



Understanding Transport Resilience: Assessment Approaches and Tools

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Abbreviations

CAPEX	Capital Expenditure
CBA	Cost-benefit Analysis
CCDR	Country Climate Development Report
CDM	Catchment Debris Management
CRRMP	Climate Risk And Resilience Management Plan
EAD	Expected Annual Damage
GCM	Global Climate Model
GDP	Gross Domestic Product
GIS	Geographic Information System
GRI	Global Resilience Index
HARMA	Hazard & Risk Multiregional Assessment Tool
HDM-5	Highway Development And Management Model-5
km	kilometer
NPV	Net Present Value
OPEX	Operational Expenditure
OSM	OpenStreetMap
RCP	Representative Concentration Pathway
RESTORE	Resilient and Strategic Transport Operational Enhancement (Malawi project)
TSFI	Transport System Fragility Index
VA	Vulnerability Assessment
WRI	World Resources Institute

*All currency values are presented in US dollars, unless otherwise specified.

Executive Summary

Road networks are critical development lifelines, enabling the movement of people, goods, and essential services and underpinning economic growth and social well-being. Yet these networks are increasingly at risk from aging assets, deferred maintenance, and increasingly severe and frequent climate hazards. Adaptation needs in developing countries are projected to exceed hundreds of billions of dollars annually by 2030, underscoring the importance of directing limited resources toward the most critical and vulnerable sections of a road network.

In this context, effective prioritization of investments, efficient resource allocation, and strengthened asset management are essential to delivering value for money. Over the past decade, risk-based road prioritization and transport resilience analysis have evolved from highly specialized studies into practical, scalable approaches that are feasible and cost-effective for most countries, including those with limited data and institutional capacity. Early studies focused mainly on physical exposure and direct asset damage, offering useful but partial insights. More recent approaches increasingly recognize that resilience is multidimensional, encompassing risks at three levels: asset level (e.g., the vulnerability of individual road segments to hazards), system level (network disruption and loss of connectivity), and user level (impacts on people, markets, and essential services).

Drawing on a review of 50 transport resilience studies across the World Bank portfolio, this report finds that, despite wide variation in scope and analytical depth, road assessments generally follow a common sequence of analytical steps: (1) map hazard exposure, (2) assess asset-level vulnerability, (3) analyze system-level criticality and network effects, (4) identify resilience measures, and (5) prioritize interventions through economic analysis.

In practice, not all assessments apply the full sequence. Many studies focus on the earlier steps—typically exposure mapping and asset-level vulnerability analysis—and fewer extend to system-level analysis or economic prioritization. This sequence has emerged progressively over time through practical application, enabling assessments to be scaled and adapted to different decision-making needs, data availability, and institutional capacities.

The report highlights two emerging tools that reflect recent advancements in the cost efficiency of resilience analysis. The Global Resilience Index (GRI), developed by the University of Oxford and widely applied by World Bank transport teams, is an open-source geospatial model that facilitates rapid, low-cost vulnerability assessments using open data. Its application in the Kyrgyz Republic and Nigeria demonstrates how the GRI can effectively screen road networks, identify priority segments, and support policy dialogue and the development of Country Climate Development Reports in contexts where data and resources are limited.

The report also highlights the Hazard & Risk Multi-Regional Assessment (HARMA) model, developed by the World Bank transport team. This model supports more in-depth analysis by assessing climate impacts on network performance, estimating economic losses from disruptions, and comparing adaptation options using cost-benefit metrics. A Pakistan case study illustrates how the HARMA model can be applied to prioritize investments, and provide economic justification for resilience interventions.

To facilitate practical application, the report includes a decision tree designed to help users choose between the GRI and HARMA models, depending on the purpose of the analysis, the availability of data, and analytical needs. The decision tree differentiates between rapid screening and diagnostic applications, for which GRI is typically well suited, and investment prioritization and appraisal decisions, where HARMA is more applicable.

This report also shares two additional case studies to highlight applications with distinctive operational value. Brazil stands out as an example where resilience analysis is fully embedded into the operational and implementation processes. Here, analytical results are translated directly into practice through the Climate Resilience and Risk Management Plan, which is incorporated into procurement processes and a new generation of performance-based maintenance contracts. Consequently, resilience analysis extends beyond upstream prioritization to inform contractual requirements, maintenance planning, and performance monitoring. This positions Brazil as a leading example of how resilience analysis can influence real-world investment and asset management.

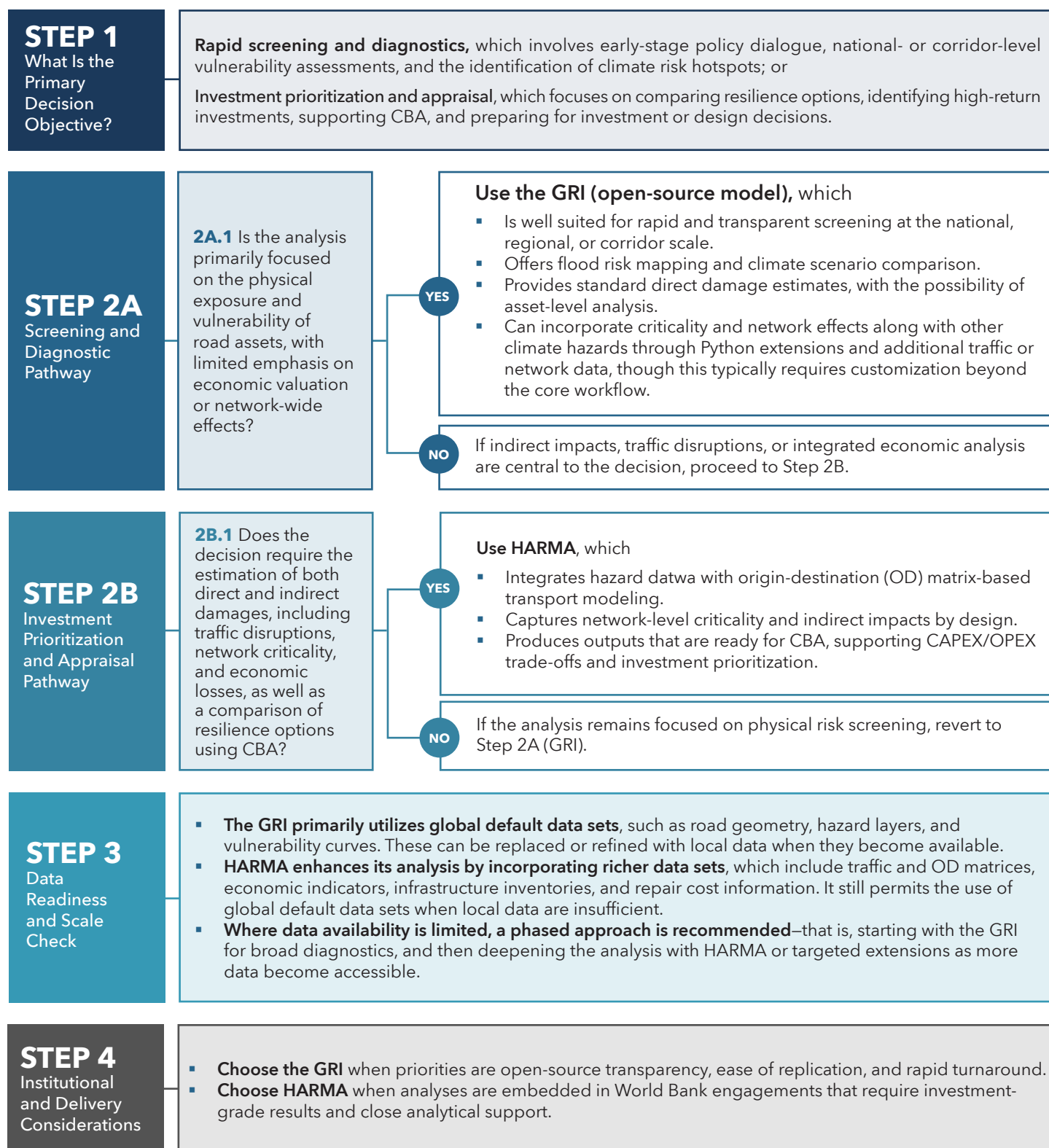
The Malawi case presents a rare example of detailed, site-specific diagnostics used to identify hotspots and develop tailored engineering interventions, which then directly inform feasibility studies and road design. Because such granular analyses are still uncommon in transport operations, the Malawi experience offers valuable insights into how field-based assessments can complement broader network-level prioritization and support the design of resilient infrastructure in highly vulnerable settings.

To advance scalable and country-owned resilience analytics, it is essential to achieve greater consistency in analytical workflows across countries and projects. This in turn, requires broader utilization of open-source and semi-open tools to reduce vendor lock-in, and continued investment in robust national data ecosystems, including hazard layers and road asset inventories. Equally important is the incorporation of resilience into procurement processes, design standards, and asset management systems, ensuring that analytical results translate into concrete investments. Taken together, the evidence presented in this report demonstrates that risk-based transport resilience analysis has moved beyond being a niche or experimental exercise. It is now a feasible and cost-effective foundation for prioritizing investments, strengthening asset management, and improving the resilience of road networks across various country contexts.

Selecting the GRI or HARMA Model for Transport Resilience Assessments

Given the diversity of decision objectives, data environments, and institutional contexts across countries and projects, no single tool is appropriate for all applications. To aid in practical tool selection, figure ES.1 provides guidance on aligning analytical approaches with decision needs, data availability, and required outputs.

Figure ES.1 A Decision Tree for Choosing the GRI or HARMA Model



1. Introduction

Road transport networks are critical development lifelines, underpinning economic activity, social inclusion, and access to essential services. Roads enable the movement of goods and people, connecting communities to markets, jobs, health care, and education, while—importantly—supporting emergency response and disaster recovery. When road networks are disrupted, the impacts are swift and far-reaching, leading to delays in freight and passenger transport, constrained access to essential services, and increased safety risks, all of which can have significant economic and social consequences.

Climate change is increasingly amplifying these disruptions. Altered weather patterns and the rising frequency of extreme weather events—such as floods, heat waves, storms, and landslides—are placing growing stress on roads, bridges, and drainage systems. This threatens both the structural integrity of infrastructure and the reliability of transport services (ITF 2016). The United Nations Environment Programme’s *Adaptation Gap Report 2023* estimates that the financing needed for adaptation is roughly five times greater than current funding levels (UNEP 2023). Recent global assessments show that, without risk-informed planning, infrastructure spending often tends to be reactive and inefficient, leading to repeated damages, escalating maintenance costs, and growing fiscal liabilities over time (Hallegatte et al. 2024). These pressures are particularly acute in most developing countries, where constrained public budgets and limited private sector participation heighten the need for the strategic allocation of scarce resources.

Against this backdrop, strengthening road resilience is not only a climate imperative but also a development and fiscal priority. Cost-effective, evidence-based approaches are essential for helping decision-makers identify the most critical risks and assets, reduce avoidable losses, and safeguard the long-term functionality of road networks under increasing climate stress.

The concept of risk provides a useful lens for understanding the impacts of climate change on transport systems. Risk encompasses not only the hazard itself—such as a flood or heat wave—but also the degree of exposure (the people and assets in harm’s way) and vulnerability (the resilience or fragility of those people and assets in the face of the hazard) (UNDRR 2017). In the context of road transport, this implies that climate impacts cannot be evaluated solely through hazards; they must also be assessed in relation to the location of the infrastructure, its criticality within the network, and its ability to withstand or adapt to climate stresses.

Over the past decade, there has been growing recognition of the need for systematic tools and approaches to integrate resilience considerations into infrastructure planning and management to reduce disaster risks (Hallegatte, Rentschler, and Rozenberg 2019). Traditional engineering design methods, often reliant on historical climate data, are increasingly insufficient in the face of uncertain future conditions. In response, transport planners and decision-makers are turning to forward-looking

risk assessment frameworks that integrate climate projections, hazard mapping, and vulnerability analysis (Koks et al. 2023). However, the application of climate risk and resilience analysis in the road sector is often hindered by limited data availability, reliance on proprietary software, and inconsistencies in methodologies (Musa Kamara et al. 2025). These challenges highlight the need for approaches that are proportionate to decision-making requirements, transparent, and adaptable to varying institutional and data contexts.

Transport resilience risks manifest at multiple, interrelated levels. At the asset level, climate hazards cause physical damage and the functional failure of individual road segments, bridges, and drainage structures, increasing maintenance costs and shortening asset lifespans—issues documented across World Bank transport operations and climate diagnostics. At the system level, the failure of critical links can disrupt network connectivity, leading to cascading impacts such as prolonged detours, loss of redundancy, and regional isolation. World Bank studies on transport network criticality and the *Lifelines* report (Hallegatte, Rentschler, and Rozenberg 2019) reveal that these indirect losses often exceed the costs of direct asset damage. At the user level, transport disruptions translate into tangible economic and social consequences for individuals and businesses, including reduced access to markets, health care, education, and emergency services. Together, these dimensions underscore the need for resilience analysis that extends beyond asset damage to capture system performance and user impacts.

In the context of growing risks and scarce resources, practitioners increasingly require practical guidance on how to assess, prioritize, and manage climate risks in road networks in ways that are scalable, decision-relevant, and feasible within existing institutional and budgetary constraints.

The present report addresses this need by synthesizing a coherent methodology for climate risk, vulnerability, and resilience analysis in road transport. It clarifies how to select fit-for-purpose approaches across different planning scales and decision contexts. The methodology emphasizes the importance of open and reproducible analytical workflows, the use of consistent and forward-looking hazard data, and the integration of exposure, vulnerability or fragility, and network criticality into actionable insights for prioritization, design, and asset management.

In four case studies, this report also examines how climate risk and resilience are being analyzed in practice. Two of the case studies illustrate how analytical tools are used to support network-level screening, prioritization, and policy dialogue, particularly in environments with limited data and resources. The other two case studies demonstrate how resilience analysis is further developed and incorporated into project design, procurement, maintenance planning, and implementation. Together, these real-world examples reflect different entry points into resilience analysis, showing how tools can initiate prioritization while operational integration determines long-term impact.

The remainder of the report is organized as follows. Chapter 2 introduces key analytical principles, cost-effective tools, and decision frameworks. Chapter 3 presents illustrative case studies that showcase the application of these approaches across different contexts and scales. Chapter 4 concludes by synthesizing key insights and identifying opportunities to strengthen the integration of climate resilience into road transport planning and operations.

2. Resilience Assessment Methodology and Tools

This chapter summarizes the common methodology and data used in transport climate risk and resilience assessments, based on a review of more than 50 transport studies conducted by the World Bank (details provided in appendix A). It also highlights a few emerging tools that are both cost-effective and avoid vendor lock-in, as well as a decision tree to assist in tool selection.

2.1 Resilience Assessment Methodology

The studies reviewed include Country Climate Development Reports (CCDRs),¹ CCDD deep dives, Advisory Services and Analytics (ASA),² and Project Appraisal Documents (PADs) from various transport operations.³ These studies range in scope from national- and corridor-level assessments of freight movement and macroeconomic disruption to rural access analyses that evaluate how climate hazards affect connectivity to essential services such as schools, health facilities, and markets.

While individual applications vary in scope, data availability, and analytical depth, they are broadly grounded in a shared analytical logic that has emerged through practice. This framework is flexible and can be applied at different scales—from national screenings to asset-level diagnostics—depending on specific decision-making needs and country capacity.

Scope and Objectives

Assessments begin by clarifying the scope and purpose of the analysis. This involves defining the scale of infrastructure being considered (e.g., national networks, corridors, rural roads, or specific assets), identifying the climate hazards of interest (such as flooding, landslides, heat, or storms), establishing relevant time horizons and climate scenarios, and determining the intended outputs. These outputs may include screening for risks, prioritization of investments, identification of resilience measures, economic appraisal, and financing needs. Defining the scope clearly ensures that the analytical effort remains aligned with decision-making requirements.

