclusion of records in review-based studies (Page et al., 2021; Rethlefsen et al., 2021). In the identification phase, records were retrieved from Scopus using the Boolean search string shown in Table 1. In the screening phase, database-level filters were applied to retain only English-language, peer-reviewed journal articles in their final publication stage. Conference papers, in-press articles, non-English publications, and non-journal sources were excluded. In the eligibility phase, the remaining records were checked for relevance to flood vulnerability, railway or transport infrastructure, and analytical approaches to vulnerability or risk assessment. The final included records were then exported in CSV format and used for bibliometric mapping and thematic interpretation in VOSviewer. This PRISMA-aligned process ensured that the construction of the bibliometric corpus was systematic, transparent, and reproducible.

Following the PRISMA-aligned screening and eligibility process, the final bibliographic dataset was exported from Scopus in CSV format and processed using VOSviewer v1.6.20. VOSviewer was selected because it supports the construction, normalisation, clustering, and visualisation of large bibliometric networks, making it suitable for identifying intellectual structures and thematic patterns within multidisciplinary research fields. Recent evaluations also confirm that VOSviewer handles large datasets efficiently and offers flexible layout, clustering, and overlay options that facilitate theory-building across domains (Dalir et al., 2025; Abushamma & Zyoud, 2024). Before network construction, the dataset was cleaned to improve analytical consistency. Author names were checked for duplication, institutional affiliations were standardised, and semantically similar keywords were merged to reduce fragmentation in the co-occurrence analysis. Network normalisation was performed using the association-strength algorithm implemented in VOSviewer.

In the resulting bibliometric maps, each node represents a bibliographic entity, such as an author, country, journal, or keyword, depending on the type of analysis conducted. Edges represent co-authorship or co-occurrence relationships, while edge thickness indicates the relative strength of these relationships. Nodes with similar link profiles are grouped into clusters, with each cluster representing a closely related collaborative or thematic structure. Node size reflects item weight, such as publication count for authors and countries, or occurrence frequency for keywords. This visual structure enables the identification of dominant contributors, collaboration patterns, and recurring conceptual themes within the reviewed literature.

The cleaned dataset was then analysed using two complementary bibliometric visualisations. First, a country-level co-authorship network was developed to identify leading national contributors and patterns of cross-regional collaboration. Second, a keyword co-occurrence map was generated using the full-counting method, with a minimum occurrence threshold of five keywords, to identify dominant and emerging research themes. Together, these analyses provided a structured basis for interpreting publication trends, collaboration networks, and thematic development in studies related to climate-induced flood vulnerability in railway and transport networks.

4. Results

4.1. Publication Analysis

4.1.1. Countries and Number of Publications

The choropleth world map (Figure 2) visualises the geographical distribution of research output pertinent to the analysed topic, with each country shaded according to its total number of publications. A pronounced concentration of

scholarly activity is evident in the United States (657 publications) and China (431 publications), which together account for the majority share of global output. The strong research output from these two countries compared to others is likely explained by more investments in research infrastructure, a high number of active scholars, and established funding systems that support both basic and applied research. Canada (122) and Australia (112) form a secondary tier, demonstrating comparatively strong publication volumes relative to their population sizes, possibly owing to well-established national research councils and collaborative networks with leading institutions worldwide.

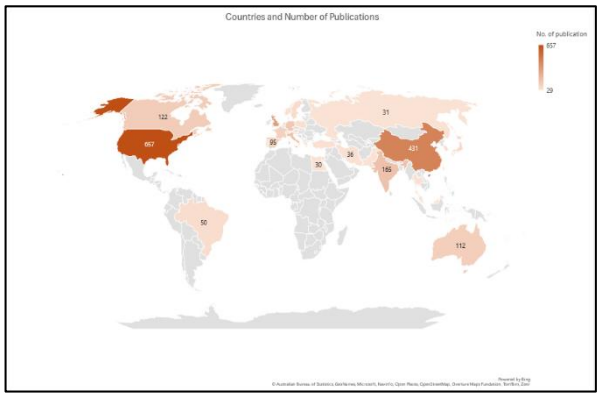

Fig. 2 – Top 10 countries with the highest number of publications in the research area

Moving further down the distribution, India (165) emerges as a notable contributor among emerging economies, indicative of its expanding higher-education sector and government initiatives aimed at addressing climate-related and infrastructural challenges. European countries appeared spread as the United Kingdom (95) leads the continent, followed by Russia (31) and Spain (30). This spread suggests that, while Europe maintains an established scientific base, research on this specific topic may be fragmented across multiple national agendas rather than coordinated at a pan-European scale. Brazil's output (50) highlights South America's limited but growing engagement, perhaps linked to its exposure to extreme weather events and consequent policy interest.

