Open Journal of Civil Engineering, 2025, 15(3), 453-477
https://www.scirp.org/journal/ojce
ISSN Online: 2164-3172
ISSN Print: 2164-3164

Integrating Grey and Green Engineering in Infrastructure Risk and Resilience Assessment: A Case of Kangundo Road

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How to cite this paper: Mbengei, C.M. Osano, S. and Othoo, C. (2025) Integrating Grey and Green Engineering in Infrastructure Risk and Resilience Assessment: A Case of Kangundo Road. *Open Journal of Civil Engineering*, **15**, 453-477.
https://doi.org/10.4236/ojce.2025.153025

Received: August 13, 2025
Accepted: August 31, 2025
Published: September 3, 2025

Abstract

This study assesses the climate change resilience of Kangundo Road, Nairobi, using an integrated modelling approach combining hydrological, geotechnical, and thermal analyses within the Fisher Climate Model framework. Historical climate data and future projections under SSP 4.5 and SSP 8.5 scenarios were used to evaluate the influence of precipitation variability, temperature change, and extreme events on road performance. Statistical results show rainfall variability (mean 77.761 mm, SD 201.410 mm) as the dominant hazard driver, with $\alpha_{\text{Sea level}}$, a rainfall proxy, weighted at 0.9967, compared to $\alpha_{\text{Temperature}}$ at 0.0027, reflecting low thermal variability (mean 18.70˚C, SD 0.627˚C). Sensitivity analysis revealed drainage deterioration (R) and hydrological flow (Q_{flow}) as the most critical resilience determinants, with their exclusion reducing resilience scores by over 80% and 55%, respectively. Interaction between R and thermal expansion (ΔL) produced non-linear risk escalation, indicating that multi-hazard impacts accelerate vulnerability beyond single-hazard effects. Grey engineering measures, including reinforced culverts, elevated embankments, and thermally resistant pavements, combined with green infrastructure such as bioswales, vegetative buffers, and permeable pavements, offer optimal resilience. The findings emphasize prioritizing drainage and stormwater capacity in adaptation planning, while incorporating thermally adaptive materials for long-term durability. Limitations include reliance on model-based projections and focus on a single corridor, warranting expansion to multi-route, socio-economic, and governance-integrated resilience assessments.

Keywords

Climate Resilience Infrastructure, Drainage Deterioration, Grey-Green

Infrastructure, Road Adaptation Planning

1. Introduction

Infrastructure systems are critical enablers of economic growth, social well-being, and national security [1] [2]. They provide essential services in transport, energy, water, and communications, forming the foundation upon which modern societies operate. In developing economies, road infrastructure plays an especially vital role in connecting communities, facilitating trade, and enabling access to markets, healthcare, and education. However, such systems are increasingly exposed to multiple and compounding risks, including climate-related hazards, environmental degradation, and anthropogenic pressures such as poor maintenance and unplanned urban expansion [3]. The growing vulnerability of infrastructure assets demands a systematic approach to risk characterization and resilience assessment to ensure their long-term functionality.

In recent decades, climate change has emerged as a dominant factor influencing infrastructure performance and reliability [4]. The Intergovernmental Panel on Climate Change (IPCC, 2022) reports that the intensity and frequency of extreme weather events such as floods, droughts, and heatwaves, have increased markedly since the mid-20th century [5]. For sub-Saharan Africa, projections indicate a 20% - 30% increase in extreme rainfall events by 2050, significantly raising the probability of flood damage to road networks [6]. According to the World Bank (2019), weather-related disruptions to infrastructure currently cost African economies between USD 4 billion and 6 billion annually [7]. These figures are expected to rise as climate variability intensifies, amplifying the vulnerability of critical assets such as Kangundo Road, a key transport corridor in Kenya.

Kangundo Road, which serves as an important link between Nairobi and the eastern regions of Kenya, is a prime example of infrastructure under increasing stress [8]. This roadway experiences high traffic volumes due to population growth, economic activity, and urban expansion along its corridor. However, it is also exposed to recurrent flooding during the rainy seasons, surface erosion, and occasional structural degradation due to poor drainage and unregulated land use in its catchment area. The Kenya National Highways Authority (KeNHA, 2021) has reported that approximately 12% of Kenya's paved roads experience moderate to severe damage annually from flood-related events, with repair and rehabilitation costs consuming a significant portion of the road maintenance budget [9]. This trend not only affects transport efficiency but also undermines economic productivity and public safety. The risk profile of Kangundo Road is further complicated by a combination of environmental and socio-economic pressures [10]. Encroachment on road reserves, inadequate stormwater management infrastructure, and poorly maintained culverts exacerbate damage during heavy rains. The Nairobi Metropolitan Area Transport Authority (NaMATA, 2022) has warned that without urgent intervention, critical roads such as Kangundo Road could face prolonged service interruptions, increasing congestion, transportation costs, and accident rates [9]-[11]. The cumulative effect of such disruptions is substantial; the African Development Bank (AfDB, 2020) estimates that transport bottlenecks in African urban areas can reduce GDP growth by up to 2% annually.

Traditional infrastructure design has primarily relied on "grey" engineering approaches, conventional hard infrastructure solutions such as concrete drainage systems, reinforced embankments, and asphalt surfacing [12]. While effective in most cases, grey infrastructure alone may be insufficient to cope with the dynamic and uncertain nature of contemporary risks, particularly those linked to climate variability [12] [13]. Increasingly, research and practice are shifting towards integrating "green" engineering, nature-based solutions such as vegetative buffers, bioswales, permeable pavements, and constructed wetlands, into infrastructure planning and adaptation strategies [14]. Green engineering solutions can complement grey measures by enhancing stormwater absorption, reducing heat stress, and promoting ecological co-benefits such as biodiversity conservation.

Globally, the economic rationale for incorporating resilience measures into infrastructure design is strong [15]. The Global Commission on Adaptation (2019) estimates that investing USD 1.8 trillion in climate adaptation strategies, including resilient infrastructure, could generate USD 7.1 trillion in net benefits by 2030 [16]. For road infrastructure specifically, integrating resilience measures could reduce life-cycle costs by minimizing the frequency and severity of damage, lowering repair expenses, and extending service life. In Kenya, where approximately 80% of cargo and passenger movement is by road (Kenya National Bureau of Statistics, 2022), enhancing resilience is not merely a technical imperative but also a socio-economic necessity.

The integration of grey and green engineering in resilience planning has shown promising results in other contexts [12] [17]. For example, in Durban, South Africa, combining engineered stormwater drains with vegetated swales reduced flood damage by 23% compared to conventional grey systems alone (eThekwini Municipality, 2020) [18]. Similarly, in Vietnam, hybrid flood protection systems reduced annual maintenance costs by 20% while improving local water quality and habitat conditions (World Bank, 2021) [19]. Such evidence emphasizes the potential for hybrid infrastructure solutions to deliver both protective and ecological benefits, making them highly relevant for Kenyan road networks.

Despite the growing recognition of hybrid approaches, there is a lack of localized studies assessing how integrated grey-green engineering solutions could be applied to specific road corridors in Kenya. Most existing road maintenance and upgrade projects continue to adopt conventional engineering solutions without systematically assessing the full range of risks and potential adaptation options. This gap is particularly concerning for high-use corridors such as Kangundo Road, where the failure to address vulnerabilities could have cascading socio-economic impacts.

