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Enhancing Water Infrastructure Resilience in Response to Climate Change: Evidence From South Africa

Joy Tuoyo Adu

Discipline of Civil Engineering, University of KwaZulu-Natal, South Africa

Correspondence: Joy Tuoyo Adu (aduj@ukzn.ac.za)

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Abstract

Climate change is intensifying extreme weather events worldwide, placing unprecedented stress on water infrastructure systems. As climate variability increases, water utilities face mounting challenges in maintaining infrastructure integrity. This study, conducted in South Africa, quantifies the relationship between climate variability and water infrastructure resilience through empirical analysis of 43 years of historical data spanning 1980 to 2023. The article uses correlation, regression, and time-series forecasting techniques to examine how extreme weather events, specifically floods and droughts, impact pipeline infrastructure performance metrics, including pipe failures, supply interruptions, and economic losses. The analysis reveals strong correlations between climate events and pipeline failures (flood-pipe failure $r = 0.78$; drought-pipe failure $r = 0.64$), with regression modelling showing that drought events have a 47% greater impact on pipe failures than flood incidents (coefficients 6.19 vs 4.21). Autoregressive integrated moving average (ARIMA) forecasting indicates an annual increase of approximately 4.5 pipe failures over the next two decades, indicating growing infrastructure vulnerability without intervention. The study concludes that enhancing resilience requires an integrated approach combining structural improvements with distributed systems and nature-based solutions, with implementation priorities guided by the vulnerability of infrastructure components to specific climate stressors. These findings provide water managers with a quantitative basis for resilience planning that addresses immediate climate threats and long-term adaptation needs.

Keywords

climate change; extreme weather events; flood incidence; resilient water infrastructure

1. Introduction

Resilience of water infrastructure has emerged as a defining priority in the face of climate change, which amplifies global water challenges, intensifies scarcity, and exposes the vulnerabilities of infrastructure systems (Amparo-Salcedo et al., 2025; Karimi et al., 2024; Olawuyi & Mushunje, 2024). Rapid urbanisation, ageing water systems, and climate-induced variability place increasing pressure on distribution and drainage networks. These pressures are particularly acute in semi-arid and arid regions, where climate variability interacts with existing supply constraints to threaten water security (Karimi et al., 2024). Water infrastructure encompasses collection, treatment, distribution, and drainage systems (Taiwo et al., 2023), but pipeline networks represent the most extensive and vulnerable of distribution systems, with pipe failures causing substantial service disruptions and economic losses (Serafeim et al., 2024; Vinke-De Kruijf et al., 2024). Extreme weather events such as droughts and floods magnify these vulnerabilities, with floodwaters damaging buried assets through hydraulic loading and erosion, and droughts triggering soil shrinkage, subsidence, and stress fractures (Ferdowsi et al., 2024). In this study, floods refer to inland flooding events, excluding coastal storm surges.

Resilience, defined broadly as the capacity to withstand shocks, adapt to change, and recover effectively, has become a central concept in climate adaptation planning (Kapucu et al., 2024). Within resilience theory, two perspectives dominate: engineering resilience, which emphasises the speed and extent of recovery to a functional state, and ecological resilience, which highlights adaptability, transformation, and the ability to maintain function under persistent chronic stressors (Folke et al., 2010). In the context of water infrastructure, engineering resilience is critical for rapid restoration after sudden shocks such as floods, while ecological resilience underpins adaptive responses to gradual, chronic stresses such as drought. Both perspectives are vital for water infrastructure, yet empirical evidence quantifying how specific climate stressors influence infrastructure performance remains limited. Many studies adopt conceptual frameworks or develop resilience indices without directly linking them to long-term performance (Mehvar et al., 2021; Vinke-De Kruijf et al., 2024). Predictive models often exclude climate variability parameters, limiting their usefulness for forward-looking adaptation strategies (Serafeim et al., 2024). Furthermore, while resilience strategies such as material upgrades, decentralised systems, and nature-based solutions are widely discussed, there is limited empirical assessment of their relative importance for different failures and climate conditions. This article addresses these gaps by combining 43 years of climate and infrastructure performance data for South Africa to evaluate the statistical relationships between extreme weather events and infrastructure failures. Regression and time-series forecasting models are developed to anticipate future failure patterns under projected climate scenarios. Drawing from these empirical insights, the study proposes targeted strategies for strengthening the resilience of urban water distribution and drainage systems, aligning both engineering and ecological resilience principles with practical adaptation planning.