By contrast, most countries in Africa and parts of the Middle East record negligible or no publications, underscoring pronounced knowledge gaps and potential vulnerabilities where empirical data are scarce. Such output may be attributed to limited research funding, fewer specialised academic centres, and infrastructural constraints that hinder large-scale data collection. Addressing these disparities through targeted international collaborations, capacity-building initiatives, and open-access data-sharing practices would not only broaden participation in scientific research but also generate more comprehensive and context-specific insights that are essential for resilient global infrastructure planning.

4.1.2 Top 10 journals with the highest number of documents

The funnel chart (Figure 3) reveals that research on the chosen topic is disseminated through a relatively concentrated set of outlets, with Natural Hazards occupying a clear lead (14 documents) and the International Journal of Disaster Risk Reduction forming the next tier (10). Together, these two titles account for almost one-quarter of the total records captured in the top ten list, underscoring their status as core venues for scholarship on climate-related hazards and infrastructure vulnerability. A second stratum comprises Reliability Engineering and System Safety (8) as well as a trio of journals Natural Hazards and Earth System Science, its companion discussion series, and Sustainability (Switzerland), each contributing seven papers; their presence signals an interdisciplinary convergence between geophysical risk analysis, engineering reliability, and broader sustainability framing.

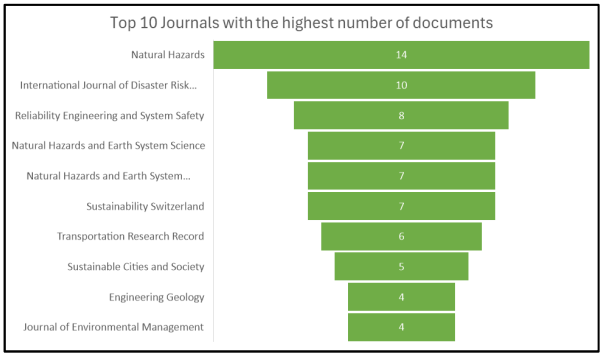

Fig. 3 – Top 10 journals with the highest number of publications in the research area

Below this, Transportation Research Record (6) bridges hazard research with transport-specific applications, while Sustainable Cities and Society (5) emphasises the urban resilience dimension. The final cluster, Engineering Geology and the Journal of Environmental Management (both with four publications), reflects geotechnical and managerial perspectives that, although numerically smaller, add methodological diversity and contextual depth. Collectively, the distribution indicates that while hazard-centred journals dominate, the field draws on complementary domains spanning engineering reliability, urban studies, transportation, and environmental governance, suggesting a healthy yet still consolidating research network that could benefit from further cross-journal dialogue and special-issue collaborations.

4.1.3 Publication Year and Number of Documents

The polar line plot (Figure 4) traces the annual volume of publications from 1984 through to the partial record for 2025, using radial distance to convey magnitude. Visually, the graphic reveals an extended gestation phase in which yearly outputs remain close to the origin, effectively negligible, until the late 2000s. Such a pattern generally reflects a developing research field that has yet to achieve sustained scholarly engagement, stable funding support, or dedicated conference communities.

A major inflection appears around 2010–2012, where counts edge into the low single digits and remain consistently above zero thereafter. This incremental growth likely reflects an alignment of several forces: increasing public concern over climate-induced disruptions, wider availability of digital geospatial data, and the gradual integration of resilience metrics into transport planning curricula. Together, these factors provided both the empirical resources and conceptual impetus needed to move beyond isolated case studies towards comparative or framework-driven investigations.

The most striking feature of the series is the steep acceleration observed from roughly 2018 onwards, culminating in a peak of more than 25 papers in 2021. That surge coincides with heightened global attention to extreme-

weather events affecting rail networks (Haghighi et al., 2025; Palmqvist & Ochsner, 2023), major infrastructure-stimulus packages emphasising climate adaptation (Sadler et al., 2024), and the maturation of analytical toolkits, particularly machine-learning frameworks for flood forecasting and network-vulnerability assessment (Zakaria et al., 2024; Kumar et al., 2025).