¹ CCDDs are World Bank diagnostic reports that integrate climate change considerations with developmental goals to help countries prioritize actions for reducing greenhouse gas emissions, boosting adaptation efforts, and achieving broader development objectives.

² World Bank ASAs are nonlending activities that provide technical expertise, tailored analysis, and policy advice to help countries achieve their development goals.

³ World Bank PADs contain detailed information about a proposed project's design, goals, objectives, and activities. These serve as the key resource for authorizing and implementing a project.

Hazard and Road Data

Hazard characterization provides the foundation for resilience analysis. Screening tools and historical data are commonly used to identify relevant hazards, with flooding and landslides being the most frequently assessed for road networks due to their significant impact on the expected damage costs. Additionally, heat-related impacts are increasingly being included in these assessments.

Hazard maps are typically derived from a combination of climate and physical models, covering multiple time periods, warming scenarios, and return periods. Using multiple models and scenarios is considered best practice to effectively capture uncertainty. Hazard data sets differ in resolution, coverage, modeled processes, and assumptions regarding the effectiveness of existing flood protection infrastructure, leading to significant variations in estimated risk. These limitations should be explicitly considered when interpreting results.

Road asset data provide information about the location and characteristics of road networks, including road class, surface type, and the presence of structures such as bridges or culverts. Open-source data sets such as OpenStreetMap are widely used for initial screening analyses, while more detailed assessments rely on validated government inventories where available. Recent advancements in remote sensing, artificial intelligence, and computer vision are making it increasingly possible to generate or update asset data using satellite imagery, unmanned aerial vehicles, and street-level photos.

Five Sequential Analytical Steps

Transport resilience assessments typically follow a sequence of five analytical steps:

1. Map exposure to characterize the extent and intensity of hazards affecting transport infrastructure. Exposure analysis overlays hazard maps with road asset data to identify which assets are located in hazard-prone areas and to visualize the spatial distribution of risk. This step establishes a preliminary basis for prioritization by identifying potential hotspots. To account for uncertainty in future climate conditions, exposure mapping should incorporate hazard information from multiple climate scenarios, reflecting various possible future patterns of rainfall, flooding, or extreme weather. This approach helps practitioners understand how exposure may evolve over time and supports more robust planning and design decisions.
2. Analyze asset-level vulnerability to identify hotspot road segments and estimate potential physical damage. Vulnerability assessment builds on exposure analysis by estimating how assets respond to hazards and translating physical impacts into expected damage metrics, such as expected annual damage or the percentage of the asset that may be damaged. Vulnerability functions and assumptions about reconstruction costs are important sources for assessing uncertainty, particularly in data-scarce contexts where global default values may not accurately reflect local conditions. Therefore, sensitivity analysis is commonly employed to test the robustness of results. Field inspections and stakeholder engagement can further improve accuracy by validating asset conditions and local risk factors.
3. Analyze system-level criticality to capture network effects and indirect impacts arising from disruptions. Focusing solely on asset-level damage does not fully capture the overall impact of transport disruptions. The system-level criticality analysis assesses how failures of individual road

segments affect overall network performance and connectivity. This typically involves estimating indirect impacts such as travel delays, detour lengths, accessibility losses, and broader economic disruptions. Criticality analysis relies on information such as traffic volumes, the importance of freight, availability of detours, and proximity to economic centers and essential services. These indicators help identify assets whose failure could impose disproportionately high costs systemwide. They are particularly important for distinguishing between assets that are merely exposed to risks and those that are strategically critical.

4. Identify resilience measures spanning engineering, operational, and institutional options. After identifying high-risk and high-criticality assets, resilience measures are developed to reduce exposure, vulnerability, or the consequences of potential failures. These measures may consist of engineering interventions, improved maintenance and operations, institutional reforms, or nature-based solutions.⁴
5. Conduct economic analysis, including cost-benefit analysis (CBA), to assess efficiency, and multicriteria analysis to incorporate user impacts and broader socioeconomic benefits when prioritizing interventions. Cost-benefit or net present value analyses are commonly used to compare resilience options based on avoided damages, reduced disruption, and life-cycle cost savings. Multicriteria approaches can complement these analyses by incorporating social equity, safety, and environmental co-benefits. The result is a prioritized investment pipeline that aligns with sector budgets, planning horizons, and implementation capacity.

While a small number of World Bank studies have examined wider economywide impacts—such as behavioral responses by firms and households, supply-chain reorganization, or inventory adjustments—these approaches are highly data and resource intensive, making them difficult to apply at scale.

The five-step framework is not prescriptive; rather, it has emerged progressively through practice. Not all applications require users to follow the entire sequence. Depending on their objectives, data availability, and institutional capacity, assessments may focus on initial diagnostic steps or extend to full appraisal and implementation. This flexibility enables countries to apply cost-effective screening approaches initially and progressively deepen their analyses as decision-making needs evolve.

2.2 Analytical Tools

Across the reviewed studies, vulnerability and resilience assessments have traditionally been developed and maintained by private sector vendors. While these vendor-led approaches can be technically robust, they are often costly, proprietary, and dependent on ongoing service contracts for updates, adaptations, or scale-up. This reliance can limit transparency, replication, and long-term ownership by countries, and contributes to persistent concerns around vendor lock-in. In response, recent years have seen the emergence of analytical tools that offer more flexible, open-source, or in-house alternatives, enabling countries and World Bank teams to conduct resilience analysis in a more cost-effective and scalable manner.

⁴ A range of practical resilience measures is documented in the practitioner guidance linked to the World Bank's *Lifelines* initiative (Hallegatte, Rentschler and Rozenberg 2019).

Global Resilience Index–Open-Source Tool

The Global Resilience Index (GRI) is an open-source geospatial modeling framework originally developed by the University of Oxford and increasingly used by World Bank transport teams and partners. Implemented in a Python environment, the GRI enables rapid vulnerability and risk screening through transparent workflows and largely open-access data sets. It is also available as a web-based application for quick screenings.⁵ Its flexibility allows users to customize analyses, making it particularly well suited for national, regional, or corridor-level diagnostics in data- and resource-constrained contexts.

The GRI focuses primarily on exposure and asset-level vulnerability, generating direct damage estimates and spatial risk indicators that support early-stage prioritization and policy dialogue. While criticality and network effects can be incorporated through extensions and additional data, this typically requires customization beyond the core workflow. Chapter 3 illustrates the application of the GRI through case studies from the Kyrgyz Republic and Nigeria.

HARMA Model

The Hazard & Risk Multi-Regional Assessment (HARMA) is a decision-support tool developed by the World Bank's transport teams to guide climate-resilient transport investments at both national and network scales. HARMA integrates hazard data with transport network modeling to evaluate the impacts of climate on network performance, quantify economic losses from disruptions, and compare adaptation options using cost-benefit metrics.

HARMA is designed to capture network-level criticality and indirect impacts by modeling traffic flows, detours, and systemwide disruptions. It facilitates the comparison of capital and operational expenditure (CAPEX and OPEX) options for both existing networks and new links, while leveraging machine learning techniques to explore redundancy and adaptation scenarios. HARMA's Python-based architecture ensures scalability and adaptability across different socioeconomic contexts, enabling effective communication of policy-relevant results. The tool has been piloted in Pakistan, Togo, and Sri Lanka, with its application illustrated through the Pakistan case study in chapter 3. More details on the GRI and HARMA models are available in appendix B.

Complementary Tools and Data Platforms

In addition to the core tools highlighted above, several complementary tools and data platforms are utilized for transport resilience analysis. The World Bank's Highway Development and Management Model (HDM-5), currently being updated in partnership with the Transport Research Laboratory, aims to support life-cycle simulations of road conditions, user costs, and cost-benefit analyses for maintenance, rehabilitation, and improvement. Once released, HDM-5 will integrate climate and resilience considerations into deterioration modeling and may serve as a platform for consolidating hazard and road asset data within road asset management systems.

⁵ The GRI Risk Viewer online application can be found at: <https://global.infrastructureresilience.org/>.

The Risk Data Library, managed by the Global Facility for Disaster Reduction and Recovery, provides structured access to a wide range of global and regional hazard and risk data sets. Although it is not specific to roads, it follows similar analytical principles and offers comprehensive inputs that can support transport resilience assessments, particularly during the screening and diagnostic stages.

Table 2.1 An Overview of Two Resilience Analysis Tools

	GRI (Open-Source Model)	HARMA
Methodology	- Combines flood hazard data with road asset exposure and vulnerability - Can add landslides/other hazards via Python extensions	- Origin-destination (OD)-matrix-based transport model integrating hazard data - Estimates exposure and vulnerability - Performs cost-benefit analysis (CBA) and provides investment scenarios (operational expenditure/capital expenditure)
Capabilities	- National-level vulnerability diagnostics - Flood risk mapping and scenario planning - Direct damages only - Asset-level analysis possible - Criticality requires Python extensions and traffic data	- Strategic vulnerability diagnostics - Economic framing (CBA) - Direct + indirect damages - Network-level + full criticality analysis
Data requirements	- Includes defaults: road geospatial data, flood layers, vulnerability curves - Can be replaced with local inputs	- Includes defaults (JBA climate database, global flood maps) - Utilizes country-level traffic and OD data, economic indicators, infrastructure inventories, and repair costs
Data sources	- GRI Risk Viewer - National road inventories	- JBA (largest climate data suite) - Custom data collection - National databases
Institutional arrangements	Responsible entity: Oxford Infrastructure Analytics Availability: open source; with the support of short-term consultants	Responsible entity: World Bank Availability: not public; delivered through engagements by in-house transport team

3. Case Studies

Four case studies were selected for inclusion in this report—from (1) the Kyrgyz Republic and Nigeria; (2) Pakistan; (3) Brazil; and (4) Malawi—because of their unique contribution to the body of transport resilience assessments.

In the Kyrgyz Republic, the bespoke modeling of landslides, combined with traffic analysis, helped identify high-risk corridors, informing priorities for intervention. In Nigeria, readily available flood and asset data were used to conduct a rapid vulnerability assessment. Both applications used an open-source GRI model and demonstrated its replicability.

In Pakistan, the HARMA tool supported a multi-hazard transport resilience analysis at a national scale. The application demonstrates how HARMA integrates hazard exposure, network performance, and economic analysis to estimate both direct asset damages and indirect losses from traffic disruption across the road network. It illustrates the model's value for comparing adaptation options, identifying high-priority corridors, and supporting evidence-based investment planning under multiple climate scenarios.

Vulnerability assessment results directly informed an operation in Brazil. The study's diagnostics—identifying hotspots and assessing asset fragility—were used to shape the Climate Resilience Management Plan (CRRMP), which is now embedded in CREMA 2.0 contracts under the Pro-Roads Program. The CRRMP translates climate-risk analytics into enforceable requirements for contractors, defining inspection routines, performance thresholds, and event-response obligations. Brazil thus provides a unique and globally relevant example of how climate-risk assessment can be institutionalized through performance-based contracting, effectively turning resilience concepts into operational practice.

In Malawi, resilience analysis was applied at the asset level through detailed, multi-resolution exposure mapping in flood-prone areas. The analysis supports the identification of site-specific hotspots and informs tailored engineering interventions—such as slope stabilization, drainage upgrades, and bridge reinforcement—which can be directly incorporated into feasibility studies and detailed design. This case demonstrates how granular, field-informed diagnostics can complement broader network-level prioritization and translate resilience analysis into concrete investment decisions in highly vulnerable settings.

3.1 Kyrgyz Republic and Nigeria: GRI Application

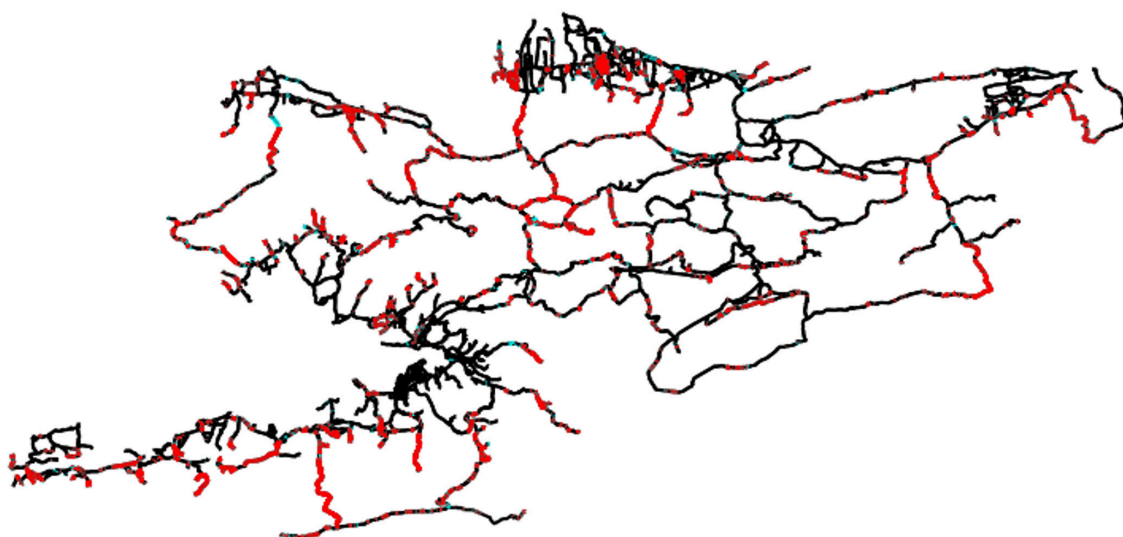
Kyrgyz Republic

The Kyrgyz Republic's mountainous and landlocked geography makes its road network a critical lifeline; however, it remains highly exposed to floods, mudflows, landslides, and avalanches (UNDRR 2024). Between 1990 and 2010, a total of 3,689 registered emergencies of a natural nature were reported (UNDRR 2024). To inform the Country Climate and Development Report (CCDR), a rapid exposure assessment was undertaken using an open-source GRI model. This assessment combined exposure and criticality analysis, resulting in corridor-level insights and a high-level prioritization of the road network.

In contrast to river flooding, where most regions (*oblasts*) are classified as low risk, all regions in the Kyrgyz Republic are considered high risk for landslides and mudflows (UNDRR 2024). This high risk became the focus of the study. While data on mudflows were unavailable, landslide exposure was modeled using customized susceptibility mapping (NatCap Insights n.d.). However, due to the limited availability of reliable fragility data for slope failures, exposure was reported as the length of roads within hazard zones, and damages were not calculated. These maps were applied for current climate conditions and projected for 2030 and 2050 under two scenarios: a midrange pathway (Representative Concentration Pathway [RCP] 4.5) and a more severe pathway (RCP 7.0).

Landslide hazard maps were analyzed in conjunction with the main road network to assess exposure levels. The national road network was sourced from open mapping platforms, specifically OpenStreetMap. The focus was on the primary functional classes, mainly paved roads, linking all findings to the Republic's core transport network. As shown in figure 3.1, landslide exposure is widespread, with around 4,000 kilometers (km) of road lanes at risk of being exposed to a 10-year event. Notably, there are significant concentrations of exposure around the M-106 (Batken). Overall, it is projected that landslide exposure will increase by 10-20 percent by 2050, depending on the climate scenario.

Figure 3.1 Exposure to Landslides in the Kyrgyz Republic



Source: World Bank.

Note: The figure shows the vulnerability of roads to a 2020 10-year landslide (red) and additional roads exposed to a 100-year landslide (dark blue). Landslide-exposed segments are slightly thicker than nonexposed segments for visual clarity.

The analysis integrated the hazard exposure data with an importance-weighted perspective of the network. To assess the importance of different network segments and prioritize roads for investment, the study developed a model depicting how people move on the roads. This involved creating a doubly constrained gravity model of passenger traffic, calibrated using gridded population data (Meta n.d.), which assigned traffic flows to the network. Criticality was then measured as the percentage increase in total network travel time during segment outages, highlighting choke points where disruptions impose significant costs on the system. Results from the hazard exposure analysis and criticality assessment were overlaid to identify high-priority links for resilience investment.