2. Climate Change and Water Infrastructure Resilience

The frequency and intensity of climate-related events place immense pressure on urban water distribution systems, with significant implications for long-term sustainability and resilience (Ferdowsi et al., 2024). Rising global temperatures, shifting precipitation patterns, and weather events such as droughts and floods increase infrastructure vulnerability and threaten water security (Arias et al., 2021; Ferdowsi et al., 2024). Analysis of global climate data reveals that between 1980 and 2023, extreme weather events affecting urban water distribution and drainage infrastructure have increased drastically, with drought durations extending significantly in arid regions (World Meteorological Organization, 2023). This trend underscores the critical need for infrastructure systems capable of withstanding acute shocks and chronic stresses. The impacts of climate change on urban water distribution systems vary significantly across regions, depending on geographical, climatic, and socio-economic factors. Prolonged droughts exacerbate groundwater depletion in arid and semi-arid regions, leading to aquifer over-pumping and subsequent land subsidence due to sediment compaction. The drying and shrinkage of soils create localised ground movement and cracking. These processes induce stress on pipelines, potentially causing failure through bending, joint displacement, or fracture (Kundzewicz et al., 2018). In regions vulnerable to extreme rainfall and flooding, overwhelmed drainage networks, rapid reservoir sedimentation, and infrastructure failures from extreme water loads are now major challenges (Madonsela et al., 2019; Nhamo et al., 2025). Studies by Kuzma et al. (2023) and Urquiza and Billi (2020) state that regions that experience high levels of water stress tend to have less resilient infrastructure. This relationship between water stress and infrastructure resilience creates a challenging dynamic. The interconnected challenges climate change poses call for a broader approach to resilience. Solutions that combine technological innovation and nature-based systems are proving to be more effective in building long-term infrastructure resilience (Adom et al., 2022; Akamani, 2023; Mehvar et al., 2021; Vinke-De Kruijf et al., 2024).

South Africa has, in recent years, faced increasing weather-related disasters. While the country's climate varies due to its geography, climate change intensifies these extremes, with rising temperatures, shifting rainfall patterns, and increasing frequency and severity of floods and droughts representing a clear departure from historical norms (Adom et al., 2022; Arias et al., 2021; Bopape et al., 2025; Henchiri et al., 2024). These shifts place considerable strain on fragile water supply infrastructure, much of which is ageing, poorly maintained, or structurally vulnerable (National Research Foundation's South African Environmental Observation Network, n.d.). Notably, this vulnerability is uneven across the country. For example, the Western Cape provinces have endured multi-year droughts, while the Eastern and Western Cape and KwaZulu-Natal provinces have experienced increasingly frequent and intense flood events. The resulting infrastructure stress is multifaceted, ranging from pipe bursts, leakages, and pressure losses to widespread service outages (Steyn et al., 2018). These failures cause physical and operational damage and have wider financial, environmental, and public health consequences. Data from the Emergency Events Database (n.d.) highlights this contrast: While floods remain the most frequent natural hazard, droughts have also imposed substantial economic costs. For instance, the 2015–2018 drought in the Western Cape resulted in losses exceeding 1 billion US Dollars, with distribution systems compromised by subsidence-induced fractures (Mahlalela et al., 2019; Visser, 2018). In contrast, the April 2022 floods in KwaZulu-Natal damaged more than 600 km of water mains in a single day, causing total infrastructure and business losses of approximately 2 billion US Dollars (Department of Water and Sanitation, 2022, 2023; Grab & Nash, 2024). Collectively, these events underscore the vulnerability of South Africa's water infrastructure to climate extremes and highlight the urgent need for resilient, adaptive infrastructure planning and investment.