The proposed study, 'Integrating Grey and Green Engineering in Infrastructure Risk and Resilience Assessment: A Case Study of Kangundo Road,' seeks to address this gap by systematically characterizing the risks faced by the Kangundo Road corridor and evaluating adaptation and resilience design options that integrate grey and green engineering approaches. By combining quantitative risk assessment methods with practical design evaluations, the study aims to develop a framework for hybrid resilience solutions tailored to the specific environmental, technical, and socio-economic context of the road. The findings are expected to inform policy, guide infrastructure investment decisions, and contribute to the broader discourse on climate-resilient transport systems in Kenya.

2. Literature Review

2.1. Definition of Key Terms

Infrastructure Risk Assessment refers to the systematic identification, analysis, and evaluation of hazards that can affect infrastructure systems, considering both the likelihood of occurrence and the severity of potential consequences [20]. Resilience is the capacity of infrastructure systems to absorb disturbances, adapt to changing conditions, and rapidly recover functionality after a disruption [21]. Resilience includes pre-disaster preparedness, adaptive responses, and post-event recovery capacity. Grey Engineering comprises conventional, human-engineered infrastructure solutions such as concrete drainage systems, asphalt pavements, and reinforced embankments, designed primarily for structural protection and service continuity [22]. Green Engineering (or nature-based solutions) involves the use of ecological processes and natural systems, such as vegetative buffers, permeable pavements, bioswales, and green roofs, to provide hazard mitigation while delivering environmental and social co-benefits [23]. Hybrid Infrastructure (Grey-Green) integrates structural grey engineering with ecological green systems to enhance adaptive capacity, sustainability, and multiple co-benefits [24]. Adaptation Pathways are phased, flexible planning approaches that allow sequential interventions over time in response to evolving hazards, climatic changes, and socio-economic conditions.

2.2. Theoretical Review

This study is grounded in Engineering Resilience Theory, which originates from Holling [25] socio-ecological resilience framework but has been adapted for infrastructure systems [26]. While socio-ecological resilience emphasizes a system's capacity to absorb disturbances without shifting into an alternative state, engineering resilience focuses on the stability of performance and the speed of recovery following a disruptive event. It is particularly suited for infrastructure analysis because it quantifies how quickly a system can return to an acceptable level of functionality after a hazard, thereby providing a practical basis for risk assessment and adaptation planning. [27] describe engineering resilience as encompassing three interrelated capacities: absorptive capacity, which is the ability of a system to buffer, absorb, or contain the effects of hazards without significant degradation in service delivery; adaptive capacity, which reflects the ability to make operational or structural adjustments when absorptive limits are exceeded; and restorative capacity, which is the ability to restore and potentially enhance functionality after disruption.

Within the context of Kangundo Road, the framework guides risk characterization by identifying points at which absorptive and adaptive limits are likely to be exceeded under conditions such as flooding, erosion, and poor drainage performance. It also directs the evaluation of adaptation measures that can strengthen restorative capacity, thereby reducing downtime and enhancing long-term performance. Integrating hybrid grey-green engineering designs within this framework aligns with its emphasis on minimizing service loss while enabling rapid recovery [28]. Grey infrastructure elements, such as reinforced culverts and durable asphalt surfacing, provide immediate structural stability, while green infrastructure components, including vegetated swales, bioswales, and permeable pavements, enhance adaptability and deliver environmental co-benefits [12] [29]. These approaches embody the principles of engineering resilience by ensuring that Kangundo Road can withstand disturbances, adapt to changing conditions, and recover quickly while maintaining environmental sustainability.

2.3. Current Thinking and Approaches

Contemporary infrastructure planning has increasingly shifted away from reliance on purely grey engineering solutions toward the adoption of integrated hybrid systems [30]. Within this paradigm, resilience is understood as a dynamic and adaptive process rather than a fixed attribute, requiring infrastructure to adjust and evolve in response to emerging hazards and changing conditions [27]. International studies on urban drainage and transport networks consistently demonstrate that the incorporation of green elements, such as permeable pavements, vegetated swales, and green roofs, can significantly reduce peak flood flows, enhance water quality, and contribute to urban cooling [31]. The adaptation pathways approach further strengthens this integration by enabling phased, flexible interventions that can be adjusted to accommodate climatic variability and socio-economic change over time [1]. Beyond their hydrological and structural benefits, nature-based solutions also deliver important socio-economic gains, including improvements in public health, enhancement of biodiversity, and stimulation of local economies. Despite these advantages, empirical evidence from African high-traffic road corridors remains scarce. Most existing hybrid infrastructure frameworks have been developed and tested in coastal or urban drainage contexts, with limited application to major inland transport routes where traffic demands, climatic stresses, and budget constraints present unique resilience challenges.

2.4. Empirical Review

Irankunda [32] developed the NIRAC and RIRA frameworks for multi-scenario road infrastructure resilience assessment, applied to rain-damaged roads in Burundi. Findings confirmed their value in guiding sustainable recovery, though testing was limited to one region. Applicability to hybrid grey-green systems remains unexplored.

Joyce [33] coupled flood risk assessment with resilience metrics in a coastal drainage system in Florida using copula-based modeling. Results showed multi-criteria evaluation improves decision-making. The study has limited application to inland road networks; co-benefits of green measures are underrepresented.

Dong [34] proposed a resilience formula incorporating social, environmental, and technological severity, comparing green and grey drainage strategies in Kunming, China. Green measures proved cost-effective under climate uncertainty. The study methodology was not tailored to road transport infrastructure.

Kapetas [22] applied adaptation pathways to evaluate grey and blue-green flood solutions in London. Monetizing co-benefits shifted preferences to hybrid solutions. The study lacks application to African road corridors with budget constraints; maintenance feasibility is underassessed.

Staddon [35] reviewed green infrastructure's role in urban resilience, identifying five key implementation challenges. Advocated hybrid socio-technical systems. Gap: scarce empirical data on road corridor performance in developing contexts. **Table 1** outlines existing gaps in the study.

Table 1. Summary of literature and critique.

Author	Study Variables	Findings	Research Gap	Critique
[32]	Road resilience; multi-scenario	NIRAC & RIRA aid sustainable recovery	Needs varied climate/economy testing	No hybrid integration
[33]	Flood risk; resilience	Coupling metrics improves management	Limited inland road application	Socio-economic co-benefits missing
[34]	UDS resilience; climate change	Green strategies cost-effective	Needs road transport adaptation	Road-specific metrics absent
[22]	Adaptation pathways; hybrid	Co-benefits favor hybrids	Lacks African road applications	Maintenance feasibility ignored
[35]	Green infrastructure; resilience	Hybrid systems beneficial	Few transports corridor studies	No empirical performance data

Table 1 indicates that the reviewed literature emphasizes the potential of hybrid grey-green infrastructure for enhancing resilience but also reveals critical gaps relevant to Kangundo Road. Existing frameworks such as NIRAC, RIRA, and adaptation pathways offer strong foundations but lack contextual testing in African high-use road corridors. Studies on drainage systems show the efficiency of green infrastructure under climate change, yet few address road-specific hazards and performance metrics. Key gaps motivating this research include: Lack of empirical testing of hybrid solutions for African road infrastructure. Absence of integrated frameworks linking risk characterization, resilience assessment, and adaptation option evaluation for transport corridors. Limited valuation of co-benefits to support decision-making and investment in road resilience. This study will address

these gaps by assessing the risks and resilience of Kangundo Road and evaluating hybrid grey-green engineering designs for their technical feasibility, cost-effectiveness, and environmental co-benefits, thereby contributing a localized, evidence-based framework for climate-resilient road infrastructure planning in Kenya.