The network criticality analysis showed that substantial portions of the core network are exposed to a 10-year landslide. Approximately 377 km of high-flow roads⁶ are currently at risk of landslides, with around 165 km classified as highly critical.⁷ These roads are primarily located in the center of the country. While the overall exposure of the road network to landslides is expected to increase by 2050, the exposure of high-flow and highly critical roads is projected to rise only marginally.

Overall, the assessment demonstrates a scalable, decision-focused approach: it involves developing fit-for-purpose geohazard data, quantifying exposure, and targeting resilience measures for a select group of high-impact corridors that carry significant socioeconomic costs (see appendix C for further details of this analysis).

Nigeria

Nigeria, with the largest population in Africa (UN 2025), serves as a critical case study for understanding climate vulnerability in road transport networks. With its vast and diverse geography, ranging from coastal lowlands to riverine floodplains, Nigeria's road infrastructure is vital for economic activity, social connectivity, and disaster response. The country was chosen for this assessment due to its high exposure to climate hazards and the strategic importance of its transport sector for regional development and trade.

The case study applied a structured flood risk assessment that links hydrodynamic hazard estimates with data on infrastructure exposure, vulnerability, and costs. This method generates consistent and comparable damage metrics across different spatial, temporal, and climate scenarios. The approach was deliberately designed to be modular and transparent, so that it could be replicated in different sectors, updated as new data became available, and stress tested under alternative assumptions.

First, hazard and asset maps were collected. Flood depths were compiled for multiple planning horizons (historical baseline, 2030, 2050, and 2080) along with two climate pathways (a milder RCP 4.5 and a more severe RCP 8.5). Additionally, a full set of return periods was included, ranging from frequent (1-year) to rare (1,000-year) events. Road exposure was represented as geocoded points, accompanied by attributes that support vulnerability and cost assignment. These two data sets were then overlaid to calculate exposure across different horizons and scenarios.

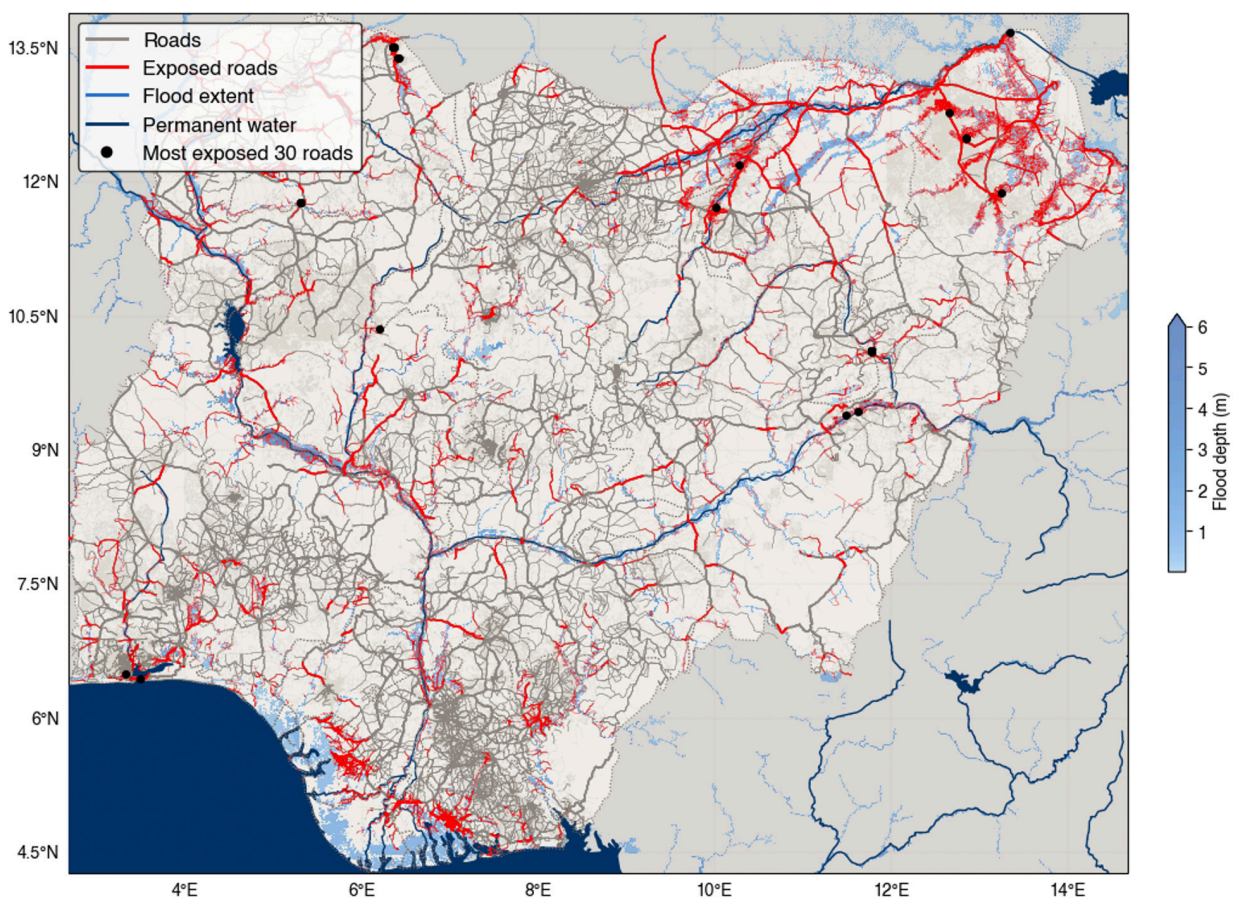
⁶ In this study, high-flow roads are defined as those in the top 10 percent in terms of traffic volume.

⁷ In this study, highly critical roads are those that increase total travel time all network users by at least 2 percent. This analysis excludes freight, focusing solely on passenger travel, resulting in a conservative estimate of the criticality of road links.

To calculate vulnerability, flood depth was converted into expected damage using vulnerability (depth-damage) curves tailored to each asset type. To account for uncertainty, damage estimates were reported with central, lower, and upper bounds. Expected damage was quantified by linking each asset to a rehabilitation or replacement unit cost, stratified by road class and surface type.

To aid in planning and prioritization, results were summarized at multiple levels. Aggregation at the national and state levels revealed hotspots where expected damages cluster under current and future climate scenarios. Overall, as illustrated in figure 3.2, Nigeria's road network is highly exposed to flooding, with repair costs from riverine (fluvial) floods estimated to range between \$500 million and \$4 billion depending on future climate scenarios. In contrast, coastal flooding poses a much smaller financial risk, with costs estimated to range from \$2.5 million to \$25 million.

Figure 3.2 Roads Exposed to a 100-Year Flood in Nigeria



Source: Oxford Infrastructure Analytics.

Note: This map illustrates 100-year flood hazard levels for fluvial flooding in Nigeria under a 2050 RCP 4.5 scenario. The 30 assets with the highest value exposed are indicated black circles. Note that many of the circles overlap on the map. m = meter.

The outputs facilitate a suite of risk-informed decisions. Asset screening identifies road segments that frequently sustain significant damages under floods, making them candidates for hardening, elevation, or relocation. Additional steps may involve refining design guidance by comparing the

marginal costs of higher design standards with the damage that can be avoided across various return periods. Details of the case study are available in appendix D.

3.2 Pakistan: HARMA Application

Pakistan faces pronounced climate and seismic risks, with both flooding and earthquakes posing serious threats to its transport network. The scale of this vulnerability was underscored by the 2022 floods, which affected 33 million people and caused over \$15 billion in economic damage (World Bank 2022b). This case study applies a structured, multistep resilience assessment tool, HARMA, to inform a potential nationwide retrofit program and provide a transparent basis for prioritizing investments.

The assessment begins by evaluating network criticality. Pakistan's transport network comprises more than 111,000 bridges and 115,000 km of roadways. Centrality analysis reveals that the disruption of several hundred key bridge links and selected roadway corridors would lead to substantial increases in travel times across multiple districts. Additionally, accessibility analysis—using data on schools, hospitals, and universities extracted from OpenStreetMap—indicates that links serving peri-urban and rural regions often generate the largest accessibility losses. When even a single link fails, travelers may lose access to essential services within a one-hour travel window.

Infrastructure vulnerability is assessed for both floods and earthquakes across return periods ranging from 20 to 1,500 years for floods and 475 to 2,475 years for earthquakes. Under a 20-year flood event, about 18,600 km of roadways and 285 bridges experience significant damage (defined as a damage ratio exceeding 0.2). For more severe 500-year floods, damage escalates to more than 31,000 km of roadways and over 500 bridges. The impacts of earthquakes are primarily seen in bridge structures: at a 475-year return period, 593 bridges incur damage, but the number increases sharply to more than 4,100 bridges under a 2,475-year event. While damage to roadways from earthquakes remains limited at lower return periods, it approaches nearly 11,000 km under the most extreme 2,475-year scenario.

Direct and indirect loss estimation reveals the financial scale of these impacts. Indirect losses reflect the additional strain placed on network users (both passengers and cargo), resulting from diminished network functionality. These losses are a function of increased travel distances and longer travel times in the post-disaster network, calculated using a traffic reassignment procedure. They are estimated through a dynamic process that involves daily prediction of traffic and associated losses for every day of the recovery period, continuing until the network regains its “normal” (pre-disaster) functionality.

The expected annual loss (EAL) for the transport network due to floods is estimated at \$138 million, which includes \$34 million in direct asset repair costs and \$104 million in indirect user losses. Notably, these indirect losses represent more than 70 percent of the total losses and reflect the prolonged increase in travel time and distance as the network recovers from flooding. Flood events with a 20-year return period already impose substantial costs, and while losses rise with the severity of the hazard, the rate of increase is gradual because frequent flooding events dominate the annualized risk. By contrast, earthquake-related EAL is much lower, at \$6.7 million, and is primarily driven by direct losses. Indirect user losses in the case of earthquakes are relatively limited because alternative routes are generally available when bridges are damaged. This allows for traffic to be diverted with less disruption than during widespread flooding.

Two adaptation strategies are evaluated to support investment prioritization. The first strategy—adaptation to any possible event—aims to protect assets against the full spectrum of flood probabilities, including rare events with a return period of 1,500 years. This plan includes retrofitting 31 bridges and approximately 910 km of roadway at a total cost of \$130 million. The second strategy—adaptation to frequent events—focuses on reducing losses from floods with return periods of 100 years or less. This approach targets improvements to 24 bridges and 790 km of roadways, at a cost of \$41 million. Both plans direct investments toward districts that experience the highest combined direct and indirect losses from floods and earthquakes.

The CBA, conducted over a 50-year horizon with a 6 percent discount rate, demonstrates strong economic performance for both strategies but substantially higher returns for the strategy focused on frequent events. Plan B achieves a net present value (NPV) of \$249 million, with a benefit-cost ratio (BCR) of 7.0 and an annualized return on investment (ROI) of 12.1 percent. In comparison, Plan A also produces positive returns, with an NPV of \$191 million, a BCR of 2.5, and an ROI of 2.9 percent. The difference in returns stems from the much higher retrofitting costs associated with preparing for rare events, which only contribute marginally to Pakistan's EAL. Since most flood-related losses originate from frequent events—those occurring roughly every 20 to 100 years—the additional protection provided by Plan A for rare events does not justify its substantial investment cost.

Overall, the Pakistan case study demonstrates the value of integrating network criticality, multihazard vulnerability, dynamic loss modeling, and economic appraisal in national-scale resilience planning. The analysis provides quantitative evidence that targeted, cost-effective upgrades focused on frequent hazards can substantially reduce annual losses, and help guide Pakistan toward a more resilient and economically efficient transport system.

3.3 Brazil: Implementation of a Road Network Resilience Assessment

Brazil's vast road network, stretching over 1.7 million km with only about 12.5 percent of the roads paved, serves as a critical backbone for the nation's economic activities. It facilitates national and regional commerce, agriculture, and logistics, connecting diverse regions across the country. However, this extensive infrastructure faces significant challenges from frequent natural hazards such as floods, landslides, and wildfires, which are exacerbated by climate change. The country's geographical diversity—encompassing six biomes and seven climate zones—adds complexity to regional vulnerabilities and necessitates tailored approaches to enhance infrastructure resilience.

Recognizing these challenges, key stakeholders came together to assess and enhance the resilience of Brazil's road infrastructure. The World Bank provided technical and financial support to state road departments responsible for managing state-level roads through performance-based contracts.

The primary focus of the study was to evaluate the vulnerability of Brazil's state road networks, identifying high-risk segments to prioritize investments in resilience. This assessment sought to ensure the reliability and sustainability of the road network in the face of increasing climate-related threats. The initiative focused on developing and testing a comprehensive methodological approach built on the following pillars:

1. **Climate hazard analysis.** Using models based on the Intergovernmental Panel on Climate Change (IPCC) scenarios, the study assessed risks from floods, landslides, and other hazards across various RCP scenarios. This analysis provided insights into how climate change could intensify existing hazards.
2. **Vulnerability assessment.** This assessment combined factors such as exposure, physical fragility, and socioeconomic criticality to create a comprehensive risk profile for each road segment. Visual inspection data were also incorporated to develop a Transport System Fragility Index (TSFI), a new metric designed to evaluate the capacity of road infrastructure to withstand and recover from climate-related impacts without compromising usability and road safety.
3. **Hotspot mapping.** By integrating hazard exposure, fragility, and socioeconomic importance, the study prioritized interventions where they were most needed. This mapping identified critical corridors and hotspots that required immediate attention.

A key aspect of the methodology was the integration of geographic information system (GIS) mapping, visual surveys, and downscaled climate models. These tools enabled region-specific assessments of vulnerabilities and facilitated the development of proactive resilience measures. However, the assessment faced several challenges, notably in data accessibility and quality. To address these capacity constraints, extensive training programs were conducted for road authorities to enhance their technical capacity. These programs equipped engineers and officials with the skills needed to effectively apply the new resilience-focused methodology and tools. Stakeholder feedback loops were also incorporated into the development process to ensure adaptability and user-centric improvements.

The assessment featured several important elements. The first standout feature was the use of the TSFI,⁸ which offered an innovative method to quantifying the extent to which different parts of the road network could withstand and recover from climate-related impacts in the context of climate change, without compromising usability and road safety conditions (Lang and Peñalver Rojo 2025). This holistic risk assessment combined physical, functional, road safety, and socioeconomic factors, offering a more comprehensive understanding of the vulnerabilities in road infrastructure and potential transportation disruptions in the event of climate shocks. The index is categorized into four bands—low, moderate, high, and very high fragility—based on systematic field inspections, and serves as a tool for planning, monitoring, and making contractual decisions.

The second noteworthy aspect of the methodological framework is the introduction of a resilience rating.⁹ This rating builds on the fragility assessment and translates climate risk considerations into a practical tool for planning and decision-making. It combines information on climate hazards, asset exposure, and infrastructure condition to provide an overall indication of how well road segments are expected to perform under climate stress. Rather than relying on a fixed formula, the resilience rating is designed to evolve over time as more field and operational data become available through

⁸ The TSFI combines road infrastructure fragility (determined through a six-month-long visual survey of road infrastructure deterioration and financial assessment of future repair costs), direct efficiency impacts (such as travel time increases resulting from disruptions), and broader disruptions and losses (including indirect impacts on fuel consumption, air pollution, stress on logistics chains, deterioration of basic service provision, and impacts on social equity).

⁹ The resilience rating is a qualitative rating with four categories from A to D, with D having the highest investment priority, based on a combination of road criticality and adaptation needs.

the implementation of the Road Rehabilitation and Maintenance Contract, CREMA 2.0.¹⁰ It supports planning cycles, investment prioritization, and performance monitoring by establishing clear and consistent thresholds, which incentivizes road authorities to achieve and maintain resilience standards (Lang and Peñalver Rojo 2025). A shared resilience rating can benefit multilateral agencies, contractors, investors, and financiers by providing transparent metrics that enhance decision-making, foster accountability, and promote resilience in road infrastructure projects.