Building resilient urban water distribution infrastructure is essential for mitigating the impacts of climate change and ensuring sustainable water availability (Ferdowsi et al., 2024; Morris & Little, 2019). An approach that integrates technological innovation and nature-based solutions can significantly enhance the adaptability and longevity of water systems. While these strategies offer promising pathways to resilience, their effectiveness varies considerably across different contexts, and each approach carries distinct limitations and implementation challenges (Akamani, 2023; Crozier et al., 2024). Nature-based solutions have gained recognition as effective strategies for enhancing urban water distribution resilience. Wetland restoration is vital in flood mitigation, water purification, and biodiversity conservation. Further, permeable pavements, urban forests, and rain gardens absorb and store stormwater, reducing overland flows and floods (Addo-Bankas et al., 2024; Fisk et al., 2024; Vinke-De Kruijf et al., 2024). Ecosystem-based water management, which integrates natural systems with engineered infrastructure, provides long-term, sustainable solutions to hydrological challenges (Addo-Bankas et al., 2024; Cohen-Shacham et al., 2016; Vinke-De Kruijf et al., 2024). Despite these benefits, nature-based solutions face significant implementation challenges that limit their widespread adoption, especially during extended drought periods followed by intense rainfall (Boogaard, 2022; Castelo et al., 2023). These solutions also face temporal limitations as many nature-based interventions require an extensive period to function fully, creating a mismatch with the immediate resilience needs as climate impacts intensify. Further, while often promoted as low-maintenance alternatives, evidence from long-term implementations depicts that nature-based solutions require consistent, specialised maintenance to maintain performance, without which efficiency may decline by 15–30% within 3–5 years of installation (Nelson et al., 2020). However, limited empirical evidence connects these strategies to specific, quantified performance outcomes under real climate variability. This study addresses this gap by linking historical climate and infrastructure failure records to targeted adaptation recommendations.

3. Methodology

This study adopts a quantitative approach to investigate the relationship between climate variability and the resilience of urban water distribution and drainage infrastructure in South Africa. The methodological framework integrates long-term climate and infrastructure failure data with statistical modelling techniques, specifically multiple regression and autoregressive integrated moving average (ARIMA) forecasting. The approach enables both the identification of historical relationships and the projection of future infrastructure performance under continued climate variability.

3.1. Data Collection and Processing

The dataset used spans the period from 1980 to 2023 and synthesises information from multiple reputable sources. International datasets were drawn from the IPCC Climate Data Archive (Arias et al., 2021), the Emergency Events Database, and Our World in Data (Ritchie et al., 2022). While regional and national datasets were obtained from the South African Department of Water and Sanitation, the National Research Foundation's South African Environmental Observation Network, and published infrastructure damage assessment reports, although some datasets originate from global repositories, the analysis focuses exclusively on South Africa. Where possible, records from international databases were filtered to extract only national-level entries. In cases where multiple data sources overlapped for the same variable, a standardisation protocol was applied to ensure temporal and definitional consistency. Units of measurement were harmonised across sources: extreme weather events were expressed as the annual count of officially recorded incidents, pipe failures as the number of documented ruptures and leaks per 100 km of pipeline per year, supply interruptions as the annual number of recorded service outages, and economic losses as millions of United States dollars per year, adjusted for inflation using historical exchange rates and price indices. Data quality assurance involved three main steps. First, temporal alignment ensured that all variables were consistently recorded annually over the 43-year study period. Second, definitional harmonisation ensured that drought events reflected official declarations and that flood incidents excluded coastal storm surges. Third, completeness checks addressed data gaps representing less than 2% of the dataset by interpolating weighted averages from adjacent years. Although interpolation preserves trend continuity, it may also smooth out short-term variability. Sensitivity tests excluding interpolated years could be conducted in future work to assess robustness. This pre-processing preserved the integrity of long-term trends while maintaining statistical robustness for subsequent analyses.

3.2. Statistical Analysis

3.2.1. Descriptive Statistics

Descriptive statistics were computed for all variables to characterise infrastructure failure trends. Pearson correlation coefficients assessed the relationships between climate events (flood and drought) and infrastructure failures (pipe bursts). The multiple regression and ARIMA models were applied to quantify the impact of climate events on infrastructure failures and to forecast future trends in infrastructure failures, focusing on the impact of climate variability over the next two decades (Box et al., 2015). Descriptive statistics were computed to characterise the distribution of climate events and infrastructure failures over the study period. The mean (μ) and standard deviation (σ) for each variable were calculated following Equations (1) and (2), where n represents the number of observations and X_i the observed values for each variable:

$$\mu = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{1}$$

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \left(X_i - \mu\right)^2} \tag{2}$$

These descriptive measures provided a baseline for understanding central tendency and variability for flood incidents, drought incidents, pipe failures, supply interruptions, and economic losses. Additional measures included minimum and maximum values to establish ranges and interquartile ranges for distribution analysis. This statistical profiling established the foundation for subsequent correlation and regression analyses by characterising the fundamental properties of each variable.