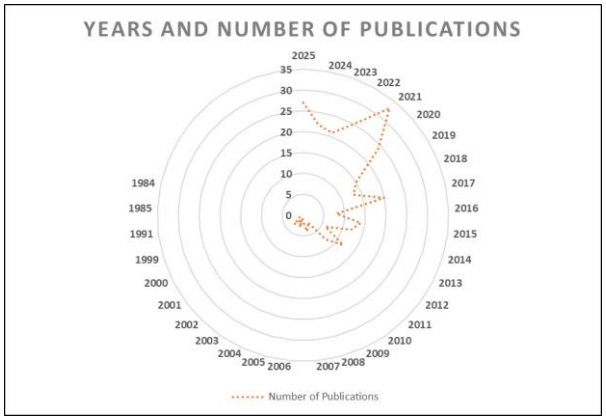

Fig. 4 – Annual distribution of publications on railway flood vulnerability from 1984 to 2025

Subsequent years exhibit a constant trend rather than a drop-off: publication counts fluctuate but remain well above the levels recorded prior to 2020, with preliminary 2025 numbers already approaching 2021. This sustained output suggests a consolidation phase in which methodological innovations are being refined, comparative studies extended to new geographic contexts, and policy-oriented syntheses produced for decision-makers. In effect, the curve intimates that the research community has achieved critical mass; barring unforeseen disruptions, future trajectories are likely to maintain or even surpass this elevated baseline as climate resilience continues to rise on both national and international agendas.

4.2 Bibliographic Analysis

4.2.1 Author Keywords and Publication Year

The keyword co-occurrence map presents a dense core in which climate change dominates discussion (Figure 5). Closely allied terms such as resilience, adaptation, floods, and vulnerability assessment orbit this centre, forming a tightly knit web of recurring concepts. The large node sizes and thick links indicate that these ideas appear frequently and are cited together, implying a shared conceptual framework across most recent studies. Geographic information system appears prominently and sits beside vulnerability assessment, signalling that spatial analysis tools remain fundamental to contemporary research practice. Modelling, risk, and critical infrastructure also cluster near the centre, showing that methodological concerns and practical applications intersect within the same conversation. Overall, the figure suggests that the field has coalesced around an integrative agenda that links climatic drivers to infrastructure risk through spatially explicit modelling.

Beyond the core, several peripheral groups reflect specialised subthemes that support the broader agenda. On the left side, soil erosion, sediment transport, and fluvial geomorphology gather together, indicating a physical science cluster concerned with landscape response to changing runoff. The upper segment contains groundwater, aquifer

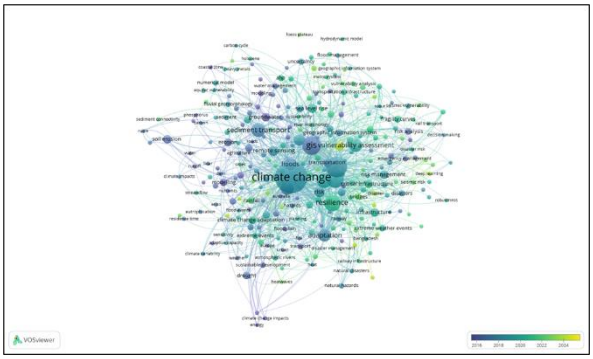

Fig. 5 – Mapping of Author's Keywords throughout the years

vulnerability, and heavy metals, pointing toward water quality and subsurface contamination issues. To the right, risk analysis, fragility curves, and seismic vulnerability outline an infrastructure performance cluster that focuses on structural response to multiple hazards. A smaller technology-oriented cluster shows remote sensing, LiDAR, and deep learning, highlighting the adoption of advanced observation and analytics tools. Even though these peripheral clusters retain some disciplinary distinction, their numerous links to the climate change hub reveal a strong trend toward interdisciplinary integration. Such connectivity implies that progress now depends on combining physical process insight with data driven techniques and decision-oriented assessments.