The last methodological advancements are rooted in cutting-edge technology and digital platforms. A digital platform is being designed to centralize resilience data and facilitate real-time analytics, to enhance decision-making processes and support dynamic data integration. This platform is expected to feature offline data collection capabilities, a modular design for integration into various geographic contexts and infrastructure types, and AI-enhanced predictive analytics for assessing long-term climate resilience.

Beyond its methodological innovations and strong uptake by Brazilian road authorities, the study has developed and operationalized the Climate Resilience Management Plan (CRRMP) as a core requirement in CREMA 2.0 contracts under the Brazilian Pro-Roads program.¹¹ Two types of CRRMPs have been established: (1) a basic CRRMP prepared by the contracting authority, which defines climate scenarios, identifies corridor hotspots, and proposes preliminary resilience actions; and (2) a project-specific CRRMP developed by contractors, which tailors and refines interventions to local conditions. This two-tiered system ensures consistent resilience standards and alignment with government objectives.

The CRRMP also introduces standardized fragility inspection protocols and embeds resilience provisions into performance-based contracts, reinforcing proactive climate risk management across planning, maintenance, and operations.

Overall, the Brazil framework exemplifies how climate resilience assessments can be translated into concrete actions. By directly linking diagnoses to contractual requirements, considerations of fragility and resilience inform performance indicators, monitoring routines, emergency response obligations, and maintenance planning. The scale of implementation under CREMA 2.0 also enables systematic learning across diverse climatic contexts, allowing resilience metrics to be progressively refined based on real-world experiences. By making resilience performance observable and contractually relevant, this approach creates clear incentives for sustained action. Additionally, its integration into procurement, supervision, and data systems fosters lasting institutional capacity beyond the duration of external support. Together, these features provide a coherent and scalable model for mainstreaming climate resilience into road infrastructure management, which is applicable to other countries facing similar climate challenges.

¹⁰ Contratos de Reabilitação e Manutenção: Brazil's updated performance-based road contracts that bundle rehabilitation and multiyear maintenance, embedding climate risk and resilience requirements through basic and detailed Climate Resilience Management Plans (CRRMPs), with payments tied to service levels rather than inputs.

¹¹ A World Bank Multiphase Programmatic Approach with Brazilian states that scales CREMA-based, climate-resilient road asset management and public-private partnerships, coupling works with institutional strengthening and standardized tools for replication.

3.4 Malawi: A Road Vulnerability Assessment for the RESTORE Project

The Malawi Resilient and Strategic Transport Operational Enhancement (RESTORE) Project targets critical road segments within the Lower Shire Valley, emphasizing the importance of the M1 highway—particularly the Thabwa-Chikwawa-Bangula section—and the S152 feeder road connecting Thabwa, Chitseko, and Seven (World Bank 2025b). These roadways serve as vital corridors for agriculture, trade, and socioeconomic activities in southern Malawi, linking rural production zones to national and regional markets. The flat lowlands and wetlands of the southern Shire River Basin, where these roads are situated, are susceptible to flooding and sedimentation. Therefore, a thorough assessment of climate-related vulnerabilities and the implementation of adaptation measures are necessary to ensure long-term resilience of this infrastructure.

Key stakeholders in this effort included the Malawi Ministry of Transport and Public Works, the Department of Water Resources, the Road Authority, the Road Fund Administration, and local governance structures such as the Chikwawa and Nsanje District Councils. International development partners, notably the World Bank, Japan's Global Facility for Disaster Reduction and Recovery program, the Global Center on Adaptation, and the European Space Agency, provided both technical and financial support. Their involvement was crucial to align the vulnerability assessments (VAs) at all levels—project roads, the road network in the project area, and the national road network—with international best practices in climate resilience, while ensuring that local priorities, data, and capacities were integral to the process.

The detailed VA at the project asset level aimed to identify sections of the M1 and S152 that are most susceptible to climate-related hazards, especially flooding and erosion. Given the complex hydrological and hydraulic dynamics of the Shire River and its tributaries, the hazard analysis incorporated multiple return periods (20-, 100-, and 400-year events) to capture both current conditions and potential extreme events intensified by climate change. Structural inspections included bridges, culverts, and embankments, examining their capacity to withstand high-discharge events and manage sedimentation. This comprehensive approach established a robust baseline for understanding infrastructure vulnerabilities and pinpointing where resilience investments would yield the greatest returns.

A critical feature of this detailed VA was the use of a multiresolution analysis for exposure mapping. The study encompassed the broader Shire Basin, linking upstream and downstream hydrological characteristics to illustrate how changes in one part of the basin could reverberate along the entire network. The aggregated flood extents were examined for tributaries and their confluence areas with the Shire River, revealing how multiple waterways interacted to shape flood patterns over wider areas. High-resolution flood hazard maps were generated using detailed Digital Terrain Models to simulate inundation depths and velocities at specific road segments. These maps facilitated granular diagnoses of structural weaknesses, indicating exactly which culverts or bridges were at risk of being overwhelmed during heavy floods.

Data and resource constraints posed significant challenges. Incomplete rainfall and discharge records from local agencies necessitated reliance on open-source satellite data and simplified hydrological models. Knowledge gaps regarding climate resilience and adaptation among local stakeholders was another crucial element. The project included capacity-building initiatives, such as training programs, workshops, and public lectures targeting both practitioners and university students, to enhance the technical skills of local officials, engineers, and decision-makers. In addition, with the support from the World Bank's Disaster Risk Management (DRM) team for Malawi, detailed VA methods were disseminated in a regional DRM symposium, which was attended by government officials of neighboring countries.

Strengthening the institutional framework ensured that the tools and methodologies introduced during the VA would remain useful over time, even as climatic and socioeconomic conditions evolve.

An innovative aspect of this assessment was the incorporation of a tailored CBA. This analysis considered various return periods for design (20, 50, and 100 years) and for hydrological and hydraulic analysis (20, 100, and 400 years) to align with the dynamic conditions in the Shire and Ruo River valleys. By integrating multiple climate scenarios and linking them to CAPEX and OPEX for proposed interventions, the CBA framework offered a climate-sensitive economic evaluation.

Yet, while the CBA approach signifies a methodological advancement, determining which types of losses (direct, indirect) to include and how to value them economically (the monetization process) proved challenging. Five key layers of benefits (related to flood damage reduction) were identified: (1) land use/land cover (including built-up areas and crops); (2) population distribution; (3) health, education, and accident metrics; (4) trade logistics (export/import); and (5) emergency relief. These data were primarily derived from the macro-scale data sources, such as night light data, optical satellite imagery to detect historical and recent trends, census data on socioeconomic activities, and basic traffic information from local authorities. All these data were integrated into a GIS environment for visualization and analysis.

The main findings of the VA revealed that critical sections of the M1 and S152 roads are particularly vulnerable to flood-related hazards. Inadequate culverts and undercapacity bridges were identified as key factors contributing to erosion and inundation risks. Increased sedimentation and runoff, driven by changing rainfall patterns and land-use practices, compounded these vulnerabilities, underscoring the need for robust engineering solutions and effective catchment debris management (CDM). Hence, in addition to the detailed VA that identified hotspots of project assets vulnerable to climate-related hazards, various CDM options were assessed, and the most economical option was selected for further investigation. By prioritizing resilience investments both on the project roads and CDM now, the project aims to reduce future disruptions, safeguard agricultural trade and community access, and enhance infrastructure resilience and climate action.

In conclusion, the Malawi RESTORE Project's VA marks a significant advancement in climate-resilient road asset management within a highly flood-prone and rapidly changing context. Its rigorous methodology, emphasis on capacity building, and alignment with international resilience agendas establish a strong model for future assessments. By leveraging open-source data sets, adaptable hazard modeling tools, and participatory methods, this approach demonstrates clear potential for replication across similar regions. The GIS-based, multilayered mapping—integrating hazards, infrastructure inventories, and socioeconomic data—provides a robust framework for identifying vulnerabilities and prioritizing hotspots. Combined with the project's asset-level focus, these insights can strengthen intervention design, improve project readiness, and accelerate feasibility analysis in Malawi and beyond.

As climate conditions continue to evolve, it will be essential to iteratively refine hazard models and maintain ongoing engagement with stakeholders. The lessons learned and approaches refined through this VA can serve as a valuable reference for similar initiatives in other regions, ultimately contributing to global efforts to build more sustainable and climate-resilient infrastructure networks.

4. Conclusion, and a Look Ahead

Climate change is reshaping the risks faced by transport systems, and this report highlights the significant evolution of resilience assessments in response to these challenges. Across more than 50 World Bank analytical and operational documents, resilience analyses have progressed from basic exposure mapping to more comprehensive approaches that integrate vulnerability, network criticality, indirect economic losses, and robust economic analysis. The four case studies demonstrate that this progression is not linear but multidimensional. Macrolevel diagnostics in the Kyrgyz Republic and Nigeria illustrate how scalable, open-source tools can inform national policy dialogue. The new HARMA model supported adaptation planning in Pakistan. Brazil demonstrates how corridor-level analytics in Brazil influenced contracting and investment decisions. Asset-level, engineering-oriented assessments in Malawi informed project preparation. Together, these examples reveal that resilience analytics are most impactful when tailored to context, aligned with decision-making needs, and embedded within country systems.

At the same time, the review points to clear opportunities for strengthening resilience practices more broadly. Emerging tools—such as the open-source geospatial model and the HARMA tool—demonstrate strong potential to improve consistency, transparency, and economic rigor across assessments. However, realizing this potential requires continued investment in data foundations, institutional capacity, and the integration of resilience into procurement, design, and asset management processes. As climate risks intensify and financing gaps widen, the ability to generate credible and actionable analyses will be crucial for directing scarce resources toward the most effective interventions. This report contributes to that objective by distilling lessons from diverse contexts and demonstrating how analytical innovation can translate into better planning and more resilient transport systems.

The transport resilience planning field continues to evolve. The following key points outline several of the technical, analytical, and institutional enhancements needed to strengthen the tool's effectiveness across diverse country contexts.

1. Expand Multihazard Coverage

Currently, both the GRI and HARMA focus primarily on flood hazards, although the GRI has the capability to incorporate landslides and other hazards through a Python extension, while HARMA can integrate custom hazard layers. A priority area for future work is to expand the range of hazards covered while improving data accuracy. This includes integrating multihazard capabilities such as landslides, extreme heat, cyclones, coastal erosion, and wildfire risk.

2. Develop Built-In Resilience Measures

There is a significant information gap on the costs and effectiveness of various adaptation measures. To address this, a reference document, drawing on expert input and insights from recent resilience

projects, could compile consistent information on adaptation options, associated costs, and performance metrics for application across regions and project types. This could feature a “no-regret” screening function to help countries in identifying low-cost, high-impact measures, even in the absence of comprehensive data.

3. Incorporate Digital Innovations and AI

Integrating satellite imagery and AI machine learning to automate detection of road damage, landslide scars, drainage blockages, and exposed assets can lead to quicker, more cost-effective, and scalable resilience assessments.

Geospatial foundation models, which are trained on large remote sensing data sets, show promise in enhancing risk analysis workflows. Examples include IBM/National Aeronautics and Space Administration’s (NASA’s) Prithvi model (designed for flood and burn scar detection) and Google’s Population Dynamics and mobility models (Schottlander and Shekel 2025). While these tools offer valuable early insights, their current limitations—such as their black-box nature, inconsistent accuracy across geographies, and challenges in auditing or validating outputs—indicate that they are best suited for preliminary screening rather than for decision-grade resilience analysis. In the near term, these tools will complement, rather than replace, traditional engineering and hazard-modeling approaches.

4. Expand Beyond Roads to a Multimodal Transport Resilience Platform

Another direction is to extend the tool’s scope from road-focused diagnostics to a multimodal transport resilience platform that includes rail, ports, and airports. Many climate shocks, especially floods, cyclones, and landslides, disrupt entire transport systems, not just road corridors. As a result, countries increasingly need integrated assessments that illustrate how disruptions in one mode cascade into others. This need is particularly urgent in urban areas, where flood-prone zones have expanded by about 122 percent since 1985, intensifying exposure and compounding network-wide impacts (Avner et al. 2022). Future versions of the tool could include mode-specific asset typologies (such as tracks, rolling-stock depots, terminals, port quays, and runways), hazard sensitivities, and adaptation measures, while also enabling systemwide network diagnostics across modes.

5. Build Local Capacity and Ensure Sustainable Uptake

Ultimately, the goal is for country governments, not just consultants or Bank teams, to run and update resilience assessments. It is important to develop a training package tailored for road authorities and to promote its use in planning. This will embed resilience analytics into national systems rather than treating them as one-off exercises. HDM5 could also serve as the repository for these data and models, once it is fully operational.

The future direction is clear: a comprehensive, multihazard, data-responsive system that supports both high-level screening and detailed decision-making. With a focus on scalability, improved usability, and country ownership, the tool can become the Bank’s central platform for national transport resilience planning and investment prioritization.

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Appendix A.

Detailed Methodology Descriptions and Data Foundations

This appendix outlines the details of common underlying principles, methodologies, and data sources commonly used in assessments of transport networks' climate risk and resilience.

A.1 Define the Scope and Objectives

Any resilience assessment must begin by defining its scope and objectives. One way to do this is to answer certain fundamental questions (listed below). This step helps align expectations, and ensures the modeling effort remains focused.

- What type of infrastructure is included (e.g., for roads, is the focus on national, rural, corridors, or bridges)?
- What hazards matter (river, rain, or coastal flooding; landslides; heat and extreme temperatures; storms)?
- What time horizons and climate scenarios are considered (current, 2030, 2050)?
- What outputs are needed (damage, resilience measures, prioritization of investment, wider economic impact, financing needs)?

A.2 Prepare Hazard and Climate and Asset Data

The resilience assessment process begins with the identification and characterization of relevant natural hazards. Historical weather records, geological characteristics, and disaster events are analyzed to determine which types of climate threats (e.g., extreme precipitation, heatwaves, flash floods, or landslides) pose the greatest risk to road infrastructure. Using qualitative screening tools such as ThinkHazard.org to identify which risks warrant deeper analysis is a useful starting point.

Transport risk analyses can address multiple climate hazards (flooding, landslides, extreme heat, or tropical cyclone winds), but flooding and landslides are typically the most relevant for road networks as they dominate expected annual damage costs globally. However, heat-related impacts are rising rapidly and are increasingly being assessed as well (Ukkusuri et al. 2025).

Hazard maps are developed through a cascade of analytical and physical models. For each epoch and climate scenario, a group of global climate models (GCMs) simulate many time series of climate variables. The output climate variables are then used to drive hazard models, and a hazard map is generated for each GCM. At each location, a probability distribution is fitted to a hazard from across the ensemble. Hazard maps are typically provided as portfolios of rasters that capture different climate scenarios (Representative Concentration Pathways, RCPs). These scenarios represent different levels of warming, as well as wetter or drier conditions.

The portfolios of hazards can span multiple time periods (epochs), future climate scenarios (e.g., RCP 4.5, RCP 8.5), and return periods (e.g., 1 in 10 years, 1 in 100 years). A return period is an estimate of the average time interval between occurrences of an event of a defined size or intensity. When the hazard maps are based on simulations from GCMs, the portfolio includes multiple hazard maps for each combination of epoch, scenario, and return period, corresponding to each GCM in the ensemble. When maps are generated for the baseline/historical epoch, they are based on historical data, and often there is only one map per epoch, scenario, and return period.

Flood Hazard Data

Flooding can be triggered by a variety of different processes, each requiring its own hazard maps:

- **Fluvial (riverine) flooding.** Overflow of rivers and streams into adjacent low-lying areas.
- **Pluvial flooding.** Caused by intense rainfall and triggered as surface water flooding (when drainage systems are overwhelmed) or flash floods (rapid runoff from extreme rainfall events).
- **Coastal flooding.** Driven by storm surge, high tides, waves, and sea-level rise in low-lying coastal areas.

While real-world events often involve compound flooding, most hazard data sets model only one flood type. They also describe the probability of flooding at a specific location but not the joint distribution of hazards across space, which creates limits for aggregation or networkwide modeling.

