



## VULNERABILITY ASSESSMENT FRAMEWORK FOR CLIMATE RESILIENT ROADS NETWORK IN ETHEKWINI MUNICIPALITY, KWAZULU-NATAL

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### Abstract

Climate change–induced extreme weather events are increasingly impacting road infrastructure systems globally, resulting in heightened risks to infrastructure performance and safety. In response to these challenges, this paper aims to conceptualize a climate vulnerability assessment framework applicable to a provincial road network. In KwaZulu-Natal (KZN), South Africa, these risks are pronounced due to climate events which have repeatedly disrupted the provincial road network. The proposed framework is illustrated through a desktop study within the eThekweni Municipality and integrates climate stressor identification, climate trend analysis and an exposure–sensitivity matrix to evaluate infrastructure vulnerability and inform adaptation measures. Historical climate events and projected climate data were used to identify climate stressors affecting the route, facilitating the classification of vulnerability levels and prioritization of adaptation measures. Application of the framework to Stapleton Road, a flood-prone low-level river crossing, indicated high vulnerability to extreme rainfall and flooding, driven by spatial exposure, asset condition and drainage limitations. The assessment informed the selection of adaptation measures, ranging from structural interventions to long-term planning responses aligned with the severity of identified risks. The findings reaffirm the importance of climate-responsive road infrastructure planning and demonstrate the value of vulnerability assessments as practical decision-support tools for enhancing infrastructure resilience. The paper contributes a context-specific framework that supports evidence-based planning and provides a foundation for scaling climate risk integration across provincial road networks and design standards.

*Keywords: vulnerability assessment, climate stressors, exposure, adaptation measures, resilient infrastructure*

## 1 Introduction

Climate change has increased the frequency and intensity of extreme weather events, posing major challenges for the resilience of road infrastructure in KZN. As a vital part of the province's progress in resilient infrastructure, the road network must be systematically evaluated to ensure its ability to withstand climate-related risks. Traditional road design approaches that place minimal focus on climate data fail to reflect the evolving nature of climate change and consequently, leave infrastructure more vulnerable to environmental hazards.

### 1.1 Problem statement

With the increasing frequency of extreme weather events, civil engineering has shifted its focus toward climate change adaptation and mitigation.

KZN has experienced a rise in climate-induced events, including intense rainfall, frequent flooding and record-high temperatures, which have significantly impacted the provincial road network. These impacts include infrastructure damage, increased maintenance costs and disruptions to mobility. While current infrastructure strategies emphasize sustainability, the integration of disaster risk reduction and climate adaptation remains limited. Existing climate vulnerability assessment frameworks primarily address broad sustainability pillars and do not sufficiently consider the unique conditions of KZN's municipalities. The absence of a localized vulnerability assessment framework can hinder informed decision-making for the design, construction and maintenance of road infrastructure. Developing a tailored assessment framework will enable proactive planning and enhance the resilience of existing and future roads to climate change impacts.

## **1.2 National policy background**

South Africa (SA) has made notable progress in aligning infrastructure development with resilience goals, through the introduction of legal frameworks and engineering innovations. Prominent frameworks include the National Development Plan 2030, The Green Transport Strategy and the Climate Change Act [1-3]. These publications share a focus on reducing greenhouse gas emissions, economic growth, and improving infrastructure. In pavement engineering, recent advancements include recycling construction materials, optimizing haulage for efficient transport, and using carbon emission calculators. These tools enhance resource efficiency while supporting the objectives of the legal frameworks. Despite legislative progress, mechanisms for proactive climate risk management are often limited. Vulnerability assessments can identify assets and areas most exposed to hazards, enabling stakeholders to prioritize interventions, evaluate adaptive capacity, and develop infrastructure that is both sustainable and resilient to future climatic uncertainties.

## **1.3 National policy background**

Vulnerability assessments are used to identify and evaluate susceptibility of regions to the effects of climate change impacts and to identify methods of protection and preservation [4]. With respect to road infrastructure, these assessments identify assets most exposed to climate-related risks. In SA, vulnerability assessments support sustainable engineering by influencing climate-adaptive design and resource allocation. However, recent studies have largely focused on health, agriculture and biodiversity.