Colour shading adds a temporal dimension, with cooler blue nodes representing average publication years near 2016 and warmer yellow nodes indicating work closer to 2024. Keywords such as climate variability, drought, and energy are shown in darker blue, indicating that they received significant attention earlier in the decade. Mid-range green shades mark keywords such as adaptation planning, resilience, and vulnerability assessment, which rose sharply around 2020 as the community began applying earlier climate insights to practical planning exercises. The lightest yellow nodes surround deep learning, extreme weather events, and natural hazards, signalling a recent pivot toward real time analytics and compound hazard frameworks. This chronological gradient suggests that the field is moving from diagnosis of climate drivers toward proactive risk management informed by high resolution data.

4.2.2 Author Keywords and Network Visualisation

The network visualisation of keyword co-occurrences (Figure 6) reveals a tightly woven core where climate change anchors the scholarly conversation. Surrounding this hub are equally high-frequency terms such as resilience, adaptation, floods and vulnerability assessment, all of which appear as sizeable nodes and share numerous links. Their spatial proximity and line density suggest that recent research treats them as an integrated conceptual package, tying climatic drivers directly to the performance of critical infrastructure. Geographic information system and modelling sit very near the centre as well, indicating that spatial analysis and quantitative approaches remain foundational. Collectively, the network structure points to a field that has matured around a unifying problem frame, managing climate risk to infrastructure, while retaining room for methodological innovation. Such an arrangement promotes cross-fertilisation, since any new subtopic introduced near the core can quickly propagate throughout the graph.

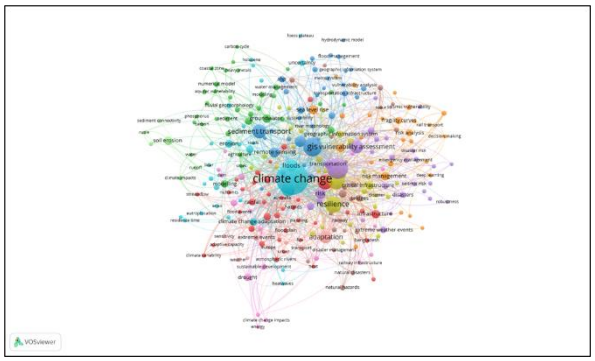

Fig. 6 – Mapping of links between Author's Keywords

Distinct colour clusters showcase several thematic communities within this broader conversation. A turquoise group features sediment transport, soil erosion and fluvial geomorphology, highlighting work on landscape processes that influence flood dynamics. An orange group gathers risk analysis, fragility curves and seismic vulnerability, reflecting an engineering perspective on multi-hazard assessment for transport assets. The green cluster links groundwater, water management and aquifer vulnerability, signalling a hydro-environmental thread concerned with subsurface impacts. A lilac cluster of remote sensing, LiDAR and deep learning represents the technological frontier, where high-resolution observation and artificial intelligence tools are being harnessed for real-time hazard mapping. Finally, a pink cluster centres on climate variability, drought and sustainable development, illustrating the policy-oriented strand that connects scientific findings to long-term planning goals. Despite their differing foci, the clusters are interlaced with numerous cross-cluster ties, confirming that interdisciplinary integration is now the norm rather than the exception.

The position and interconnections of these clusters suggest a field progressing from hazard identification toward actionable decision support. Topics concerned with physical processes occupy the network's left flank, while those tied to risk management and infrastructure robustness migrate to the right, hinting at a conceptual flow from cause to consequence to solution. The extensive links between technology-oriented keywords and both the process and management clusters imply that advanced analytics act as a bridge, converting raw environmental data into policy-relevant metrics. Meanwhile, the presence of sustainable development near the adaptation cluster shows that equity and long-term societal goals are increasingly embedded in technical studies. In general, the visualisation shows that the field combines basic science with new methods and practical use.

5 Discussion

The bibliometric patterns revealed in this review can be interpreted most effectively through the lens of vulnerability theory, which defines disaster risk as the joint product of exposure, sensitivity, and adaptive capacity (Turner et al., 2003). The global distribution of publications shows that research effort is highly exposed to data produced in the United States, China, and a small group of European nations, yet it remains markedly sensitive to the absence of local studies in tropical and low-income regions that face escalating flood hazards. This spatial imbalance constrains adaptive capacity at both scientific and operational levels because policy guidance derived from temperate railway systems may not be fully applicable to mixed-gauge networks constructed on lateritic soils or to railway corridors exposed to the combined effects of storm surges and monsoonal rainfall. Consequently, the unequal distribution of research attention, technical expertise, and knowledge production may inadvertently reinforce the very vulnerabilities that the research community seeks to reduce. The thematic clusters identified in this study correspond to the three dimensions of vulnerability, albeit unevenly represented across the literature. In particular, climate-change attribution, hydraulic modelling, and infrastructure fragility have contributed significantly to the evaluation of exposure and sensitivity. Conversely, adaptive capacity is captured in keywords such as resilience planning, maintenance funding, and social equity which remains peripheral in both network graphs and publication counts. This misalignment implies that the field still privileges diagnostic science over solution-oriented inquiry. It also explains why only a modest share of studies quantifies indirect losses or recovery trajectories, even though service disruption frequently exceeds direct repair costs (Bi et al., 2024). Embedding adaptive-capacity metrics into bibliometric searches, for instance by including terms such as "governance" or "contingency planning", would broaden the analytical frame and foster more holistic research agendas.