2.5. Contribution

This study will contribute to the growing body of knowledge on climate-resilient infrastructure by providing the first detailed, empirical assessment of risks and resilience for the Kangundo Road corridor in Kenya. While previous research has established the increasing vulnerability of road infrastructure to climate change and highlighted the potential benefits of integrating grey and green engineering solutions, there remains a lack of localized, data-driven frameworks for their practical application in high-use transport corridors within the Kenyan context. By systematically characterizing the specific climatic, environmental, and socio-economic risks affecting Kangundo Road, this research will generate a comprehensive risk profile that can guide targeted adaptation planning. Furthermore, the study will evaluate hybrid grey-green engineering design options, assessing their technical feasibility, cost-effectiveness, and potential co-benefits. The resulting framework will provide policymakers, engineers, and infrastructure planners with actionable strategies for integrating hybrid resilience measures into road infrastructure projects, ultimately enhancing service continuity, reducing maintenance costs, and contributing to sustainable urban and regional development.

3. Methodology

3.1. Study Area

Kangundo Road, as presented in **Figure 1**, lies in a low-elevation zone that naturally functions as a catchment for runoff from surrounding highlands.

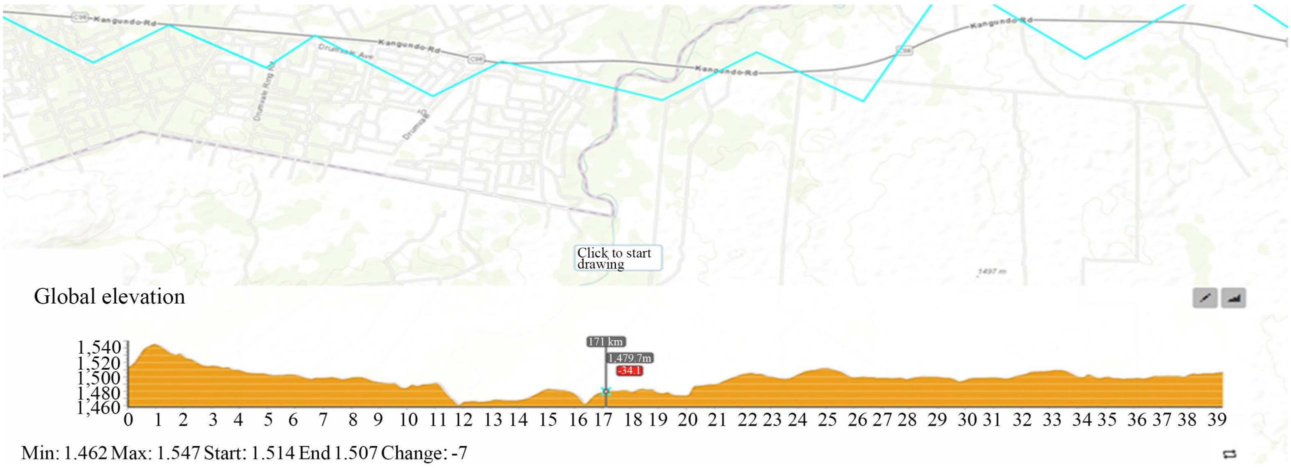

Figure 1. Image showing Kangundo region is on the lowest elevation; hence prone to flooding.

Figure 1 indicates that Kangundo road is the lowest point in its vicinity, making it highly susceptible to flooding during heavy rainfall. The adjacent regions, Kiambu, Ngong, and Machakos, are situated at significantly higher altitudes, with Ngong representing the highest elevation. Rainfall in these upland areas produces considerable runoff that flows downhill towards the Kangundo-Kamulu stretch. The gradient from Kiambu to Kangundo further accelerates this flow, directing large volumes of water into flood-prone sections of the road. Machakos, as another high-altitude area, contributes additional runoff during intense rainfall events, compounding the flood risk. The combination of topography and hydrological patterns frequently overwhelms the road's drainage systems, resulting in water pooling, flash floods, and damage to the infrastructure. These conditions make Kangundo Road an appropriate case study for climate-resilient infrastructure research, particularly in the design of effective drainage systems, the use of flood-resistant construction materials, and the integration of predictive flood management systems to mitigate risks in similar low-lying, flood-prone areas.

3.2. Study Methodology

The climate datasets used in this study were sourced from the Kenya Meteorological Department and the World Bank Climate Knowledge Portal. To ensure their suitability for modelling within the Fisher Climate framework, a systematic data-processing workflow was applied: Temporal Range: Historical precipitation and temperature records spanning several decades were extracted to capture both long-term variability and the frequency of extreme events affecting the Kangundo Road corridor. Quality Control: Raw data were screened for errors and inconsistencies, including the removal of statistical outliers, verification of station-level continuity, and cross-checking against regional climatological norms. This step ensured that anomalies reflected genuine climatic extremes rather than measurement errors. Gap-Filling Methods: Where gaps existed in the Kenya Meteorological Department records, complementary data from the World Bank portal were used. Interpolation techniques were applied for short, isolated gaps, while longer discontinuities were supplemented through cross-station substitution and trend-based estimation. The cleaned and harmonized datasets were then normalized and parameterized to generate the climate variable weights (α values) that support the Fisher Climate Model's scenario simulations.

The Fisher Climate Model was applied to generate future scenarios using hydrological data on river flows, groundwater levels, and soil moisture to map hazard exposure along Kangundo Road. Its integration of hydrological, geotechnical, and thermal processes within a single framework enables multi-hazard interactions such as drainage deterioration, flooding, and thermal expansion to be analyzed simultaneously, making it particularly suitable for road-scale risk assessment where rainfall variability and drainage efficiency are dominant drivers [34]. Sensitivity assessments considered susceptibility to flooding, thermal stress, and material degradation, while adaptive capacity was evaluated through drainage efficiency, material resilience, and maintenance practices. Engineering interventions, such as elevated roadbeds, upgraded culverts, and heat-resistant asphalt, were modelled alongside nature-based solutions, including vegetative buffers, wetland restoration, and bioswales, to enhance resilience. Key hydraulic, geotechnical, and thermal processes were simulated using literature-based equations, including Manning's equation for drainage, thermal expansion for heat, and limit equilibrium for slope stability. A combined resilience model, incorporating SSP4.5 and SSP8.5 climate scenarios, evaluated performance under moderate and extreme conditions, with resilience scores computed using weighted factors for material quality, design, adaptability, and projected climate impacts. Cost-benefit analysis and life-cycle evaluation guided prioritization of adaptation measures, with recommendations integrated into updated engineering standards and broader transport planning to ensure long-term climate resilience of Kangundo Road.

4. Findings

4.1. Recap of Mathematical Findings

Historical climate data on temperature, precipitation, and extreme events were sourced from the Kenya Meteorological Department. The section presents equations that were used in modelling the infrastructure based on a literature review.