## **1.4 Aim and objectives**

This paper aims to explore the conceptual development of a climate vulnerability assessment in KZN. The paper shall review the theoretical basis and developmental process underpinning the framework and review an example of an applied vulnerability assessment. The scope of the paper covers the following key areas:

- identify climate stressors in a selected KZN district municipality, by utilizing climate data and climate trends
- formulate a vulnerability assessment framework using an exposure and sensitivity matrix
- application of the framework to the selected district municipality road
- recommend adaptation measures to inform decision making.



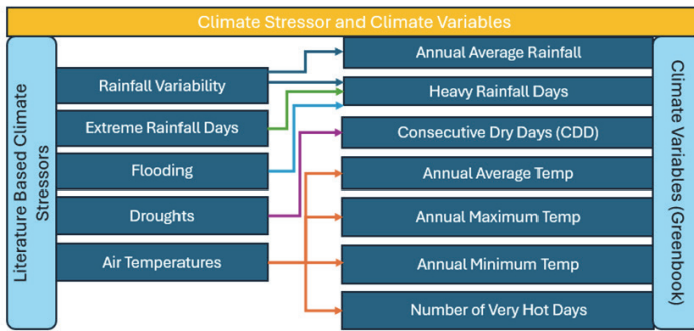


Figure 2 Climate stressors and variables

Figure 3 presents the extracted climate data in the form of a climate trend analysis. The following definitions should be noted:

- heavy rainfall day: a day experiencing total daily rainfall greater than 20 mm
- consecutive dry days: a period of minimum 5 days with less than 1mm of rainfall
- very hot days: days where temperatures exceed 35°C.

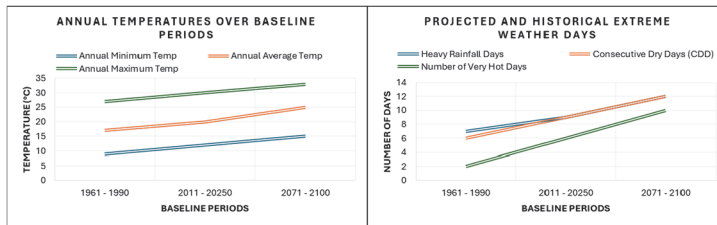


Figure 3 Climate trends for baseline periods

A general increase is noted from the analysis for all climate variables. Based on this finding, these variables will be included in the vulnerability assessment. Due to the location of the study area, coastal flooding can be included in applicable.

### 2.3 Climate stressors and the road network

To assess vulnerability to a climate stressor, the impacts a stressor can have on the road network must be understood. Table 1 presents the stressors identified in the preceding section with examples of associated impacts.

Table 1 Climate stressor impacts on the road network

Climate stressor	Impact on road network
Extreme rainfall days	Surface flooding and ponding; accelerated water infiltration and formation of distresses; slope failures and landslides; traffic disruptions and restricted access
Coastal flooding/sea level rise	Overtopping; erosion; damage of stormwater systems; accelerated pavement degradation due to inundation; disruption of transport and emergency accesses
Droughts/consecutive dry days	Subgrade shrinkage leading to layerwork weakening; increased pavement cracking from asphalt becoming dry and brittle
High temperatures (air and surface)	Reduced binder viscosity with vehicle loading leading to rutting and depressions; bleeding of the surface; expansion in higher temperatures and contraction when cooled can lead to cracking

Beyond impact identification, exposure and sensitivity to stressors must be assessed. Exposure refers to the presence of assets in areas affected by climate variables, while sensitivity describes the degree to which a system is affected [9]. An exposure–sensitivity matrix can then be used to identify at-risk assets and prioritize those requiring adaptation. Figure 4 presents the exposure and sensitivity matrix which can be applied to different climate stressors.