Methodological reflections further qualify the strength of the findings. Reliance on just one English-language database creates a bias because it gives more attention to well-known journals and leaves out important studies published in other languages or regional journals. Comparative studies demonstrate that Web of Science and OpenAlex capture complementary subsets of engineering literature (Maddi et al., 2025), and omitting these sources may therefore understate innovation emerging from local or open-access venues. Also, using a minimum keyword limit of five in VOSviewer can unintentionally hide new but important ideas, like ensemble downscaling for combined flood hazards. Sensitivity testing with fractional counting or lower thresholds would reveal whether peripheral themes merely reflect analytical settings or truly occupy the margins of the field.

Despite these caveats, the review offers clear and actionable implications. For researchers, the results underscore the need for mixed-methods designs that align high-resolution flood data with socio-economic indicators of railway dependence, thereby translating exposure maps into passenger-centred risk metrics. For national rail operators, the documented success of network-science stress tests and machine-learning rainfall generators suggests that incremental integration of real-time data feeds into asset management could yield immediate resilience dividends. Funding agencies should prioritise South-South collaborations that pair emerging research groups with established modelling hubs, because the co-authorship analysis shows that publications originating from such partnerships gain higher betweenness scores and diffuse methodological advances more widely. Journal editors can accelerate this process by commissioning multi-lingual special issues that foreground under-represented geographies and encourage open-data archiving.

Looking forward, three research frontiers appear most urgent. First, locally calibrated depth-damage and depth-disruption functions are needed for ballast types and sleeper materials typical of tropical Asia and Africa; without them, economic loss projections will remain speculative. Second, probabilistic frameworks that unite fluvial flooding, pluvial flash events, and coastal surge in a single rail-specific hazard model should be developed, because climate projections indicate an increasing concurrence of these drivers. Third, evaluative studies that track the life-cycle cost of adaptation interventions, such as green revetments or

dynamic speed restrictions, will allow planners to balance capital expenditure against avoided passenger delays, thereby embedding adaptive capacity within routine investment appraisal.

Overall, the field of railway flood vulnerability research has matured into a coherent, data-rich domain, yet its knowledge base is asymmetrically distributed and thematically weighted towards exposure and sensitivity. To fix these imbalances, researchers need to use a mix of methods, work together across different regions and disciplines, and focus more on practical solutions that help measure and improve how well rail systems can adapt to floods. By re-aligning bibliometric evidence with the full spectrum of vulnerability theory, future studies can provide the balanced, context-specific insights necessary for resilient rail transport in a changing climate.

6 Conclusion

This bibliometric review demonstrates that research on railway flood vulnerability has evolved from a scattered niche topic into a recognised and rapidly growing field. Clear thematic focus on resilience, and the increasing use of analytical tools such as remote sensing, deep learning, and high-resolution modelling reflect the field's methodological and conceptual maturation. These advancements now provide integrated insights into the complex relationships among hydrological hazards, infrastructure performance, and human systems. However, significant spatial and linguistic biases persist. As a result, some of the world's most flood-prone railway corridors remain under-represented in the evidence base, limiting the applicability of existing models and policy guidance. Addressing these gaps is important to make sure that all regions can adapt fairly to climate change.

Future research could prioritise detailed, locally grounded case studies, particularly in tropical and otherwise under-represented regions. Open data sharing should be encouraged so that models can be refined and replicated. Integrating multiple hazard drivers, including fluvial flooding, extreme rainfall, and coastal surge, will provide more realistic risk projections. At the same time, incorporating social and economic disruption indicators will enhance cost–benefit analyses. Applications of machine learning, although promising, should progress from experimental development to routine use. This requires long-term performance evaluation and integration into daily infrastructure management practices. Continuous bibliometric tracking across multiple languages will be needed to evaluate whether global participation in this field is expanding. These forms of feedback will help the research community stay aligned with the rapidly shifting nature of climate risk.