Manning's Equation for open channel flow:

$$Q_{\text{flow}} = \left(1/n\right) AR^{\frac{2}{3}} S^{\frac{1}{2}} \tag{1}$$

Thermal Expansion Equation for extreme heat:

$$\Delta L = \alpha L_0 \Delta T \tag{2}$$

Frost-Heave Equation for heavy snow ice:

$$h_f = C_f \, \Delta T/d \tag{3}$$

Limit Equilibrium Equation for landslide:

$$FS = \left(c \cdot L + W \cdot \cos\left(\theta\right) \cdot \tan\left(\phi\right)\right) / \left(W \cdot \sin\left(\theta\right)\right) \tag{4}$$

Bruun Rule for predicting shoreline retreat based on sea-level rise:

$$R = S/\left(\tan\left(\beta\right)\right) \tag{5}$$

The combined model equation for climate-resilient infrastructure, considering the relative importance of each factor, was given by:

$$\text{Resilience Score} = w_1 Q_{\text{flow}} + w_2 \Delta L + w_3 h_f + w_4 FS + w_5 R \tag{6}$$

where w_1, w_2, w_3, w_4, and w_5 are weights representing the relative importance of each factor. The model incorporated climate scenarios SSP 4.5 (conservative) and SSP 8.5 (worst-case) to evaluate the resilience of infrastructure under different climate change conditions. SSP 4.5 represented a moderate climate change scenario with some mitigation, while SSP 8.5 represented a scenario of higher emissions and greater climate impacts. The model calculates the resilience score (*R*) of infrastructure considering these scenarios and other critical factors influencing infrastructure performance. Thus, R in Equation (6) becomes

$$R = w_1 X_1 + w_2 X_2 + \cdots + w_n X_n + \beta_1 SSP_{4.5} + \beta_2 SSP_{8.5} \tag{7}$$

where $w_1, w_2, \cdots, w_n$ are the weights representing the importance of various factors influencing infrastructure resilience, $x_1, x_2, \cdots, x_n$ are the factors representing material quality, design, adaptability and β_1 and β_2 are coefficients representing the impact of climate scenarios SSP 4.5 and SSP 8.5, respectively. $SSP_{4.5}$ and $SSP_{8.5}$ are variables representing projected climate impacts such as temperature, sea level rise under these scenarios. By incorporating both SSP 4.5 and SSP 8.5, the model evaluates the resilience of infrastructure under moderate and extreme climate change scenarios. The variables $SSP_{4.5}$ and $SSP_{8.5}$ represent expected changes in climate variables such as temperature, sea-level rise, or frequency of extreme weather events under these scenarios. The coefficients β_1 and β_2 adjust the overall resilience score based on the projected climate impact for each scenario. This approach ensures that the model accounts for a range of future climate conditions, helping decision-makers design infrastructure that can withstand both conservative and worst-case scenarios.

The SSP 4.5 (conservative) and SSP 8.5 (worst-case) climate change scenarios represent different future pathways for greenhouse gas (GHG) emissions, which affect temperature rise, sea-level rise, and extreme weather events. These scenarios can be represented through mathematical equations to model the impact of climate change on infrastructure resilience.

For temperature increase, ΔT for SSP 4.5 and SSP 8.5, the temperature increase over time can be modeled as:

$$\Delta S_{SSP_{4.5}}(t) = 0.3 + 0.005t + 0.0002t^2 \tag{8}$$

$$\Delta S_{SSP_{8.5}}(t) = 0.3 + 0.01t + 0.0004t^2 \tag{9}$$

where t is time in years, and the coefficients 0.02 and 0.04 represent the annual rate of temperature increase. For sea-level rise ΔS, Sea-level rise can be modeled as a quadratic function due to potential acceleration over time. However, since this case study area is not near the sea, sea-level rise is used as an analogy for the erosion of road structures caused by poor drainage design:

$$\Delta S_{SSP_{4.5}}(t) = 0.3 + 0.05t + 0.0002t^2 \tag{10}$$

$$\Delta S_{SSP_{8.5}}(t) = 0.3 + 0.01t + 0.0004t^2 \tag{11}$$

where t is time in years, and the quadratic terms represent the potential acceleration in sea-level rise. The frequency or intensity of extreme weather events can be modeled as follows:

$$E_{SSP_{4.5}} = 1 + 0.01t \tag{12}$$

$$E_{SSP_{8.5}} = 1 + 0.02\mathrm{e}^{0.03t} \tag{13}$$

where the exponential term in the SSP 8.5 equation reflects the accelerated increase in extreme weather events. To evaluate the overall effect of the SSP 4.5 and

SSP 8.5 scenarios on infrastructure resilience, the combined effect of temperature increase, sea-level rise, and extreme weather events can be represented as:

$$SSP_{4.5}(t) = \alpha_1 \Delta T_{SSP_{4.5}}(t) + \alpha_2 \Delta S_{SSP_{4.5}}(t) + \alpha_3 E_{SSP_{4.5}}(t) \tag{14}$$

$$SSP_{8.5}(t) = \alpha_1 \Delta T_{SSP_{8.5}}(t) + \alpha_2 \Delta S_{SSP_{8.5}}(t) + \alpha_3 E_{SSP_{8.5}}(t) \tag{15}$$

where α_1, α_2, and α_3 are the weights representing the relative importance of temperature, sea-level rise, and extreme weather events.

4.2. Data

The data was collected from https://climateknowledgeportal.worldbank.org/country/kenya/climate-data-historical. A summary of the data is presented in **Table 2**.

Table 2. Data statistics.

Item	Mean	Standard deviation (SD)
Rainfall	77.761	201.410
Temperature	18.7˚C	0.627

Table 2 indicates that the rainfall records show a mean of 77.761 mm with a standard deviation of 201.410 mm, indicating exceptionally high variability relative to the average. This large dispersion suggests that precipitation in the Kangundo Road catchment is highly irregular, with extreme wet periods interspersed with prolonged dry spells. Such variability aligns with the related literature on the increasing intensity and frequency of extreme weather events in sub-Saharan Africa, which elevates flood risk for low-lying infrastructure like Kangundo Road. This inconsistency in rainfall is a critical driver of the recurrent flooding and drainage overloads described in your study area section, reinforcing the need for resilient stormwater management interventions that can accommodate both extreme inflows and prolonged low-flow periods.

In contrast, the temperature data reveal a mean of 18.70˚C with a small standard deviation of 0.627˚C, reflecting a stable thermal regime over the study period. The low variability implies that thermal stress on materials is minimal compared to hydrological stress, meaning that temperature-related degradation, such as thermal expansion damage, is less likely to be a dominant hazard driver in this corridor. However, the article's methodology section still appropriately considers thermal expansion effects in resilience modelling, since even small temperature shifts can affect material performance over long design lifespans.

These findings highlight that rainfall-driven hazards should be the primary focus of adaptation planning for Kangundo Road. The combination of high precipitation variability and the road's low-lying topography creates recurrent and severe flood exposure. Hybrid grey-green engineering solutions, such as reinforced culverts integrated with vegetated swales and upstream wetland restoration. These approaches can increase absorptive capacity to handle extreme rainfall events while delivering ecological co-benefits, thereby directly addressing the hydrological variability revealed by the statistical analysis.

4.3. Simulation

4.3.1. Parameter Fitting

α values were calculated by normalizing statistical features of the temperature and precipitation data. α represents weights used to define the contribution of each climate variable to climate impact indices or scenario models. The α weights in **Table 3** were derived through min-max normalization of the statistical features (mean and standard deviation) of the climate variables, ensuring that each parameter contributed proportionally to the overall risk index within the Fisher Climate Model. The normalization procedure rescales each variable x_i to a 0 - 1 range according to:

$$\alpha_i = \left(x_i - x_{\min}\right) / \left(x_{\max} - x_{\min}\right) \tag{16}$$

where x_i is the observed feature value of the variable i such as rainfall and temperature. $x_{\min}$ and $x_{\max}$ are the minimum and maximum values across all variables, and α_i is the resulting normalized weight. After normalization, the weights were rescaled so that $\sum \alpha_i = 1$. This ensured comparability across climate drivers and allowed the Fisher Climate Model to emphasize the dominant stressor. The results are presented in **Table 3**.

Table 3. Climate scenario weights.