Multiple open-source and proprietary flood hazard data sets are available, each with trade-offs related to resolution, geographic scope, modeled processes, and inclusion of protection measures. Table A1.1 provides examples of commonly used data sets. Practitioners must balance the need for high resolution with adequate scenario coverage, depending on project objectives. Licensing constraints associated with proprietary data sets may limit the sharing or publication of data and should be assessed early in assessment design.

Table A1.1 Selection of Available Flood Models with Global Coverage

Name	Flood Type	Open Source	Resolution	Epochs	Scenarios	Return Periods (Years)
WRI Aqueduct Floods Hazard Maps	Coastal and riverine	Yes	1 km, 10 km	2010, 2030, 2050, 2080	RCP 4.5, RCP 8.5	2, 5, 10, 25, 50, 100, 250, 500, 1,000
Deltares Global Flood Map (Deltares 2021)	Coastal	Yes	90 m, 1 km, 5 km	2018, 2050	RCP 8.5	0, 2, 5, 10, 25, 50, 100, 250
JRC Global River Flood Hazard Maps (Russell et al. 2025)	Riverine	Yes	90 m	NA	NA	10, 20, 50, 100, 200, 500
Fathom Global Flood Maps (Fathom 2022)	Riverine, pluvial, and coastal	No	~30 m, 10 m	2020–2100	RCP 2.6, RCP 4.5, RCP 8.5 SSPs, NGFS	5, 10, 20, 50, 100, 200, 500, 1,000

Source: World Bank.

a. Proprietary product purchased by the World Bank.

Note: JRC = Joint Research Centre of the European Commission; km = kilometer; m = meter; NGFS = Network for Greening the Financial System; RCP = Representative Concentration Pathway; SSP = Shared Socioeconomic Pathway; WRI = World Resources Institute.

Landslide Hazard Data

Global-scale landslide data sets are available. The Global Landslide Hazard Map commissioned by the World Bank/ Global Facility for Disaster Reduction and (GFDRR/Arup 2021) provides annual frequency estimates for landslides triggered by rainfall and earthquakes. These estimates are suitable for exposure screening. The layers of the Landslide Hazard Assessment for Situational Awareness (LHASA) of the National Aeronautics and Space Administration (NASA 2021) provide dynamic information on susceptibility to landslides and events triggered by precipitation. Where detailed decisions are required, custom landslide modeling can be performed using locally calibrated data on slope, lithology, vegetation, and rainfall.

Extreme Heat Data

For extreme heat and temperature exposure mapping, World Bank studies typically rely on a standardized stack of climate data and screening tools to ensure consistency and replicability. At the national level, teams use the Climate Change Knowledge Portal to retrieve historical trends and future projections for temperature-based indicators (e.g., mean/maximum temperature, number of hot days, heat indices) under Coupled Model Intercomparison Project Phase 6 (CMIP6) scenarios.

Limitations of Hazard Data

Hazard maps are subject to important limitations related to data quality and modeling assumptions. Observational inputs vary significantly across locations, while results are sensitive to choices regarding physical processes, spatial resolution, climate models, and whether existing flood protection infrastructure is assumed to be present and effective. These uncertainties can lead to substantial variation across hazard estimates. For example, a comparison of six flood models applied in Africa revealed wide differences in the estimated extent of flooding, projected economic losses, and exposed populations (Avner et al. 2023). To account for this uncertainty, conducting hazard modeling using an ensemble of models, and using a number of different warming scenarios, is recommended (World Bank 2025c).

Road Asset Data

Road asset data define the spatial distribution and characteristics of road networks in vector formats such as Shapefile, GeoPackage, or GeoJSON. These data sets typically include road class (e.g., primary, secondary, tertiary), surface type, lane count, and whether structures such as bridges or culverts are present.

OpenStreetMap (OSM), licensed under the Open Database License, represents a widely used open-source data set with global coverage. While OSM is suitable for screening-level studies, data quality varies significantly across countries. For detailed asset-level assessments—particularly where cost estimates or engineering decisions are involved—OSM data should be validated against local or government data sets, if available.

Recent advances in artificial intelligence (AI) and computer vision allow countries to generate road asset data even where traditional inventories are incomplete or outdated. High-resolution satellite imagery, imagery generated by unmanned aerial vehicles, and street-level photographs can now be processed using AI models to automatically classify pavement types, detect surface distress (e.g., cracking, potholes, rutting), estimate road width and shoulders, identify drainage features, and infer slope stability risks.

A.3 Assess Exposure and Vulnerability at the Asset Level

Following hazard analysis, hazard exposure maps are developed using geographic information systems (GISs). Hazard exposure maps enable spatial visualization of how risks are distributed across a road network. These maps typically combine historical hazard records with future projections under Shared Socioeconomic Pathways (e.g., SSP4-2.6 or SSP5-8.5), as well as geological and geotechnical surveys. Analysis of the developed hazard exposure maps helps identify road segments most exposed to climate threats and guides prioritization in subsequent vulnerability assessment phases.

A vulnerability assessment goes a step further by quantifying the exposure of individual road segments and applying vulnerability functions to estimate expected damages. Common outputs include maps showing exposed or highly vulnerable assets, along with key metrics such as expected annual damage (EAD) or percentage of damaged assets. The EAD represents the monetary value of losses, averaged over a year, taking into account the probability of different hazard events and the severity of the damage they would cause.

However, vulnerability functions and reconstruction cost estimates—used to convert physical damage into monetary EAD—remain major sources of uncertainty, particularly in global or data-scarce contexts. Engineering standards, material prices, and labor costs vary widely across countries, meaning that global default values often diverge from local realities. Recent advances can help narrow this gap: ongoing World Bank work is modeling road replacement costs using a regression framework that draws on a database of roughly 5,000 construction projects from the past 15 years, accounting for factors such as project scale and complexity, terrain, rainfall, built-up density, income levels, and regional effects (World Bank forthcoming). Where local data collection remains infeasible, sensitivity analysis continues to play an important role in illustrating how cost assumptions affect results and in strengthening the robustness of decision-making.

In addition, on-site inspections may complement analytical tools for verifying infrastructure conditions and identifying maintenance deficiencies for critical components such as bridges, drainage systems, retaining walls, or culverts. The frequency and severity of exposure inform an understanding of risk accumulation over time. Engaging with local stakeholders (e.g., road authorities, community members, and experts) is also crucial. Firsthand knowledge and experience contribute to a more nuanced understanding of the vulnerabilities. For instance, local communities might provide historical accounts of flooding patterns and impacts that are not captured in existing data.

A.4 Conduct a System-Level Criticality Analysis

Criticality of a network can be assessed by simulating disruptions to the network and measuring the resulting loss of functionality. This criticality assessment is usually performed to support decision-making beyond direct asset-level damages (e.g., EAD) and estimate indirect impacts across the network, such as travel delays, detour lengths, accessibility losses, and broader economic disruption. This network-level assessment typically relies on factors such as annual average daily traffic (AADT); freight intensity; detour length in case of network failure; and proximity to productive zones, ports, and essential services. These metrics can be combined into a criticality score for each segment and used to calculate importance-weighted EADs, highlighting corridors where outages would impose disproportionate system-level costs and helping identify priority targets for resilience investment. This process is often referred to as criticality analysis. A key input is traffic, for example, AADT, which

can be obtained from road agencies where traffic counts are available, or estimated using gravity models that infer travel demand from population, economic activity, connectivity patterns, and the locations of essential services.

A.5 Identify Resilience Measures

Once vulnerable assets and high-risk segments are identified, resilience and adaptation strategies are developed to mitigate exposure and reduce sensitivity. Interventions are classified into soft measures (e.g., improved maintenance protocols, early warning systems, or policy reforms) and hard measures, including road raising, pavement strengthening, slope stabilization, embankment reinforcement, and drainage upgrades. Nature-based solutions, for example, restoring the composition and structural function of the vegetation in the buffers including slopes and embankments, are also considered where appropriate.

Measures are selected based on effectiveness, technical feasibility, and expected benefits. The objective is to make infrastructure less vulnerable while ensuring continuity of service under both current and future climate conditions. Resilience strategies are designed to be scalable, cost efficient, and compatible with broader sustainability objectives. Options should also reflect local engineering standards and maintenance capacity.

A.6 Prioritize Investments Through Economic and Multicriteria Analysis

The costs and benefits associated with each resilience measure are typically assessed using benefit-cost ratio or net present value (NPV) analysis. Key benefits, such as avoided EAD, social importance, and network criticality, are factored in. Prioritization can also be guided by a multicriteria framework that considers expected risk reduction; economic efficiency; feasibility of implementation; and co-benefits such as safety, inclusivity, and environmental outcomes. Together, these methods provide a transparent and evidence-based foundation for identifying high-value investments along critical corridors.

Conventional cost-benefit analyses in transport often underweight tail risks, which are associated with events that exceed design standards or occur if multiple hazards compound one another. The potential for catastrophic loss (e.g., bridge collapse leading to prolonged isolation of a region) may justify enhancing resilience at the expense of headline NPV. Practical ways to embed extremes include (1) testing options under multiple return periods and scenarios, (2) reporting not only expected values (EAD, NPV) but also distributional metrics (e.g., value at risk, or expected NPV if an extreme event occurs), or (3) applying decision rules that cap unacceptable outcomes. Where catastrophic failure is plausible, resilience measures that reduce tail risk, such as elevating critical links, redundancy, and accelerated recovery protocols, can be prioritized even if they slightly lower the expected NPV.

The economic analysis described in this report focuses on transport infrastructure and network-level impacts, including direct damages to assets and indirect losses arising from traffic disruption, detours, and loss of connectivity. It does not extend to the modeling of behavioral responses of firms and households across an economy (responses that include inventory strategies, supply chain diversification, or modal substitution). As highlighted in the Lifelines framework, these broader responses can significantly influence total welfare losses and the perceived criticality of infrastructure assets.

A small number of World Bank transport studies—for example, those for Argentina (Kesete et al. 2021) and Malawi (Narain et al. 2022), firm-level survey work in Tanzania (Kim et al. 2021), and a recent analysis of impacts on social well-being (Middelani et al. 2025)—extend beyond transport networks to assess wider economic and social consequences of disruptions. These studies show that the criticality of transport assets varies across supply chains and user groups, reflecting differences in the geographical location of economic activity, as well as the differences in product type, perishability, and storage options.

However, such economywide assessments have significant data and resource requirements. They need detailed information on freight flows, supply chain linkages, behavioral responses, and recovery dynamics. As a result, they are difficult to replicate at scale and are not yet readily supported by emerging, cost-efficient tools such as the Global Resilience Index (GRI) or Hazard & Risk Multiregional Assessment tool (HARMA). For this reason, most resilience assessments continue to focus on transport infrastructure and network-level impacts while recognizing that wider economic effects remain an important area for future methodological development.

The next step involves ranking investment options and developing a prioritized pipeline that aligns with sector budgets. This pipeline can be structured across short-, medium-, and long-term horizons and should include cost estimates, implementation sequencing, and institutional responsibilities. Integrating the pipeline into GIS-based asset management systems, capital planning processes, and sector budgeting frameworks helps embed resilience considerations into routine operations. To ensure long-term sustainability, capacity building for road agencies, particularly in the use of GIS tools and climate data, and vulnerability modeling, is highly recommended.

Box A1.1 A Summary of Model Details and Real-World Examples of Five Analytical Steps.

Exposure analysis. Three broad approaches were identified. The first approach involved advanced hydrodynamic modeling tailored to the study area (e.g., Argentina [Kesete et al. 2021], Albania [Xiong and Espinet Alegre 2019], Vietnam [Oh et al. 2019]). Tools such as Delft3D or fine-resolution inundation models comparable to Fathom were often used, and availability of data and budgets made detailed analysis possible. The second approach relied on existing hazard maps and data sets to characterize hazard magnitude and likelihood (e.g., Cambodia [World Bank 2020], Haiti [World Bank 2022a], Philippines [Costa et al. 2019]). The use of existing hazard maps and data sets enabled credible exposure estimates without the need for bespoke modeling. The third approach applied simple binary exposure mapping. Assets were flagged as “in” or “out” of floodplains or landslide-prone zones in cases where hazard intensity information was not available.

Vulnerability assessment. Approaches varied across countries: a few assessments applied empirical fragility curves to translate hazard intensity into damage states and costs (e.g., Haiti [World Bank 2022a]), while many relied on expert-judgment vulnerability tables or functions that map intensity bands to damage categories (e.g., Philippines [Costa et al. 2019], Viet Nam [Oh, et al. 2019], Albania [Xiong and Espinet Alegre 2019]). In more data-constrained contexts, vulnerability was sometimes treated in a binary manner, assuming that exposed road segments would experience disruption or damage (e.g., Cambodia [World Bank 2020], Cameroon [World Bank 2023a]). Regional network studies estimated expected annual losses or expected annual damages by combining repair costs with user delay costs. Restoration times were informed by expert judgment and evidence from recent events (e.g., Viet Nam [Oh et al. 2019], Brazil [Ogita and Pedroso 2019], Haiti [World Bank 2022a]). In some country applications, analysis primarily focused on direct costs of repair (e.g., Ecuador [World Bank 2023c], Malawi [Narain et al. 2022]).

Criticality analysis. While less commonly undertaken, where implemented, it included graph-based redundancy and connectivity analytics to prioritize links based on their role in maintaining network function (e.g., Viet Nam [Oh et al. 2019], Philippines [(Costa et al. 2019], Haiti [World Bank 2022a], Yemen [World Bank 2024b]), as well as multicriteria approaches that combined traffic volumes, hub connectivity, tourism importance, and access to critical facilities (e.g., Albania [Xiong and Espinet Alegre 2019]). Corridor-focused studies quantified economic impacts from hazard-induced freight and trade disruptions, as well as from network delays, using network analysis where traffic and freight data were available (e.g., Argentina [Kesete, et al. 2021], Albania [Xiong and Espinet Alegre 2019]). The Lifelines report (Hallegatte, Rentschler and Rozenberg 2019) highlighted the benefits of increasing redundancy in a network as a way to prevent loss of functionality when assets are disrupted.

Adaptation measures. Approaches ranged from structured appraisals of the effectiveness of specific measures in reducing EAD or shortening restoration times—drawing on expert judgment and local engineering practice (e.g., Albania [Xiong and Espinet Alegre 2019], Philippines [Costa et al. 2019], Haiti [World Bank 2022a])—to simplified scenario-based assumptions in which adaptation packages deliver percentage reductions in losses (e.g., Colombia [World Bank 2023b]).

Economic analysis. The methods generally aligned with the level of detail of adaptation design and were as follows: probabilistic cost-benefit analysis using hazard occurrence simulations and climate scenario adjustments to estimate net present value and benefit-cost ratios (e.g., Haiti [World Bank 2022a], Albania [Xiong and Espinet Alegre 2019]); deterministic analyses applying average values and climate scenarios (e.g., Brazil [Ogita and Pedroso 2019], Philippines [Costa et al. 2019]); and streamlined deterministic appraisals based on fixed assumptions on avoided losses (e.g., Colombia [(World Bank 2023b)]).

Appendix B.

A Comparison of GRI and HARMA

B.1 Global Resilience Index (GRI)

The GRI tool provides a standardized framework for assessing climate risk and vulnerability in the transport sector. The focus is on road infrastructure. The tool enables rapid and cost-effective vulnerability analyses using open-access data and scalable workflows. The GRI is open access and has a web browser version, called the GRI Risk Viewer, for fast and easy assessments.

An analysis using the GRI tool is typically done in three steps:

1. Intersect the flood and infrastructure layers and calculating flood depth for each infrastructure asset for every epoch (historical, 2030, 2050, 2080), climate scenario (RCP 4.5, RCP 8.5), and return period (from an event that occurs on an annual basis, to an event that occurs once in 1,000 years).
2. Use suitable vulnerability curves for each asset type to calculate expected (percentage) damage as a function of flood depth. By asset, this step is repeated for every epoch, climate scenario, and return period.
3. Use the estimated rehabilitation cost of different asset types to translate the expected damage of an asset into an estimate of the cost due to direct damage.