For practitioners, the current concentration of knowledge within a few high-impact journals can make literature scanning more convenient, but it may also reinforce dominant assumptions and limit context-specific innovation. In fast-growing countries, policymakers and infrastructure planners need to check whether design standards from other countries actually match their local climate realities. Where possible, they should test pilot projects on-site before large-scale implementation. Regulators can use the co-authorship and keyword maps from this review to identify suitable experts for peer review and to determine whether funding priorities are keeping pace with emerging areas of concern. Rail operators can benefit from real-time flood forecasting tools that connect directly to maintenance schedules. Evidence from London-based case studies has already shown that such tools can significantly reduce service interruptions (Bi et al., 2024). Incorporating these systems into daily operations will strengthen resilience. Additionally, funding mechanisms must be designed to ensure that remote or lower-volume lines are not neglected, as this may result in infrastructure blind spots that are highly vulnerable to climate threats.

Although this study is limited to Scopus-indexed, English-language publications and uses only one bibliometric tool, validation against prior reviews and current case-based studies supports the reliability of its core findings. This review helps lay the groundwork for future research and policy by showing who is leading the field, where the gaps are, and which methods are gaining momentum. If appropriately applied, these insights can help build a more inclusive, methodologically diverse, and practically useful research agenda that responds to the substantial climate-related challenges facing railway infrastructure globally. The field now stands at a decisive moment, where technical innovation must be matched by collaborative and context-aware efforts to ensure climate resilience for all rail systems.

7 Online License Transfer

All authors are required to complete the Procedia exclusive license transfer agreement before the article can be published, which they can do online. This transfer agreement enables DID Malaysia to protect the copyrighted material for the authors but does not relinquish the authors' proprietary rights. The copyright transfer covers the exclusive rights to reproduce and distribute the article, including reprints, photographic reproductions, microfilm or any other reproductions of similar nature and translations. Authors are responsible for obtaining from the copyright holder, the permission to reproduce any figures for which copyright exists.

Acknowledgement

This study is funded by the Ministry of Higher Education (MOHE) under the Fundamental Research Grant Scheme (FRGS), Registration Proposal No: FRGS/1/2024/TK06/UTM/02/2.

References

[1] Abushamma, F., & Zyoud, S. H. (2024). Analysing global research trends and focal points in the utilisation of laser techniques for the treatment of urolithiasis from 1978 to 2022: Visualisation and bibliometric analysis. Urolithiasis, 52(1), 67. https://doi.org/10.1007/s00240-024-01568-1

[2] Adger, W.N. (2006) Vulnerability. *Global Environmental Change* 16(3):268–281. https://doi.org/10.1016/j.gloenvcha.2006.02.006

[3] Aria, M., & Cuccurullo, C. (2017). Bibliometrix: An R-tool for comprehensive science-mapping analysis. Journal of Informetrics, 11(4), 959–975. https://doi.org/10.1016/j.joi.2017.08.007

[4] Bi, W., Schooling, J., & MacAskill, K. (2024). Assessing flood resilience of urban rail transit systems: Complex network modelling and stress testing in a case study of London. Transportation Research Part D: Transport and Environment, 135, 104362. https://doi.org/10.1016/j.trd.2024.104362

[5] Binti Sa'adin, S. L., Kaewunruen, S., & Jaroszweski, D. (2016). Operational readiness for climate change of Malaysia high-speed rail. Proceedings of the Institution

of Civil Engineers - Transport, 169(5), 308–320. https://doi.org/10.1680/jtran.16.00031

[6] Bubeck, P., Dillenardt, L., Alfieri, L., Feyen, L., Thieken, A. H., & Kellermann, P. (2019). Global warming to increase flood risk on European railways. Climatic Change, 155(1–2), 19–36. https://doi.org/10.1007/s10584-019-02434-5

[7] Dalir, A. H., Pezeshki, Z., Ravanshadnia, M., Krinitsky, E., & Sultanguzin, I. A. (2025). Automatic monitoring in construction projects: Scientometric analysis and visualization of research activities. Human-Centric Intelligent Systems, 5(1), 21–43. https://doi.org/10.1007/s44230-025-00089-3