Weight	Value
$\alpha_{\text{Temperature}}$	0.0027
$\alpha_{\text{sea level}}$ (proxy of rainfall)	0.9967
$\alpha_{\text{extreme evens}}$ (proxy of rainfall)	0.006

Table 3 shows that the very low $\alpha_{\text{Temperature}}$ aligns with the previously reported low temperature standard deviation (0.627˚C), confirming minimal variability and negligible thermal impact on road deterioration. This makes temperature mitigation measures less critical. In contrast, $\alpha_{\text{Sea level}} = 0.9967$, a proxy for cumulative rainfall, dominates, underscoring precipitation as the primary climate risk. Sustained soil saturation and high pore pressures weaken subgrades, causing rutting, potholing, and erosion, highlighting the need for robust drainage systems. $\alpha_{\text{Extreme events}} = 0.0060$, though modest, reflects occasional storm impacts that can overwhelm drainage. Resilience planning should prioritize water-related stressors in design and maintenance. The objective was to assess infrastructure risks and resilience for Kangundo Road under various climate stressors, including floods, extreme heat, landslides, and sea-level rise. Findings show flooding as the dominant hazard, driven by the road's location in low-lying, poorly drained clay soils and compounded by inadequate drainage slopes, particularly between Umoja and Komarocks. These conditions cause runoff accumulation and long-term satura-

tion during heavy rains. While Nairobi lacks snowfall, climate models suggest potential frost-heave impacts from future temperature volatility, worsening siltation and drainage inefficiency. Steep slopes further increase landslide risk, and limited stormwater infrastructure heightens the road's vulnerability to water-related hazards.

4.3.2. Infrastructure Risks and Resilience Assessment for the Road Assert

In this study, the resilience score is defined as a composite vulnerability index, where higher values indicate greater cumulative climate-induced stress such as lower resilience, while lower values reflect stronger resilience and adaptive capacity. The simulation results presented in **Figure 2** are based on resilience score in Equation (3).

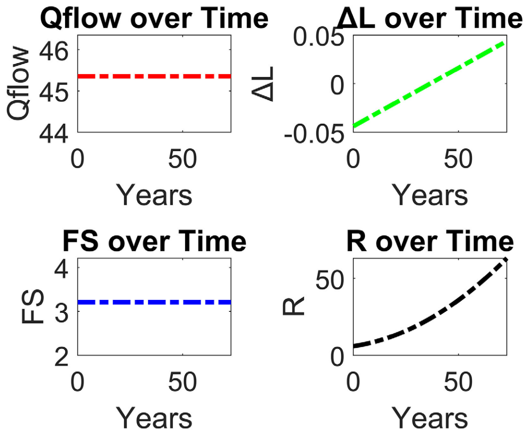

Figure 2. Simulation of infrastructure components.

Figure 2 illustrates the temporal trends of four key parameters, Q_{flow}, thermal expansion (ΔL), factor of safety (FS), and shoreline retreat (R), central to assessing road infrastructure resilience under climate change. Q_{flow} remains stable at ~45.5 over 80 years, suggesting consistent drainage capacity but no dynamic adaptation to changing rainfall patterns. ΔL increases linearly from slightly negative to ~0.05, indicating gradual thermal expansion of materials and potential long-term deformation if not addressed in design. FS stays slightly above 3.0, implying stable slopes, though the model may underestimate impacts from rainfall, seismic events, or soil saturation. The most concerning is R, which rises exponentially from <10 to >60, signaling escalating erosion risks that could undermine road foundations. Erosion (R) and thermal expansion (ΔL) emerge as the most time-sensitive threats, highlighting the need for climate-responsive road designs prioritizing erosion control and material resilience to ensure long-term functionality. **Figure 3** presents resilience score over the study duration.

Figure 3 shows a steady increase in the road infrastructure's resilience score from ~9 to ~30 over an 80-year simulation, indicating escalating vulnerability as cumulative stressors intensify. Lower scores therefore represent greater resilience, while higher scores signal declining performance under climate stress. This growth reflects the combined effects of hydrological capacity, material thermal response, frost heave resistance, landslide stability, and drainage line performance, evaluated under SSP 4.5 and SSP 8.5 scenarios. Enhanced drainage design, including optimized slope, width, and depth, plays a key role in mitigating flood risks. The results suggest a declining risk profile if adaptive measures are maintained, though the outcome remains model-dependent. Simulation of resilience score against time and thermal expansion is presented in **Figure 4**.

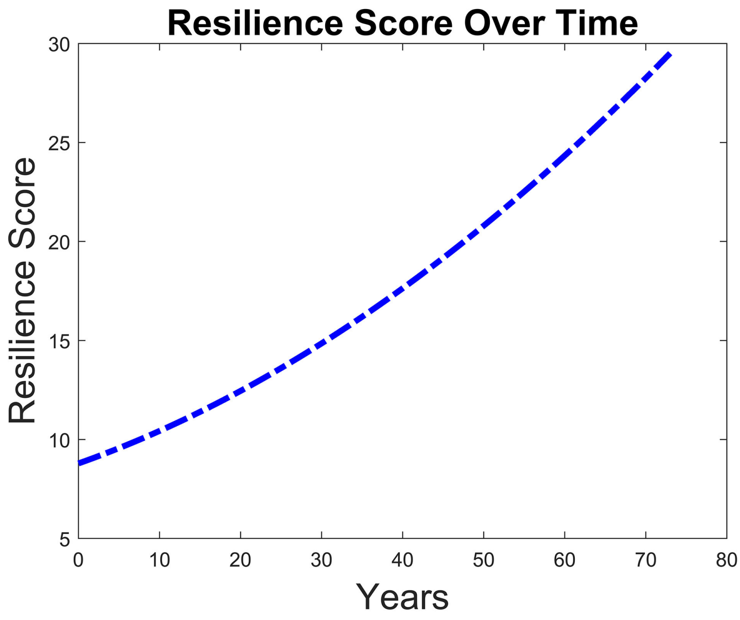

Figure 3. Simulation of resilience score.

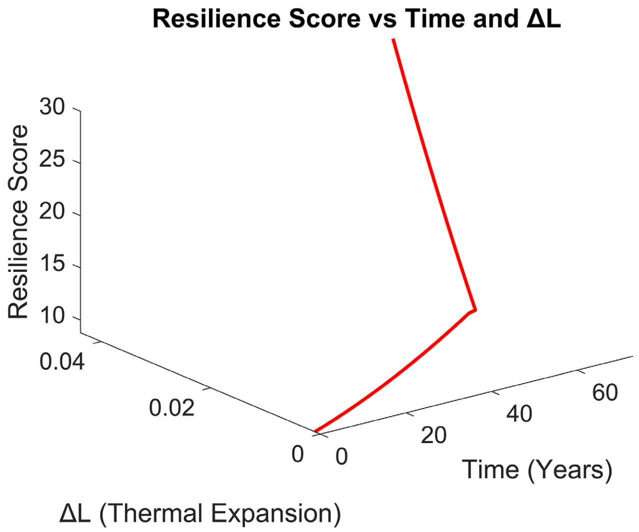

Figure 4. Simulation of resilience score against time and thermal expansion.

Figure 4 presents a 3D plot showing the relationship between thermal expansion (ΔL) and road infrastructure resilience over time. Initially, ΔL is near zero, indicating minimal heat-induced deformation. Over time, ΔL increases due to rising temperature anomalies, paralleled by a rise in the resilience score, used here as a composite indicator of climatic stress impacts rather than resistance. The non-linear escalation suggests that beyond certain thresholds, small thermal changes could cause disproportionately large damage, accelerating deterioration. This highlights the need for heat-resistant materials and thermally adaptive designs, ensuring road performance accounts for long-term thermal trends and anticipated climate-driven stresses. **Figure 5** shows simulation of resilience score against drainage deterioration against time.