The GRI tool can be used for three levels of analysis: national-, subnational-, and asset-level. It allows exposure and vulnerability for specific road segments.

The GRI Risk Viewer provides direct access to flood hazard data sourced from the Aqueduct Global Floods Hazard Maps of the World Resources Institute (WRI), which cover coastal and riverine flooding.¹² The hazard maps are raster based, with spatial resolution of approximately 1 km (30" × 30"), and offer global coverage. Flood inundation depths are represented in meters for return periods ranging from 1 in 2 years to 1 in 1,000 years. Road and rail asset data provided by the GRI Risk Viewer are sourced from OSM. The corresponding data set was extracted in October 2021.

The GRI Risk Viewer compiles reconstruction costs from multiple sources published over the past decade. The reconstruction costs offer a foundation for high-level screening and for identifying variability across regions.

¹² These data sets are made available under the Creative Commons Attribution International 4.0 License supporting open data principles and broad accessibility. The WRI has published comprehensive reports and peer-reviewed articles detailing the methodology behind the Aqueduct flood maps. The case study for Nigeria provides an example of a more detailed evaluation of the Aqueduct flood map in a specific context.

Key model assumptions:

- **Pluvial (rainfall-runoff) flood hazard** is not included in Aqueduct hazard products. Where urban pluvial flooding is material, separate products (e.g., Fathom pluvial) are often used in complementary urban analyses.
- **Coastal hazard projection.** Future coastal flooding in Aqueduct integrates sea-level rise and land subsidence. Tropical cyclone intensity and wave setup are not explicitly modeled in this product.
- **Return-period maps** are pixelwise. They do not reflect spatial dependence. Two neighboring pixels may show inundation for a given return period even if joint exceedance is less likely.
- **Regional skill varies.** Quality of input meteorological and terrain data differs across regions. This influences calibration and performance. Users should, where possible, compare global layers with local studies or gauge data.

Practical guidance for using the GRI tool:

- The Aqueduct flood hazard maps used in the analysis are effective for broad, national-level screening, but may underestimate flood extent in certain areas, particularly wide, flat floodplains. Limitations in meteorological data, especially for periods before 1950 and in tropical regions, could affect the accuracy of results. While the model is sensitive to different climate scenarios and flood severities, findings should be interpreted with an understanding of these data constraints. Where the policy or investment question requires finer scales (e.g., structure-by-structure design), complement the broader-scale flood mapping results with local digital elevation models (e.g., Light Detection and Ranging [LiDAR]) and hydrodynamic studies or validated national flood maps.
- Note compound risk. Coastal and riverine layers are developed separately. Their joint occurrence is not represented. If compound flooding is relevant, flag it for future detailed analysis.
- The values in table B.1, which were used for reconstruction costs, are screening-level proxies compiled in the GRI Risk Viewer from multiple sources over the past decade. They are suitable for comparing relative risk and identifying hotspots but should be replaced with locally verified unit rates during feasibility/design (e.g., bill-of-quantities or agency unit-cost catalogs). Differences across sources and contexts (labor, materials, design standards) can be large, and costs are typically some of the main uncertainty drivers in vulnerability studies. Sensitivity analyses in World Bank studies show that vulnerability curves and unit costs often dominate the uncertainty of global risk estimates, and local engineering standards, materials, gross domestic product (GDP) per capita, typical embankment heights, and drainage/bridge details materially shift damage ratios and repair costs (World Bank 2024a).

Table B.1 Rehabilitation Costs Used in the GRI Risk Viewer

Asset Type	Rehabilitation Cost (\$/km/lane)
Bridge	40,805,816.00
Motorway	2,289,717.82
Trunk road	348,280.34
Primary road	348,280.34
Secondary road	164,059.77
Tertiary road	164,059.77
Residential road	164,059.77
Road (unclassified)	164,059.77
Paved road	164,059.77
Unpaved road	23,545.10

Source: Koks et al. 2019; World Bank 2008; US Federal Highways Agency 2020; ADB 2025.

Note: km = kilometer.

B.2 Hazard & Risk Multiregional Assessment (HARMA) Tool

HARMA is designed to offer a tailored decision-making experience to the user. The tool, serving different strategic risk management priorities, decision styles, and risk appetites, is envisioned to support two decision streams: the resilience planning stream and the business continuity stream.

Resilience planning is meant to assist in long-term planning. It results in decisions aiming to safeguard the transportation networks of South Asian countries against any plausible future natural disaster. Such decisions are best served through a probabilistic risk assessment framework that estimates the expected losses on the network, as generated by all events that could possibly occur during the period of the assessment, each with its probability of occurrence. The expected loss is hence the aggregation of losses from multiple events—frequent and infrequent—that may impact different parts of the network.

Business continuity, on the other hand, supports short-term planning. It results in decisions that aim to reduce disruption and losses from frequently occurring climate events. Contrary to the resilience planning stream, the decisions analyzed in the business continuity stream may include soft-engineering strategies or small-scale interventions targeted toward network components/sections that are the most likely to experience recurring damages in low-impact events. The financial outlay for implementing those strategies is often significantly lower compared with that required for building protection against extreme events. As such, they are considered low-risk investment options that are ideal for resource-constrained environments (especially when losses due to frequently occurring events constitute a significant proportion of the total possible loss).

Utilizing the tool, it will be possible to identify the vulnerability hotspots of the network (i.e., those that cumulatively induce higher losses across all possible hazard scenarios) and prioritize upgrade interventions. It will also help identify road segments that have the potential to introduce the highest disruption on the network and based on that (1) estimate emergency response funds for repairs and replacements, (2) analyze the network's post-disaster performance (i.e., changes in traffic flows), and (3) plan for redundancies in network sections attracting increased post-disaster flows. Ultimately, it will support decision-makers on how to invest in interventions that have the greatest potential to minimize the expected loss, while guaranteeing cost efficiency.

To achieve these goals, HARMA will perform:

1. **Network analysis**, to monitor traffic loads and their redistribution in case of disastrous events (i.e., indirect costs) and assess the criticality of different network segments;
2. **Hazard mapping**, to visualize the extent and intensity of natural hazards potentially affecting the network and the exposure of networks' infrastructure to them;
3. **Vulnerability analysis**, to identify sensitive assets/segments;
4. **Loss assessment**, to quantify potential damage, including costs for repair (direct damages), and the cost of reduced network operability, including societal and economic consequences; and
5. **Cost-benefit analysis**, to assess the efficiency of alternative adaptation options against likely disaster impact scenarios.

HARMA, which is a system-level decision-support tool for making transport systems more climate resilient, integrates origin-destination (OD)-matrix-based transport models with hazard data, infrastructure data, and socioeconomic indicators. HARMA captures both direct and indirect damages and performs cost-benefit assessments for adaptation options, making high-level contingency liability assessments, which are critical for financial planning, possible. The tool is especially valuable for governments seeking strategic decision support, informed investment planning, and a clearer understanding of funding gaps. HARMA can be applied to upstream diagnostics, including Country Climate and Development Reports, national adaptation plans, and transport sector resilience strategies. It provides a robust framework for prioritizing interventions to increase make limited resources more effective.

Appendix C.

Detailed Results for the Kyrgyz Republic Case Study

C.1 High-Level Results

The length of road exposed to landslide risk is projected to increase from 4,300 km during a 1-in-100-year event in 2020 and grow 10 percent (RCP 4.5) or 20 percent (RCP 7.0) by 2050, indicating increasing vulnerability.

Subnational Risk

While nearly all of the Kyrgyz Republic is vulnerable to landslides, there are notable points of concentration. In particular, there is a very high concentration of landslides around the M-106 highway in Batken. The highest overall landslide exposure is along the important 3M-04 highway (which is also second in flood exposure), followed by the M-106 and other highways.

Criticality Analysis

The gravity model was used to assign traffic flow to the road network. Only about 3 percent of road highway stock, which is concentrated in the 3M-04 and 3M-12, sees 50 percent of network flow. The highest criticality was observed on the important 3M-04 highway, peaking near Osh, at around 15 percent (meaning a blockage there would delay total network travel time by 15 percent), but also high around Bishkek. Aside from the 3M-04, the 3M-12, which is an alternative north-south route, peaks near 8 percent, and the 3M-16 reaches 7 percent.

Implications for Policy and Practice

With respect to landslides, there is significantly more exposure of critical and high-flow roads. Around 165 km of critical roads are exposed to landslide risk (this rises through 2050 as well but only marginally). These roads tend to be in the center of the country.

C.2 National Risk Overview

The effects of changing climate conditions can be understood through increases in damages according to the return period.

Landslide exposure (rather than damages due to landslides) is studied because there is no reliable fragility curve that maps the exposure metric from NatCap Insights to landslide-induced damages.

The metric for vulnerability to landslides will necessarily be higher than the metric for vulnerability to floods, as more roads are generally risk exposed than expected to have damages.

Broadly, we estimate that around 4,000 km of lanes are vulnerable in a 10-year (return frequency = 0.1) landslide plain, 4,300 km of lanes are vulnerable in a 100-year landslide, and 4,500 km of lanes are vulnerable in a 100-year landslide plain. Given land cover growth through 2050 and a milder climate pathway (RCP 4.5) under business as usual, these numbers are projected to grow roughly 10 percent—but on the more severe climate pathway (RCP 7.0), they are expected to grow 20 percent. The growth scenario with reformed land-use policies has only a very small effect in reducing these estimates.

C.3 Criticality Analysis

Here, we used a doubly constrained gravity model of population flow to assign traffic flows to the same roads considered above (see methodology section). According to this model, traffic flow will be higher along faster routes between populous areas. The doubly constrained element ensures that flows are reflective of population, and it will result in higher flows on routes that offer few ways of traversing from origin to destination. There is an exponential time delay function, which means flow will be higher when a route is shorter in terms of time (using OSM-derived speeds and road lengths). This model will tend to reflect internal traffic and may somewhat undercount border traffic. To better model this border traffic, we also use population near (within 10 km) border areas, to reflect this aspect of traffic flow. The resultant flow is proportional to the number of people that would be expected to travel along any particular path.

According to this doubly constrained gravity model of population flow, the route with the most traffic in the country is by far the 3M-04, which connects Bishkek to Osh and the southwest of the country. This is corroborated by official traffic counts, which also show that this road sees the most traffic in terms of total flow. It is followed by the 3M-12 (Jalal-Abad to Kazarman), the 3M-18 (Kochkor to Töö Ashuu Pass), the 3M-11 (Bishkek to Torugart), and the 3M-18 (Osh to Isfana).

Regarding the corroboration of modeled flow with traffic counts, we compare maximum modeled flow per highway to traffic counts on an undesignated portion of the same highway. For comparison, we also compare total network flow to the same traffic counts. Visually, we find a much stronger correlation with maximum flow, which seems appropriate since the comparison is to single-point traffic counts on the highways rather than total flow. However, the small amount of data points limits our ability to validate the model comprehensively.

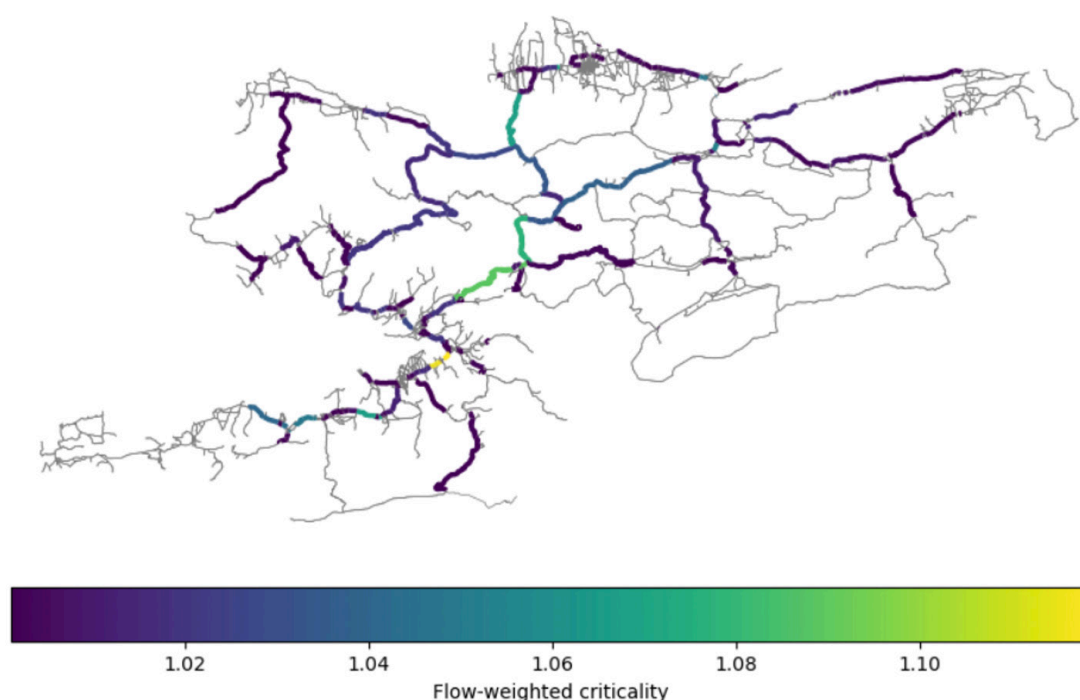
We find that traffic flow is concentrated in key areas of the network, especially in the 3M-04 highway. In particular, if road segments are sorted by flow and the portion of flow is compared to the proportion of road stock, then we find that only about 3 percent of road highway stock, which is concentrated in the 3M-04 and 3M-12 highways, has 50 percent of flow in the entire network.

Next we move on to analysis of road criticality. In brief, criticality measures the importance of a road to a network. That is, the criticality of a road link represents the percentage increase in total time added for the whole network due to a road blockage of two hours (selected arbitrarily) on this link. Criticality can be computed with the original formula, which does not account for road traffic flow, or weighted by traffic flow. For this analysis here, we focus on criticality weighted by traffic flow. While

high-flow links are more likely to be critical, this is not always the case (there is a moderate correlation here, that is, a Pearson's coefficient of 0.49).

As with traffic flow, the highest criticality is observed on the important 3M-04 highway, peaking near Osh, at around 15 percent (meaning a blockage here would increase the total travel time for the entire network by 15 percent). Criticality along the 3M-04 highway also reaches high values near Bishkek and at various intermediate points. Aside from the 3M-04, the 3M-12, which is an alternative north-south route, peaks near 8 percent and reaches 7 percent on the 3M-16 in criticality. Outside of these highways, only a few other points have significant criticalities (>1 percent delay). Criticality is visualized in figure C.1.

Figure C.1 Flow-Weighted Criticality in the Kyrgyz Republic



Source: World Bank, 2025 analysis

With respect to landslides, critical and high-flow roads are significantly more exposed. Because 20-year data are not available for landslides, we focus on the 10-year return period. Regarding flow, we find that a large swath of the important (top 10 percentile flow) roads have landslide vulnerability over a length of at least 1 km. Regarding criticality, we define critical roads to be those whose disruption increases the total travel time for the network by at least 1 percent. These roads become highly critical if the total travel time increases 2 percent or more. Roughly 377 km of critical roads are exposed to 10-year landslide risk in the baseline (year 2020). This figure grows only marginally through to 2050. The distribution of highly critical (>2 percent) roads with landslide risk is lower but still significant. In the baseline, around 165 km of critical roads are exposed to landslide risk (this rises through 2050 also but only marginally). These roads tend to be in the center of the country.

Appendix D.

Detailed Results for the Nigeria Case Study

D.1 High-Level Overview

The assessment applied the GRI model. Road network data were sourced from OSM and flood hazard maps from the WRI's Aqueduct platform. The analysis considered fluvial (riverine) and coastal flooding under multiple climate scenarios and time horizons. Preprepared data have been made available to facilitate the replication of this analysis. They are freely accessed at <https://global.infrastructureresilience.org/downloads/regions/nga>.