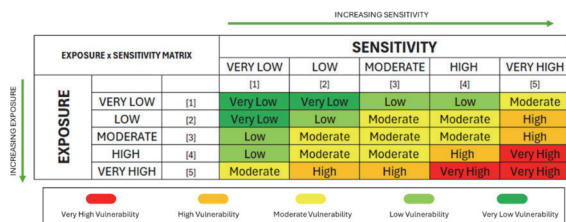


Figure 4 Exposure and sensitivity matrix

### 3 Conceptual vulnerability assessment framework

The conceptual vulnerability assessment framework provides a structured approach to evaluate asset exposure and sensitivity to climate stressors. This section applies the framework to a road in eThekweni, generating a vulnerability rating to guide adaptation and planning.

#### 3.1 Basis of the framework

The development of a vulnerability assessment can be grounded in methodologies from international and national work, with prominent publications listed below:

- National Climate Risk and Vulnerability (CRV) Assessment Framework [10]
- Climate Risk and Vulnerability: A Handbook for Southern Africa [11]
- North West Climate Risk and Vulnerability Report [12]
- FHWA Vulnerability Assessment and Adaptation Framework (VAAF) [4].

These assessments commonly evaluate vulnerabilities and propose adaptation strategies. Reviewing methodologies provides a foundation for developing a road infrastructure vulnerability assessment, integrating climate projections, qualitative and quantitative data, exposure and sensitivity analysis and performance-based prioritization to support resilient transport planning. The North West Climate Risk and Vulnerability Assessment offers a comprehensive baseline by detailing provincial infrastructure impacts, while the FHWA VAAF further informs adaptable methods focused on the structural and functional vulnerability of road infrastructure.

#### 3.2 Framework components

The framework is structured around a set of interrelated components that can collectively capture how climate hazards impact road infrastructure networks. Figure 5 presents a summary of the conceptual framework’s components.

<b>OBJECTIVES &amp; SCOPE</b>
<ul style="list-style-type: none"> <li>• Define study area.</li> <li>• Define scope of works (rehabilitation, resurfacing, periodic maintenance, upgrade)</li> </ul>
<b>DATA</b>
<ul style="list-style-type: none"> <li>• Collect &amp; compile climate data (municipal based).</li> <li>• Conduct climate trend analysis using data &amp; incident records.</li> <li>• Identify key climate stressors &amp; impacts.</li> <li>• Assess route condition using pavement history &amp; maintenance records.</li> <li>• Conduct visual assessment if required to understand existing condition.</li> </ul>
<b>EXPOSURE &amp; SENSITIVITY MATRIX</b>
<ul style="list-style-type: none"> <li>• Assess exposure &amp; sensitivity, populate ratings on matrix.</li> <li>• Achieve vulnerability rating for climate stressors.</li> </ul>
<b>ADAPTATION MEASURES</b>
<ul style="list-style-type: none"> <li>• Propose road infrastructure based adaptation options.</li> </ul>

Figure 5 Vulnerability assessment framework components

### 3.3 Applied example: vulnerability rating in EtheKwini

#### 3.3.1 Route description

Stapleton Road in the city of Durban was selected for application of the conceptual vulnerability assessment. It is classified as an urban flexible pavement that functions as a local distributor linking residential and industrial areas to nearby arterial roads and highways. The route was prioritized due to its low-level river crossing and history of recurrent flood overtopping and associated safety risks during extreme rainfall events. Figure 6 depicts the location of the section under consideration, showing proximity to a river nearby.



Figure 6 Route location

#### 3.3.2 Selection of climate stressors

Figure 7 depicts various flooding incidents along the route which had led to overtopping and structural collapse, between 2022 and 2025.



Figure 7 Structural collapse and overtopping along Stapleton road [13-15]

Despite repeated repairs, the bridge remains highly susceptible to flooding due to its location. The primary climate stressors driving vulnerability along this route are extreme rainfall and associated flooding, which will be included in the exposure and sensitivity matrix.

### 3.3.3 Exposure and sensitivity matrix

The route demonstrates high exposure to the selected climate stressors due to its location, infrastructure characteristics and traffic volumes. Its function as a low-level crossing, combined with proximity to embankments that have previously failed increases flood exposure. Inadequate stormwater drainage has resulted in frequent water ponding, confirming the route as a flooding hotspot and elevating user risk during flood events. The route can be classified as highly sensitive to climate stressors, with sensitivity linked to its current condition. Roads in warning or poor condition are more susceptible to accelerated deterioration under extreme rainfall and flooding. Existing structural weaknesses amplify climate impacts, leading to reduced usability during extreme events and increased vulnerability to embankment erosion and structural instability under high flow velocities and saturation. Based on the above, the exposure and sensitivity matrix for extreme rainfall and flooding can be populated, as shown in figure 8.