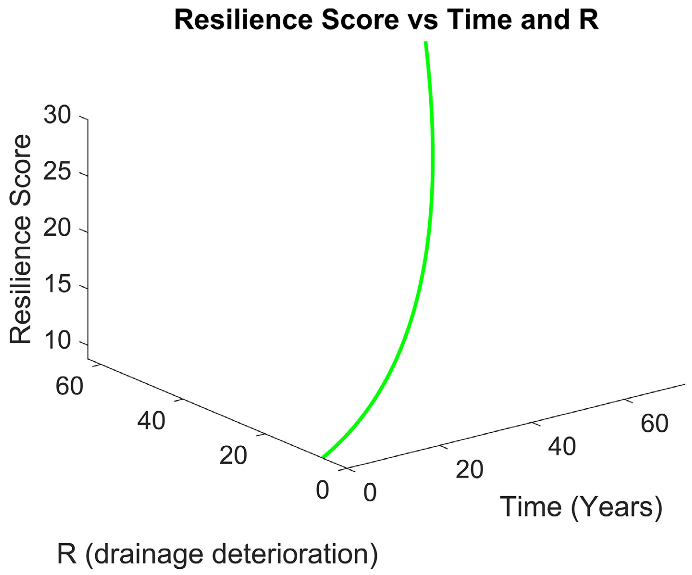

Figure 5. Simulation of resilience score against drainage deterioration against time.

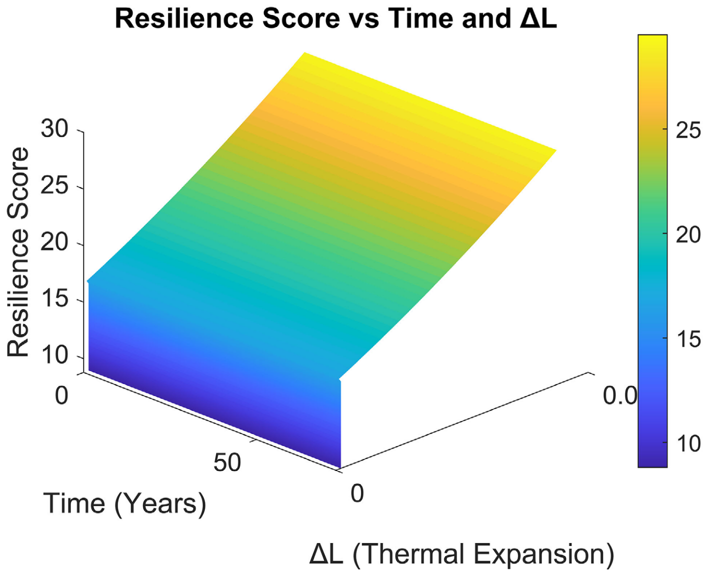

Figure 6. Simulation of resilience score against time and thermal expansion.

Figure 5 shows that resilience scores rise with increasing drainage deterioration (R), confirming that higher scores reflect greater vulnerability caused by declining drainage efficiency. Over time, R rises non-linearly, driven by erosion, storm surges, and reduced sediment replenishment, causing resilience scores to escalate sharply. The concave curve suggests a tipping point where small increases in R trigger disproportionately high risk, particularly in coastal or low-lying areas. This non-linear behavior underscores the urgency of early mitigation to prevent rapid transitions from stability to critical risk. Figure 6 shows the combined effects of time and thermal stress (ΔL) on road infrastructure resilience.

Figure 6 shows that as thermal expansion (ΔL) increases over time, the resilience score also rises, reflecting steadily compounding vulnerability due to material fatigue. The near-linear gradient suggests continuous risk accumulation from thermal expansion, driven by gradual material fatigue rather than sudden failures. The color shift from blue (low stress) to yellow (high stress) visually emphasizes growing thermal risk. These findings highlight the need for heat-resistant materials and designs to address persistent, long-term degradation under projected climate warming. Figure 7 presents simulation of resilience score vs time and R (drainage deterioration).

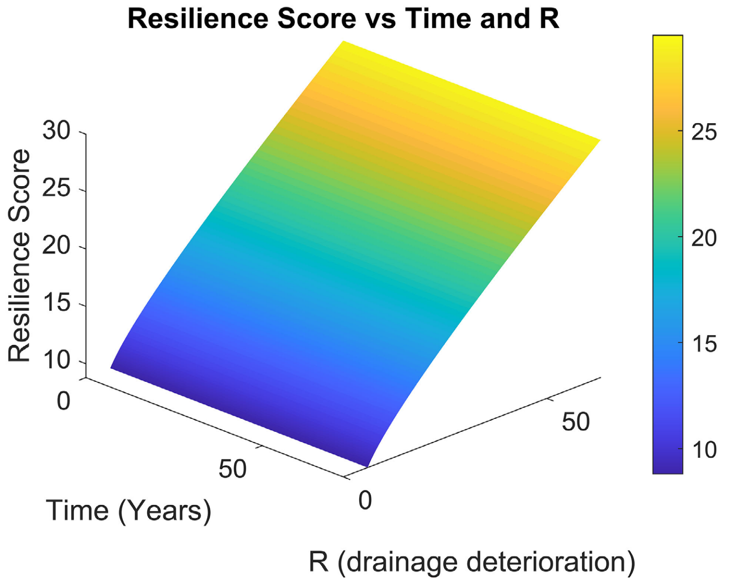

Figure 7. Simulation of resilience score vs time and R (Drainage deterioration).

Figure 7 illustrates how shoreline retreat or drainage deterioration (R) and time combine to influence road infrastructure resilience. The resilience score represents cumulative risk from prolonged environmental exposure rather than structural strength. At early times and low R, scores remain modest, reflecting limited stress. Figure 7 and Figure 8 illustrate that combined increases in drainage deterioration (R) and thermal expansion (ΔL) escalate resilience scores rapidly, confirming that higher scores signal compounding vulnerability under multiple simultaneous stressors. The non-linear surface gradient and color shift from blue (low risk) to yellow (high cumulative risk) underscore how long-term deterioration compounds vulnerability. This pattern emphasizes the need for proactive drainage design and timely interventions to prevent escalating climate-related risks.

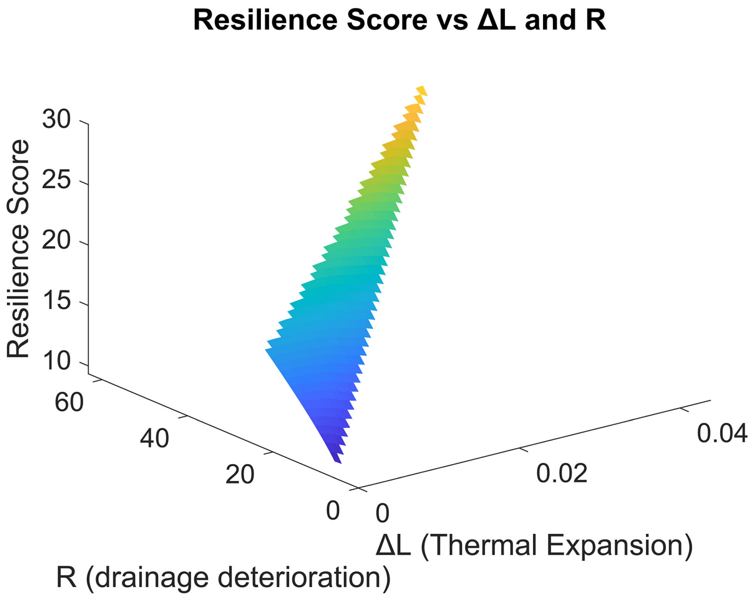

Figure 8. Resilience score vs ΔL and R (Drainage deterioration).