National-Level Risk

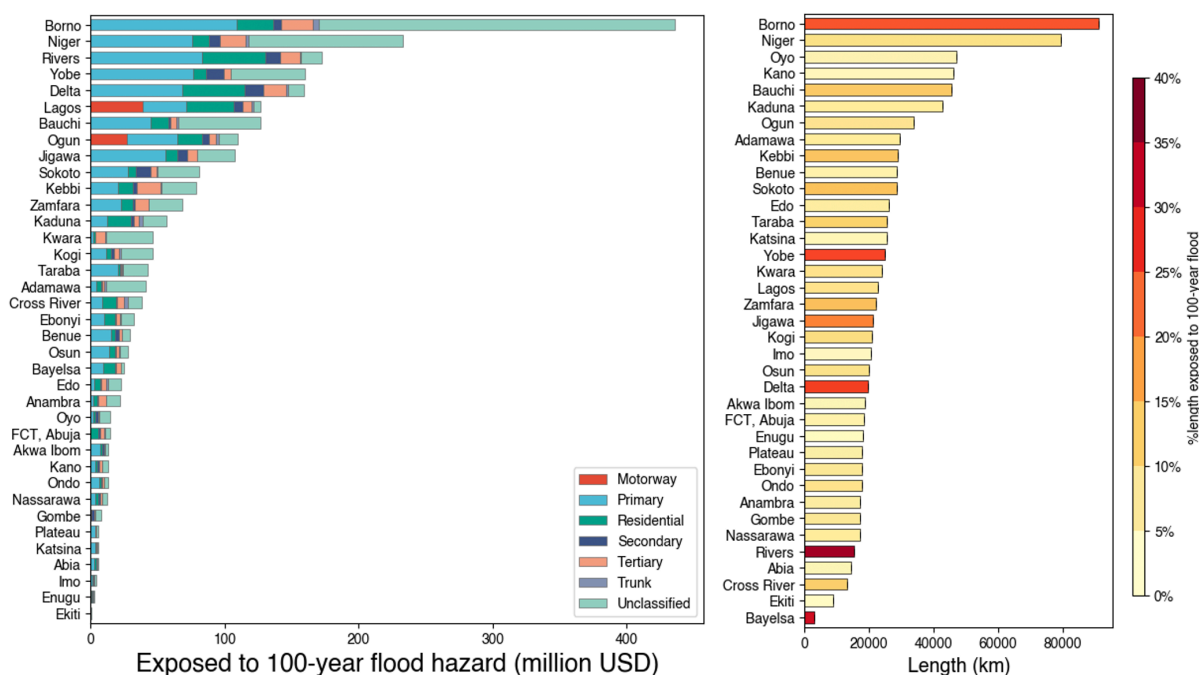
Nigeria's road network has high flood exposure. Estimated repair costs due to riverine (fluvial) floods are between \$500 million and \$4 billion depending on future climate scenarios. Given Nigeria's GDP in 2025 was approximately \$194 billion (IMF 2021), these losses represent about 0.26-2.05 percent of its GDP. In contrast, coastal flooding poses a much smaller financial risk. Costs range from \$2.5 million to \$25 million.

Risk by Road Type

Primary roads, while fewer in number, constitute a large share of potential flood-related costs due to the high expenses for their rehabilitation. Unclassified unpaved roads, which are widespread, also represent a significant economic burden. These findings point to the importance of focusing resilience investments on both primary and unpaved road segments.

Subnational Risk Patterns

Flood risk is not evenly distributed across Nigeria. States such as Borno, Rivers, and Niger have the highest exposure to riverine flood damage, while Lagos and Ogun also show substantial risk, especially for motorway repairs. This can be seen in figure D.1. In the Niger Delta, including rivers, delta, and Bayelsa states, coastal flooding is a major concern, with large portions of the road network at risk and potential for significant disruption to daily life. The analysis also highlights that riverine and coastal hazards can overlap, especially in the Niger Delta, compounding the region's vulnerability.

Figure D.1 Proportion of Roads Exposed to a 100-Year Flood in 2050 in Nigeria

Source: Oxford Infrastructure Analytics.

Note: Exposure to 100-year flood hazard under a 2050 RCP4.5 scenario. Left: Total repair cost for road assets exposed to 100-year flooding across Nigerian states. Bar length represents the total repair cost per state (million \$) and colors indicate the contribution of road categories to this cost. Right: Percentage of road length exposed to a 100-year flood hazard for each state. Bar length indicates the overall road network length per state and shading indicates the percentage of road network length that is exposed. FCT = Federal Capital Territory; km = kilometer.

Asset-Level Insights

The study identifies specific road segments with the highest EADs, such as residential unpaved roads in Lagos. This detailed information supports targeted, microlevel prioritization for resilience investments.

Implications for Policy and Practice

Overall, the results highlight an urgent need for climate-resilient road infrastructure planning in Nigeria. Prioritizing investments in primary and unpaved roads, especially in the most vulnerable states and segments, can help reduce economic losses and strengthen societal resilience. In regions like the Niger Delta, where multiple hazards converge, integrated management strategies will be essential to address the complex risks faced by communities and infrastructure.

D.2 National Risk Overview

The analysis is conducted at the national scale first—the national-scale analysis integrates asset-level results for the whole country. Such analysis can provide a useful overarching summary of risks, which can encourage action from a variety of stakeholders, including national officials.

Total repair costs for coastal flooding vary between \$2.5 and \$25 million, which is approximately 0.001–0.01 percent of Nigeria's GDP in 2025.

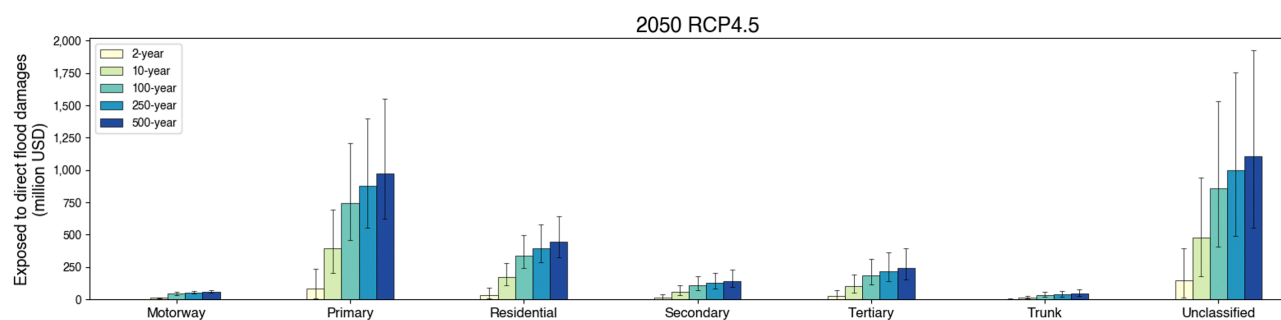
The overall trend for coastal flooding and riverine flooding is similar—increasing total repair costs by return period, climate scenario, and epoch. However, we see that the magnitude of differences is more pronounced during the 2080 epoch for coastal flooding. Coastal floods do however have a much lower overall repair cost relative to riverine flooding. For example, total repair costs for historic 1 in 1,000-year riverine flooding are approximately \$2800 million, versus \$5 million for historic coastal flooding for the same return period event. The coastal region constitutes only a small portion of Nigeria’s total area and contains fewer roads, resulting in lower flood exposure estimates. The western coastlines of Delta, Bayelsa, and Rivers experience most of the coastal flooding; however, their road networks are predominantly located inland to the east.¹³ Although Lagos is a densely developed coastal area, its exposure stems primarily from riverine rather than coastal sources, although coastal flood risks to the city are expected to increase in the future.

D.3 Risk by Road Type

To examine how different classes of roads contribute to these cost estimates, this section visualizes how the repair costs for exposed assets are distributed across road categories under a 2050 RCP 4.5 scenario (which represents a near-future, middle-of-the-road climate scenario). Figure D.2 compares the repair costs for exposed assets across different road classifications. Unclassified, primary, and unpaved roads account for the highest proportion of repair costs. The OSM “unclassified” tag is used for minor public roads, typically at the lowest level of the administration hierarchy. These roads are mostly unpaved roads. Error bars on all graphs represent the maximum and minimum values across the GCM ensemble, and bar heights show the mean value across the ensembles.

Despite their smaller number, primary roads in Nigeria contribute more significantly to overall flood exposure levels than the far more numerous residential roads. This disproportionate impact is primarily due to the higher costs associated with rehabilitating primary roads after they are damaged. However, when considering total costs due to flood damage across Nigeria, unclassified unpaved roads represent the largest economic burden, simply because they constitute most of the country’s road infrastructure.

Figure D.2 Repair Costs in Nigeria, by Road Type



Source: Oxford Infrastructure Analytics.

Note: Upper panel: Total repair cost for all assets exposed to fluvial flood hazard under a 2050 RCP 4.5 scenario, across different road type classifications. Error bars represent the maximum and minimum values across the GCM ensemble, and bar heights show the mean value across the ensembles. Color intensity indicates the count of road segments in each category. RCP = Representative Concentration Pathway.

¹³ This can be verified on the fly using the GRI Risk Viewer.

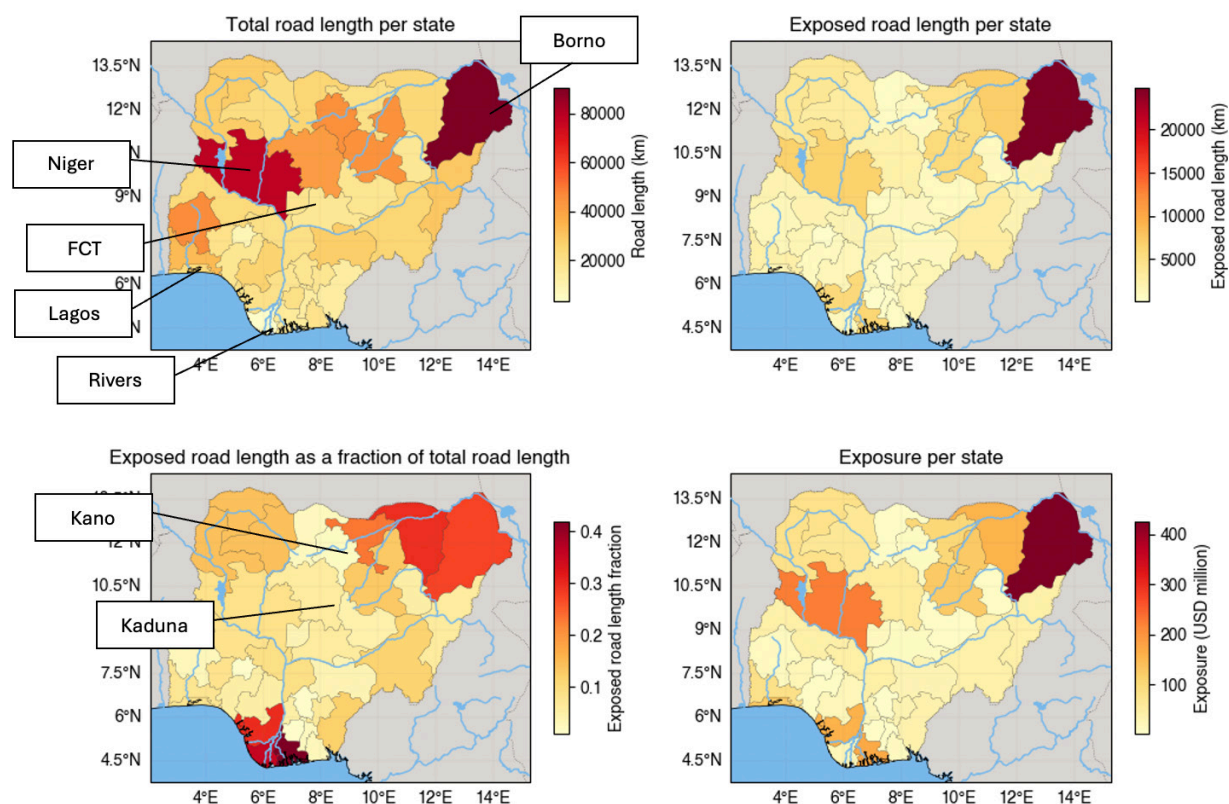
D.4 Subnational Risk Overview

This section examines risk at a subnational level and compares the risk of direct road exposure between different states (Level 1 administrative area—which includes 36 states total). Such analysis can provide a useful summary of the spatial distribution of risks, which may provide a useful rationale for budget allocation.

Figure A4.3 plots the repair costs for assets exposed to a 100-year flood under a 2050 RCP 4.5 scenario, by state and asset type. The plot shows that road network exposure to flood damage is the highest in the states of Borno, Rivers, and Niger. Most of this cost stems from potential damage to unclassified and primary roads, although for Lagos and Ogun, expected motorway repair costs are also significant—reaching almost \$50 million for Lagos.

It is also useful to view subnational results with choropleth maps, overlaid with relevant geographical features, such as permanent water and rivers. For a 100-year flood under a 2050 RCP 4.5 scenario, figure D.3 maps the following metrics: (1) total road length per state, (2) total exposed road length per state, (3) fraction of road length exposed per state, and (4) total repair cost for exposed assets per state. By all metrics, Borno in the northeast region stands out as highly exposed. Rivers, which lies in the Niger Delta region, also stands out in having a high percentage of its relatively small road network exposed.

Figure D.3 Exposure of Nigerian Roads to Riverine Flooding, by State

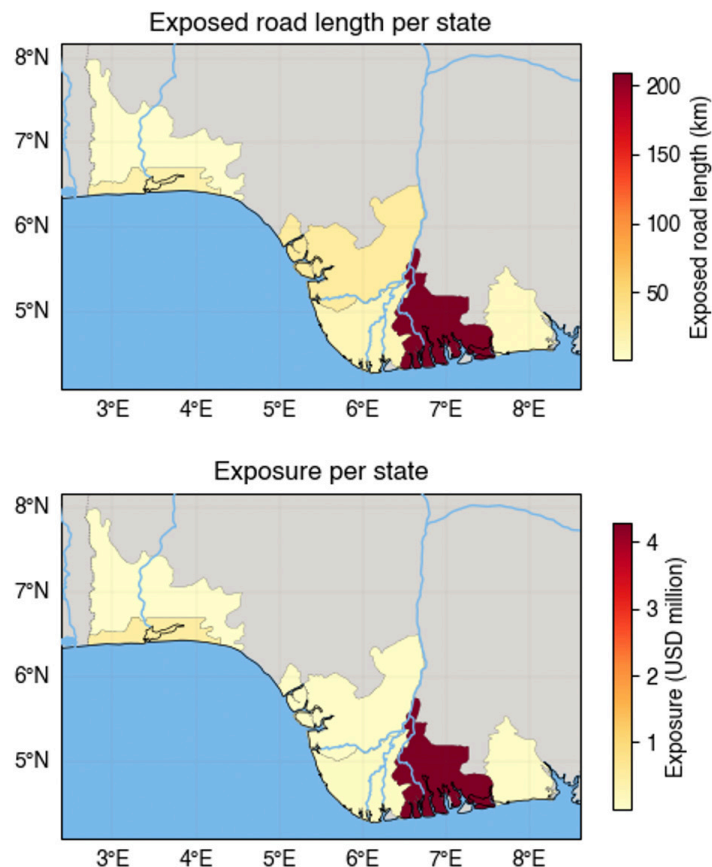


Source: Oxford Infrastructure Analytics.

Note: Top right: Exposure per state in Nigeria in terms of total road length (km) exposed to fluvial flooding from a 100-year flood hazard under a 2050 RCP 4.5 scenario. Bottom left: Percentage of total length exposed to fluvial flooding from a 100-year flood hazard under a 2050 RCP 4.5 scenario, in terms of total value (\$) exposed. FCT = Federal Capital Territory; km = kilometer.

Figure D.4 maps the same set of metrics for coastal flooding. It shows that the Niger Delta states are also highly exposed to coastal flooding. This is indicative of potentially compounding flood hazards. Fluvial and coastal hazards often co-occur during storms when strong onshore winds push waves and storm surges and drive moist air onto land, causing precipitation, leading to far worse flooding than if fluvial and coastal flooding were to occur separately.