EXTREME RAINFALL DAYS			SENSITIVITY					FLOODING			SENSITIVITY				
			VERY LOW	LOW	MODERATE	HIGH	VERY HIGH				VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
			(1)	(2)	(3)	(4)	(5)				(1)	(2)	(3)	(4)	(5)
EXPOSURE	VERY LOW	(1)	Very Low	Very Low	Low	Low	Moderate	EXPOSURE	VERY LOW	(1)	Very Low	Very Low	Low	Low	Moderate
	LOW	(2)	Very Low	Low	Moderate	Moderate	High		LOW	(2)	Very Low	Low	Moderate	Moderate	High
	MODERATE	(3)	Low	Moderate	Moderate	Moderate	High		MODERATE	(3)	Low	Moderate	Moderate	Moderate	High
	HIGH	(4)	Low	Moderate	Moderate	High	Very High		HIGH	(4)	Low	Moderate	Moderate	High	Very High
	VERY HIGH	(5)	Moderate	High	High	Very High	Very High		VERY HIGH	(5)	Moderate	High	High	Very High	Very High
			Very High Vulnerability		High Vulnerability		Moderate Vulnerability		Low Vulnerability		Very Low Vulnerability				

Figure 8 Exposure and sensitivity matrix: extreme rainfall days and flooding

Based on the key climate stressors, the route is highly vulnerable to extreme rainfall and flooding, guiding the implementation of appropriate adaptation measures. For roads with limited condition data, visual assessments are recommended to evaluate existing distresses and inform sensitivity.

### 3.3.4 Adaptation measures based on assessment findings

Adaptation measures are guided by qualitative research, guidelines, and observed asset performance to address identified vulnerabilities. These can be applied to existing assets through maintenance or disaster management and to new assets during planning and design [4]. For low-vulnerability cases, more intensive interventions may not be necessary. Table 2 presents adaptation measures for the route, based on primary climate stressors, exposure, and sensitivity, categorized by type and intensity. Selection of measures depends on their feasibility within the municipal context.

**Table 2** Adaptation measures for the route, based on primary climate stressors, exposure, and sensitivity, categorized by type and intensity

Adaptation Category	Aspect/Asset	Adaptation Intensity	Adaptation Measure
Structural	Pavement layerworks	High	Stabilize layerworks to reduce swelling or erosion; open graded asphalts to avoid surface ponding; waterproofing layers to limit water penetration
	Earthworks and embankments	Moderate	Gabions or geotextiles to prevent erosion and stabilize embankments
Stormwater & Drainage	Surface and subsurface drainage	Moderate	Improve drainage systems and hydraulic capacity
	Maintenance	Low	Routine road inspections
Traffic management	Road safety	Low	Flood warning signage and road closure barriers during flooding
	Emergency response	Moderate	Make diversion routes known to road users and implement flood response procedures
Long term	Condition monitoring	Low	Conduct post-flood inspections to update asset management records
	Route planning and realignment	High	Replacement of low level crossings with raised bridges; realignment to higher road levels

## 4 Conclusion

This paper demonstrated the application of a vulnerability assessment, using a desk-top-based analysis of key climate stressors and historic climatic events, to evaluate road infrastructure vulnerability and inform adaptation measures. Identification of primary climate stressors provided a basis for selecting targeted, context-specific adaptations aligned with identified vulnerabilities. The findings reaffirm the need for climate-responsive road planning in KZN, where climate change-related events increasingly compromise road performance, serviceability, and longevity. The conceptual framework, demonstrated through the eThekweni Municipality case study, highlights the value of data-driven analysis in identifying climate risks, supporting informed decision-making and strengthening infrastructure resilience. Overall, the study underscores the importance of formalized vulnerability assessments as a practical tool for resilient infrastructure development. Future work should focus on broader provincial application and integration into planning and design practices.

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