[8] Füssel, H.M. & Klein, R.J.T. (2006) Climate change vulnerability assessments: An evolution of conceptual thinking. *Climatic Change* 75(3):301–329. https://doi.org/10.1007/s10584-006-0329-3

[9] Garmabaki, A. H. S., Naseri, M., Odelius, J., Famurewa, S., & Asplund, M. (2024). Assessing climate-induced risks to urban railway infrastructure. International Journal of System Assurance Engineering and Management. Advance online publication. https://doi.org/10.1007/s13198-024-02413-9

[10] Haghighi, E., Kasraei, A., Famurewa, S., Strandberg, G., & Sas, G. (2025). Climate change risks on railway infrastructure: A systematic review and analysis. Sustainable Cities and Society, 129, 106504. https://doi.org/10.1016/j.scs.2025.106504

[11] Jiang, Y., Chen, Z., Wang, Y., Gao, J., Zhang, X., Hu, R., & Wu, H. (2024). The impact of precipitation changes on the safety of railway operations in China under the background of climate change. Frontiers in Earth Science, 12, 1319736. https://doi.org/10.3389/feart.2024.1319736

[12] Kellermann, P., Schöbel, A., Kundela, G., & Thieken, A. H. (2015). Estimating flood damage to railway infrastructure: The case study of the March River flood in 2006 at the Austrian Northern Railway. Natural Hazards and Earth System Sciences, 15(11), 2485–2496. https://doi.org/10.5194/nhess-15-2485-2015

[13] Koks, E. E., Rozenberg, J., Zorn, C., Tariverdi, M., Vousdoukas, M., Fraser, S., Hall, J. W., & Hallegatte, S. (2019). A global multi-hazard risk analysis of road and railway infrastructure assets. Nature Communications, 10, 2677. https://doi.org/10.1038/s41467-019-10442-3

[14] Kostianaia, E. A., & Kostianoy, A. G. (2023). Railway transport adaptation strategies to climate change at high latitudes: A review of experience from Canada, Sweden and China. Transport and Telecommunication Journal, 24(2), 180-194. https://doi.org/10.2478/ttj-2023-0016

[15] Kumar, V., Sharma, K. V., Mangukiya, N., Tiwari, D. K., Ramkar, P. V., & Rathnayake, U. (2025). Machine learning applications in flood forecasting and predictions: Challenges and way-out in the perspective of changing environment. AIMS Environmental Science, 12(1), 72–105. https://doi.org/10.3934/environsci.2025004

[16] Liu, S., Raghavan, S. V., Ona, B. J., & Nguyen, N. S. (2023). Bias evaluation in rainfall over Southeast Asia in CMIP6 models. Journal of Hydrology, 621, 129593. https://doi.org/10.1016/j.jhydrol.2023.129593

[17] Maddi, A., Maisonobe, M., & Boukacem-Zeghmouri, C. (2025). Geographical and disciplinary coverage of open access journals: OpenAlex, Scopus, and Web of Science. PLOS ONE, 20(4), e0320347. https://doi.org/10.1371/journal.pone.0320347

[18] Ochsner, M., Palmqvist, C.-W., Olsson, N. O. E., & Hiselius, L. W. (2023). The effects of flooding on railway infrastructure: A literature review. Transportation Research Procedia, 72, 1786–1791. https://doi.org/10.1016/j.trpro.2023.11.654

[19] Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., ... Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ, 372*, Article n71. https://doi.org/10.1136/bmj.n71

[20] Palmqvist, C.-W., & Ochsner, M. (2023). Train delays due to extreme weather events in Sweden 2001–2020. Transportation Research Procedia, 00, 000–000.