Figure 8 illustrates the combined effects of thermal expansion (ΔL) and drainage deterioration (R) on road infrastructure resilience. Both factors individually increase the resilience score, indicating escalating vulnerability due to compounding stressors, but their simultaneous rise produces a compounding effect, sharply elevating risk. The surface gradient shows that moderate increases in either factor raise vulnerability, while high ΔL and R together push the system into a critical risk zone, as highlighted by the upper-bound color shift. This underscores that roads facing both heat stress and poor drainage are most prone to failure. The results stress the need for integrated adaptation strategies addressing both thermal and hydrological stressors.

4.3.3. Adaptation and Resilience Design Option in Grey and Green Engineering to Address Identified Risks

Adaptation and resilience design in grey and green engineering is essential for integrating climate risk into road design and ensuring long-term infrastructure resilience. With escalating threats from extreme heat, intensified rainfall, flooding, and sea-level rise, proactive responses to vulnerabilities are critical. Grey measures, such as reinforced drainage, elevated embankments, and thermally resistant pavements, offer robust, immediate protection. Embedding these within a climate-integrated design framework enables balanced decisions on performance, cost, and sustainability. This objective bridges the gap between risk assessment and actionable design, ensuring that climate-informed evaluations translate into resilient infrastructure capable of safeguarding road networks against future climate uncertainties. Figure 9 presents absolute impact of component exclusion on resilience score.

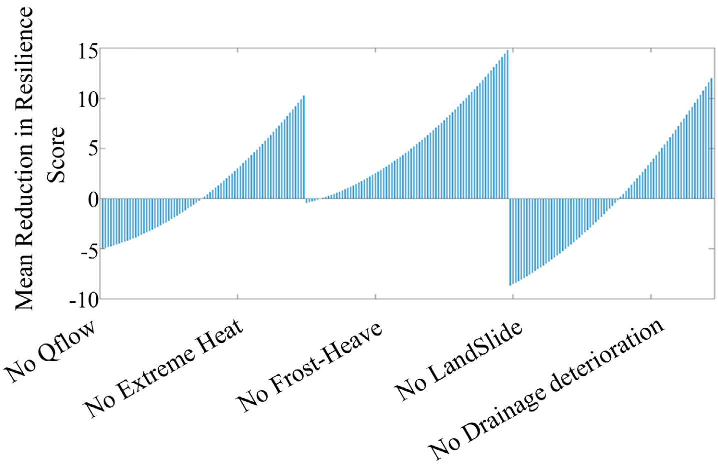

Figure 9. Absolute impact of component exclusion on resilience score.

Figure 9 shows sensitivity analysis in assessing how removing key stressors affects road infrastructure resilience. Excluding landslide susceptibility (FS) yields both positive and negative changes, showing complex interactions and variability in its influence. In contrast, removing drainage deterioration (R) consistently reduces resilience, confirming it as a dominant stressor. Frost-heave (h_f) has a smaller but noticeable effect, reflecting its secondary role. The differing magnitudes highlight that R and FS are the most critical factors, while Q_{flow} and ΔL would also contribute meaningfully if included. The analysis shows resilience is stressor-dependent, with drainage and landslide risks requiring the highest priority in adaptation strategies. The analysis indicates that without effective drainage, the road's capacity to withstand disruptions falls sharply. Grey engineering responses include larger culverts, lined channels, and improved cross-drainage, while green measures, such as bio-retention systems, vegetated swales, and rain gardens (**Figure 10**) enhance infiltration, reduce surface runoff, and complement structural drainage upgrades.

Figure 10. Example of vegetated swales.

The exclusion of frost-heave effects results in a moderate drop in resilience score, indicating that temperature-induced ground movements remain relevant under extreme heat or cold. Grey engineering could address this through structural reinforcements, while green measures, such as increased vegetation cover, can stabilize surface temperatures and retain soil moisture, reducing freeze-thaw vulnerability. Landslide susceptibility (*FS*) also shows notable influence, with resilience declining when excluded, underscoring the need for slope stability in hilly areas. Solutions range from retaining walls and slope drainage (grey) to reforestation and terracing (green). **Figure 11** confirms drainage management as the most critical factor, and integrating both engineering and ecological strategies offers the strongest pathway to climate-resilient, sustainable road infrastructure.

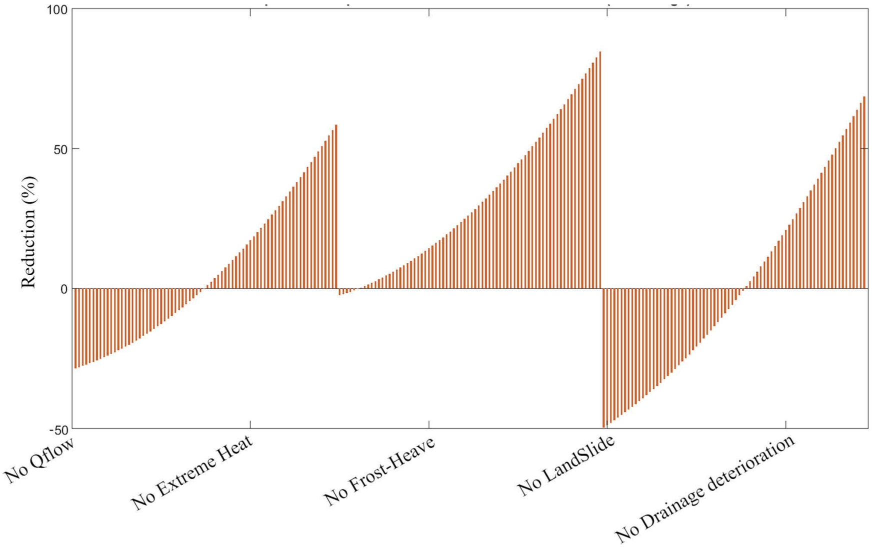

Figure 11. Percentage of impact of component exclusion on resilience score.

Figure 11 shows the percentage reduction in resilience score when key factors are excluded. Removing frost-heave causes the largest reduction, exceeding 80% in some cases, confirming drainage as the most critical resilience determinant. Grey measures like reinforced channels and culverts, and green solutions such as bioswales and permeable pavements, are vital under intense rainfall. Excluding hf yields the smallest drop, though its importance rises in freeze-thaw climates. *FS* exclusion shows substantial impact, highlighting slope vulnerability in steep or unstable terrain. Compared to **Figure 9**, absolute reductions, **Figure 12** presents a relative perspective for prioritizing cost-effective, targeted interventions, combining grey and green strategies.

Figure 12 quantifies the impact of key variables on road infrastructure resilience. Excluding Q_{flow} (hydrological flow) causes the largest reduction, nearly 55%, underscoring the importance of stormwater management through grey measures like engineered channels, culverts, and retention basins. R (drainage deterioration) follows, with about a 30% reduction, reflecting the need for hybrid green-grey strategies such as bioswales, buffer strips, and permeable pavements to counter intensified rainfall and flooding. ΔL (thermal expansion), h_f (frost-heave), and

FS (landslide safety) have smaller impacts (<10%), indicating localized or secondary importance in this setting. Together with **Figure 9** and **Figure 11**, the results highlight that prioritizing drainage, hydrological capacity, and thermal resilience through integrated grey and green engineering is crucial to maintaining road performance under climate stress.