Figure D.4 Exposure of Nigerian Roads to Coastal Flooding, by State



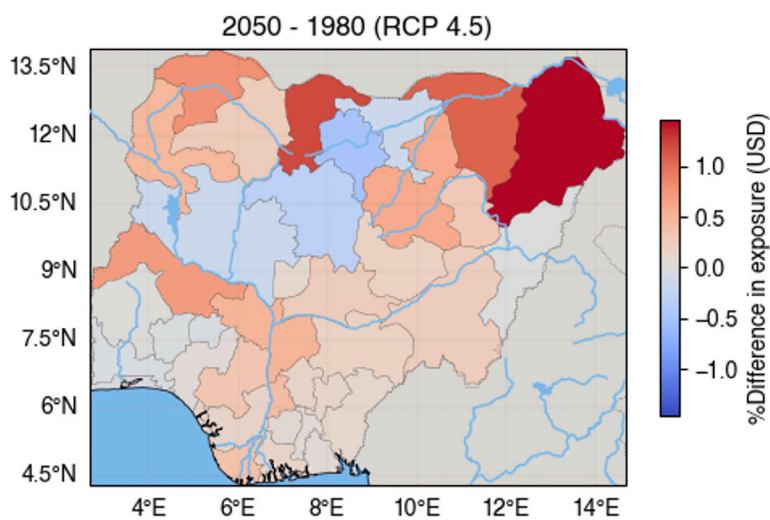
Source: Oxford Infrastructure Analytics. Exposure per-state in Nigeria in terms up total length (km) exposed (top), total value (\$) exposed (bottom) to coastal flooding from 100-year flood hazard under a 2080 RCP 4.5 scenario.

Note: km = kilometer.

Figure D.5 explores how repair costs for flood-exposed assets vary across states for a 100-year flood. The relative exposure difference between two scenarios is calculated as a percentage difference.

As would be expected, there is a general trend of increasing flood exposure levels further into the future and for more severe climate scenarios such as RCP 8.5. In RCP 4.5 visualized below, from 1980 to 2050, exposure particularly increases in the northeast of the country. There is, however, an apparent decrease in exposure for some of the central states such as Niger and Kaduna over this period.

Figure D.5 Differences in the Value of Exposed Assets in Nigeria, Based on the Climate Scenario



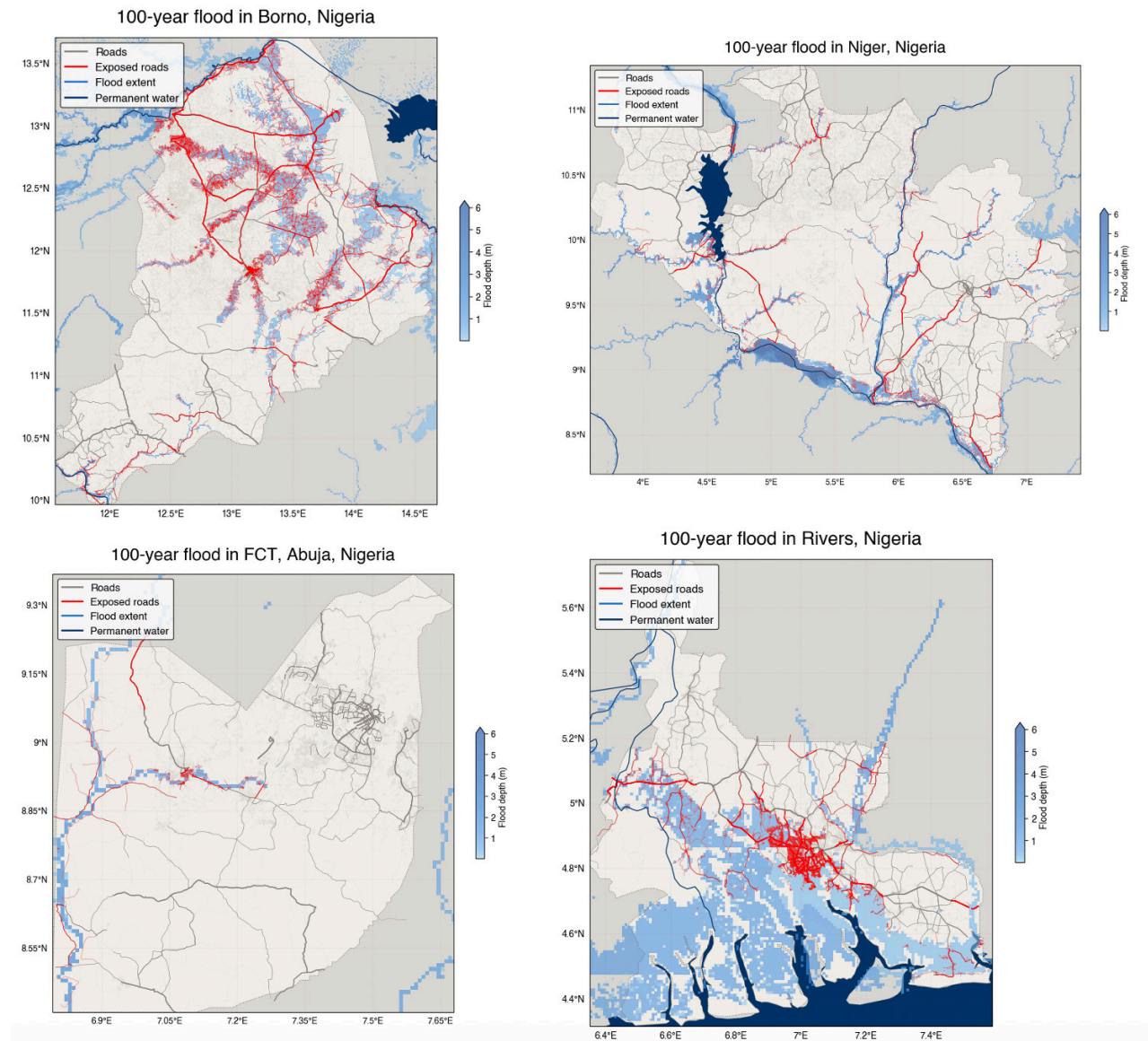
Source: Oxford Infrastructure Analytics.

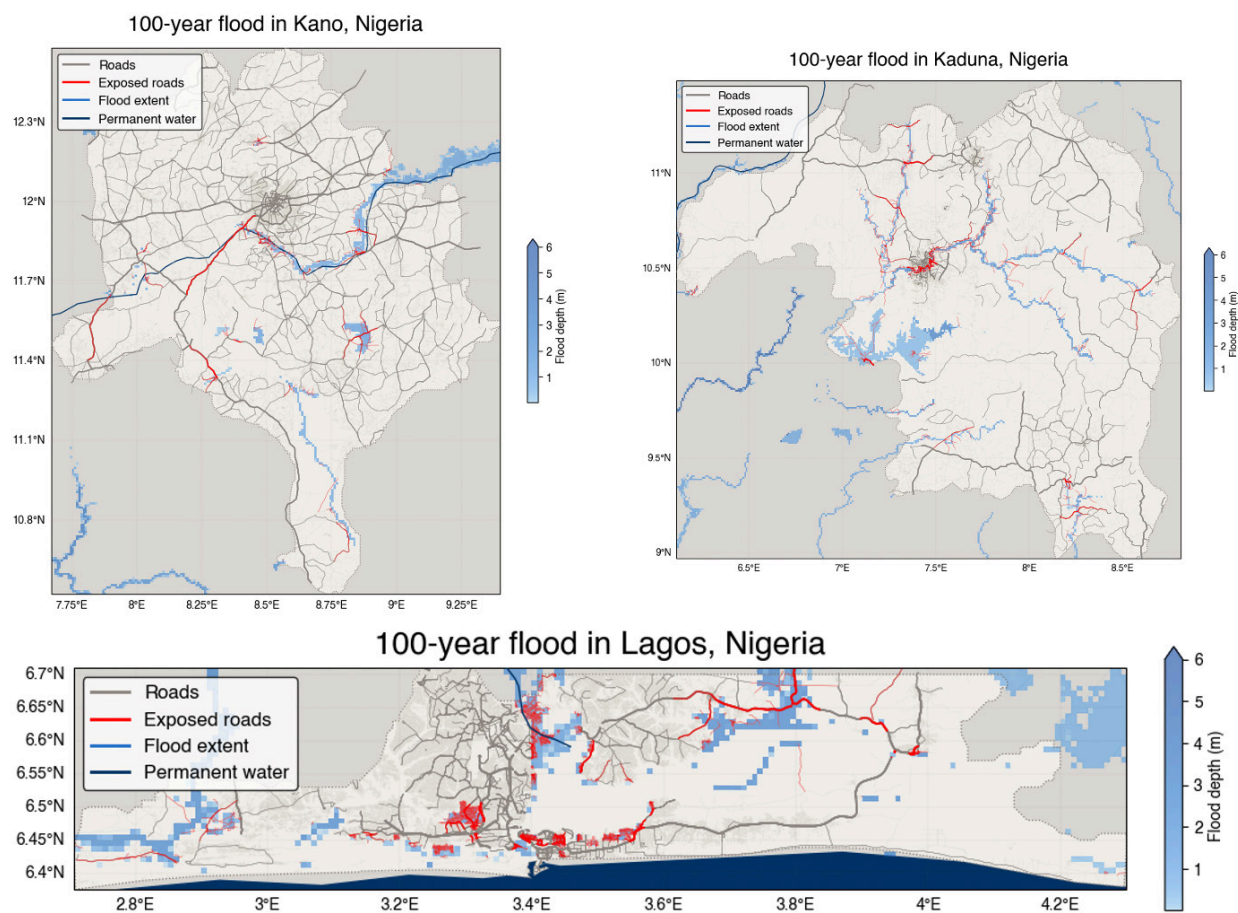
Note: Percentage differences in the value of exposed assets between climate scenarios for a 100-year fluvial flood hazard. States where the relative difference increases between scenarios are shown in red and states where relative difference decreases are shown in blue. RCP = Representative Concentration Pathway.

D.5 Exposure Distribution Within States

For a clearer picture of what is happening at the level of individual states, the maps in figure D.6 overlay the 100-year fluvial flood hazard with the road network for the states of Borno, Niger, Lagos, Rivers, the Federal Capital Territory (FCT), Kano, and Kaduna under a 2050 RCP 4.5 scenario. Borno and Niger are the two most exposed states in terms of repair costs, Lagos has many exposed motorways, and Rivers is disproportionately exposed for a relatively small road network.

Figure D.6 Flood Exposure of Nigerian Roads, by State





Source: Oxford Infrastructure Analytics.

Note: 100-year fluvial flood hazard for the states of Borno, Niger, Federal Capital Territory (FCT), Rivers, Kano, Kaduna, and Lagos. FCT = Federal Capital Territory; m = meter.

D.6 Asset-Level Risk Overview

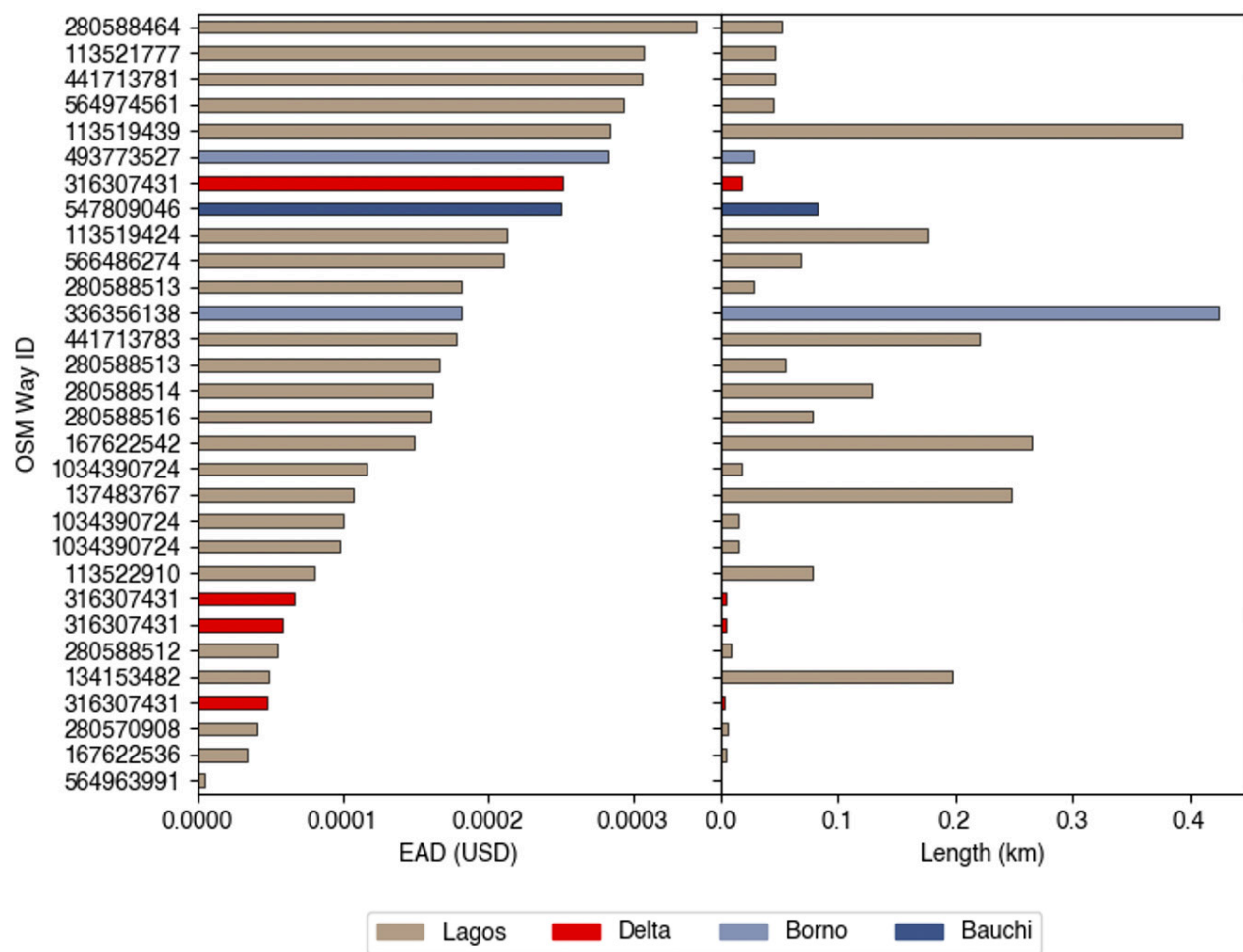
Asset-level analysis can provide a useful means by which to identify and prioritize action to make individual network assets more resilient. That could either be through investments in flood adaptation measures or through changes to operation and maintenance schemes relating to the assets. Such analysis can help address the following questions:

- Which roads within Nigeria have the highest EADs?
- What type of roads are they?
- What road lengths do they correspond to?

Figure D.7 displays EADs (in millions), length (in kilometers), and state for the 30 road segments with the highest EADs from riverine flooding, labeled by their OSM IDs. The most exposed state is Lagos. Though roads may be of similar length or type, their EADs can differ if their exposure is different. For example, a longer road segment slightly higher on a hill may only be exposed to more extreme events. This would make the EAD seem comparatively lower than a smaller segment located lower on a hill.

The OSM IDs can be used to look up each road using the OSM website. More information on the road segments with the highest EADs, for example, can be found at <https://www.openstreetmap.org/way/280588464>. This page lists road segments as residential, unpaved roads in Lagos that were last updated 10 months ago. Sometimes additional data, such as road names, are listed in these pages.

Figure D.7 Expected Annual Damages on Nigerian Roads Most Affected by River Floods



Source: Oxford Infrastructure Analytics.

Note: The figure shows the 30 roads with the highest expected annual damages (in \$ millions) from riverine flooding under a 2050 RCP 4.5 scenario. Colors denote road type (bars) and state (legend). EAD = expected annual damage; km = kilometer; OSM = OpenStreetMap.