[21] Pant, R., Thacker, S., Hall, J. W., Alderson, D., & Barr, S. (2018). Critical infrastructure impact assessment due to flood exposure. Journal of Flood Risk Management, 11(1), 22–33. https://doi.org/10.1111/jfr3.12288

[22] Pregnolato, M., & Dawson, D. A. (2018). Adaptation investments for transport resilience: Trends and recommendations. International Journal of Safety and Security Engineering, 8(4), 515–527. https://doi.org/10.2495/SAFE-V8-N4-515-527

[23] Pregnolato, M., Ford, A., Wilkinson, S., & Dawson, R. J. (2017). The impact of flooding on road transport: A depth–disruption function. Transportation Research Part D: Transport and Environment, 55, 67-81. https://doi.org/10.1016/j.trd.2017.06.020

[24] Rethlefsen, M. L., Kirtley, S., Waffenschmidt, S., Ayala, A. P., Moher, D., Page, M. J., Koffel, J. B., & PRISMA-S Group. (2021). PRISMA-S: An extension to the PRISMA statement for reporting literature searches in systematic reviews. *Systematic Reviews, 10*, Article 39. https://doi.org/10.1186/s13643-020-01542-z

[25] Ricciardi, A., Scholz, M., Palma, M. & Parodi, S. (2024). Climate resilience and vulnerability assessment of railway infrastructure exposed to coastal flooding. *Reliability Engineering & System Safety* 242:109747. https://doi.org/10.1016/j.ress.2023.109747

[26] Ricciardi, G., Ellena, M., Barbato, G., Alcaras, E., Parente, C., Carcasi, G., Zarelli, C., & Franciosi, A. (2024). Risk assessment of national railway infrastructure due to sea-level rise: An application of a methodological framework in Italian coastal railways. Environmental Monitoring and Assessment, 196, 822. https://doi.org/10.1007/s10661-024-12942-2

[27] Rosli, N. N., et al. (2025). Assessing climate change impact on storm surge and funding strategies in east peninsular Malaysia. Frontiers in Climate. https://doi.org/10.3389/fclim.2025.1634062

[28] Sadler, A., Ranger, N., Fankhauser, S., Marotta, F., & O'Callaghan, B. (2024). The impact of COVID-19 fiscal spending on climate change adaptation and resilience. Nature Sustainability, 7, 270–281. https://doi.org/10.1038/s41893-024-01269-y

[29] Samela, C., Manfreda, S., Troy, T. J., & Fiorentino, M. (2023). A methodological framework for flood hazard assessment for land-transport infrastructures. International Journal of Disaster Risk Reduction, 84, 103491. https://doi.org/10.1016/j.ijdrr.2022.103491

[30] Smit, B. & Wandel, J. (2006) Adaptation, adaptive capacity and vulnerability. *Global Environmental*

*Change,*16(3):282–292. https://doi.org/10.1016/j.gloenvcha.2006.03.008

[31] Supari, T. F., Juneng, L., Cruz, F., Chung, J. X., Ngai, S. T., Salimun, E., … Aldrian, E. (2020). Multi-model projections of precipitation extremes in Southeast Asia based on CORDEX–Southeast Asia simulations. Environmental Research, 184, 109350. https://doi.org/10.1016/j.envres.2020.109350

[32] Supharatid, S., Nafung, J., & Aribarg, T. (2022). Projected changes in temperature and precipitation over mainland Southeast Asia by CMIP6 models. Journal of Water and Climate Change, 13(1), 337-356. https://doi.org/10.2166/wcc.2021.015

[33] Turner, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., Eckley, N., Kasperson, J. X., Luers, A., Martello, M. L., Polsky, C., Pulsipher, A., & Schiller, A. (2003). A framework for vulnerability analysis in sustainability science. Proceedings of the National Academy of Sciences, 100(14), 8074–8079. https://doi.org/10.1073/pnas.1231335100

[34] Xu, L. (2022). Variations of summer extreme and total precipitation over Southeast Asia and associated atmospheric and oceanic features. Journal of Climate, 35(19), 6395-6409. https://doi.org/10.1175/JCLI-D-21-1020.1

[35] Zakaria, A.-R., Oommen, T., & Lautala, P. (2024). Automated flood prediction along railway tracks using remotely sensed data and traditional flood models. Remote Sensing, 16(13), 2332. https://doi.org/10.3390/rs16132332

[36] Zhu, W., Liu, K., Wang, M., Ward, P. J., & Koks, E. E. (2022). System vulnerability to flood events and risk assessment of railway systems at national and river-basin scales in China. Natural Hazards and Earth System Sciences, 22(5), 1519-1540. https://doi.org/10.5194/nhess-22-1519-2022

[37] Zhu, Y., Chen, J., Wang, H. & Deng, W. (2022) Flood risk assessment of railway infrastructure considering hazard, exposure and vulnerability. *International Journal of Disaster Risk Reduction* 75:102938. https://doi.org/10.1016/j.ijdrr.2022.102938