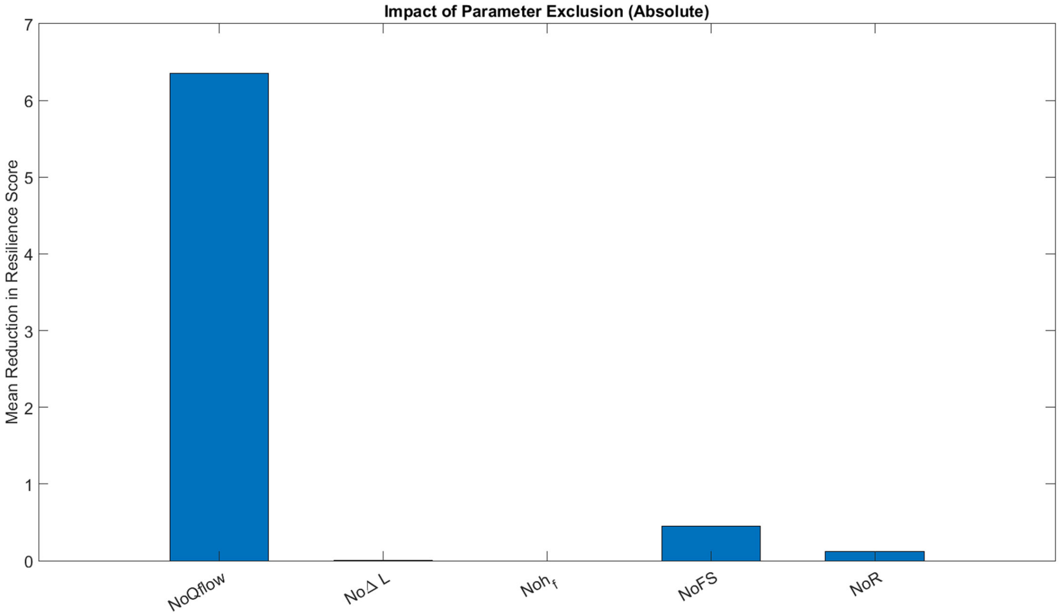

Figure 12. Sensitivity of resilience score to component exclusion.

4.4. Discussion

The simulation results quantitatively reinforce the conceptual and empirical foundations outlined in the literature review, particularly regarding the dominant role of hydrological stressors and the complementary value of hybrid grey-green engineering approaches. The weight analysis (**Table 3**) indicates that $\alpha_{\text{Sea level}}$, used as a proxy for cumulative rainfall and drainage deterioration, exerts the greatest influence (0.9967) on resilience, while $\alpha_{\text{Temperature}}$ and $\alpha_{\text{Extreme events}}$ have minimal values. This finding aligns with evidence that flood-related hazards dominate road infrastructure vulnerability in tropical contexts [22] [34]. For Kangundo Road, this confirms the need to prioritize water-related hazard mitigation, consistent with the adaptation planning perspectives in [12] [30]. The practical implication is that climate adaptation budgets and infrastructure upgrade programmes should allocate proportionately greater resources toward drainage system design, expansion, and maintenance, rather than heavily investing in temperature-specific mitigations.

Temporal simulations show that while Q_{flow} remains stable, R (drainage deterioration) increases exponentially, signaling escalating erosion and drainage inefficiency, trends consistent with projected increases in extreme rainfall for sub-Saharan Africa [5] [6]. Without intervention, this trajectory implies a transition from manageable wear to accelerated functional degradation, shortening asset lifespan and increasing life-cycle costs. Thermal expansion (ΔL) displays steady growth, supporting the argument that even small temperature variations can accumulate to cause long-term material fatigue [17]. This implies that thermally adaptive designs should be incorporated during new road construction, even if temperature is not the dominant hazard, to avoid compounded maintenance burdens in the future.

The combined hazard plots (**Figures 4-8**) reveal non-linear risk escalations when ΔL and R interact, emphasizing the necessity for integrated strategies that address both thermal and hydrological stressors through reinforced drainage and thermally adaptive designs [31] [35]. Such patterns suggest that single-hazard adaptation approaches are insufficient, as combined stresses can push the system past critical thresholds much earlier than individual hazards would. Sensitivity analyses (**Figures 9-12**) highlight drainage deterioration and hydrological flow as the most critical resilience determinants, aligning with identified empirical gaps that call for drainage-focused interventions in African high-use road corridors [32].

While frost-heave and slope stability rank lower in this context, their significance in other climatic or topographic conditions underscores the value of the flexible, context-specific resilience planning framework outlined in [27]. The implication is that resilience frameworks should be locally calibrated but still maintain modularity to incorporate emerging risks. The results operationalize the engineering resilience principles by demonstrating that Kangundo Road's resilience is most threatened by water-related stressors, and that hybrid grey-green engineering offers the most robust pathway to sustainable, climate-resilient performance. The findings also support the need for integrated infrastructure-climate planning policies that mandate multi-hazard risk assessment at the design stage, link maintenance cycles to climate projections, and promote nature-based solutions alongside structural upgrades to ensure both robustness and sustainability.

5. Conclusions

This study has shown that climate-related hazards, particularly hydrological stressors, present the greatest threat to the structural integrity and operational performance of Kangundo Road. Simulation outputs identified drainage deterioration (R) and hydrological flow (Q_{flow}) as the most critical resilience determinants, with their exclusion reducing resilience scores by over 80% and 55% respectively. These findings confirm that water-related hazards, amplified by intense and irregular rainfall, are the dominant drivers of vulnerability in the study area [22] [34]. Thermal expansion (ΔL), frost-heave (h_f), and landslide susceptibility (FS) had smaller impacts under current climatic conditions, but their influence may increase under different environmental scenarios. The observed non-linear escalation when thermal and hydrological stressors interact reinforces the need for integrated multi-hazard adaptation strategies [31] [35].

From an adaptation standpoint, hybrid grey-green engineering solutions emerge as the most effective pathway for building climate-resilient road infrastructure. Grey interventions, such as reinforced culverts, elevated embankments, and thermally resistant pavements, provide robust structural protection, while green measures, including bioswales, vegetative buffers, and permeable pavements, enhance infiltration, reduce runoff, and deliver ecological co-benefits. Prioritising drainage capacity enhancement, slope protection, and thermally adaptive materials will extend infrastructure lifespan and reduce life-cycle costs [12] [30].

Limitations of the study include reliance on model-based projections, which assume constant design parameters for drainage and material performance over the simulation horizon. The study also focused on a single road corridor, which may limit the generalizability of findings to other regions with different climatic, geological, or socio-economic conditions. Additionally, the scope did not explicitly assess institutional, financial, and governance factors that may influence adaptation feasibility.

A key limitation of the resilience score is that it has not yet been validated against observed failure data from Kangundo Road, as long-term field records of drainage collapse, pavement cracking, or flood-induced service interruptions are scarce. Future field monitoring campaigns that track hydrological performance, material degradation, and failure occurrences could be used to calibrate the score, improving its predictive accuracy and decision-support value for road-scale climate resilience planning.

Recommendations arising from the findings are threefold: Policy and Planning: Mandate multi-hazard climate risk assessments in road design standards, with emphasis on drainage system resilience and hydrological capacity. Investment Priorities: Allocate a larger proportion of infrastructure funding to stormwater management, erosion control, and green-grey hybrid adaptation measures.

Future Research: Extend the modelling framework to multiple road corridors and integrate socio-economic, governance, and maintenance capacity factors to provide a holistic resilience assessment.

By operationalizing engineering resilience principles within a locally calibrated framework, this study offers both an evidence base and a practical roadmap for safeguarding critical transport infrastructure against escalating climate risks while ensuring long-term socio-economic and environmental sustainability.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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