3.2.2. Correlation Analysis

Pearson correlation coefficient was employed to assess relationships between climate events and infrastructure failures (Kakoudakis et al., 2018). The correlation coefficient (r) was calculated using Equation (3), where Z_i and Y_i represent paired observations of climate events and infrastructure metrics, while $\overline{Z}$ and $\overline{Y}$ represent their respective means:

$$r = \frac{\sum_{i=1}^{n}\left(Z_i - \overline{Z}\right)\left(Y_i - \overline{Y}\right)}{\sqrt{\sum_{i=1}^{n}\left(Z_i - \overline{Z}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}} \tag{3}$$

This analysis quantified the strength and direction of the relationship between climate events and pipe failures, supply interruptions, and economic losses. Statistical significance was determined using t-tests for correlation coefficients, with significance thresholds established at $p < 0.05$ and $p < 0.01$. This enabled determining whether observed correlations represented genuine relationships or could reasonably be attributed to random variation (Taiwo et al., 2024, 2025).

3.2.3. Multiple Regression Analysis

A multiple linear regression model was applied to quantify the influence of extreme weather events on infrastructure failures. The general form of the model, as shown in Equation (4), expresses infrastructure failures Y as a function of flood incidents X_1 and drought incidents X_2:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \varepsilon \tag{4}$$

Here, Y denotes the number of pipe failures per 100 km per year, β_0 is the intercept, β_1 and β_2 are the regression coefficients, and ε is the error term. A second model of identical form was developed to estimate annual economic loss as a function of climate exposure and infrastructure vulnerability. While robust, this approach does not capture indirect or long-term costs such as health impacts, environmental damages or business losses, which means estimates likely understate the actual economic burden. Model parameters were estimated using ordinary least squares estimation, as expressed in Equation (5), where $\hat{\beta}$ is the vector of estimated coefficients, X is the matrix of independent variables, and Y is the dependent variable vector:

$$\hat{\beta} = \left(X^T X\right)^{-1} X^T Y \tag{5}$$

Model performance was evaluated using the coefficient of determination (R^2) and tested for multicollinearity, residual normality, and homoscedasticity using standard diagnostic plots. Multicollinearity was assessed using the variance inflation factor, with values below 5 indicating acceptable levels. Residuals were tested for autocorrelation using the Durbin–Watson statistic, normality using the Shapiro–Wilk test, and homoscedasticity using the Breusch–Pagan test. Where necessary, corrective measures such as variable transformation were considered.

3.2.4. ARIMA Time-Series Forecasting

An ARIMA model was employed to forecast future trends in pipe failures over 20 years (2024–2044). The ARIMA model, represented in Equation (6), captures both short-term autocorrelation structures and long-term trends (Box et al., 2015):

$$\varnothing(B)(1 - B)^d X_t = \theta(B)_{\varepsilon_t} \tag{6}$$

where

$$\varnothing(B) = 1 - \varnothing_1 B - \varnothing_2 B^2 - \cdots - \varnothing_P B^P$$
$$\theta(B) = 1 + \theta_1 B + \theta_2 B^2 + \cdots + \theta_q B^q$$

where B is the backshift operator ($BX_t = X_{t-1}$), $\varnothing(B)$ is the autoregressive polynomial of order p, $(1 - B)^d$ denotes differencing of order d to achieve stationarity, and $\theta(B)$ is the moving average polynomial of order q. ε_t is white noise with zero mean and constant variance σ^2:

Model identification followed the Box–Jenkins methodology, which involved assessing autocorrelation and partial autocorrelation plots to determine the orders p, d, and q. Stationarity of the series was confirmed through the Augmented Dickey–Fuller test. The Ljung–Box test was applied to verify the absence of autocorrelation in residuals, while normality was assessed using the Shapiro–Wilk test. Model selection was guided by minimising the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC). Forecasts were generated with 95% confidence intervals using Equation (7), where $\hat{Y}_{t+h}$ is the point forecast for the time series at $t+h$ and $\hat{V}_{t+h}$ is the forecast error variance:

$$CI_{t+h} = \hat{Y}_{t+h} \pm 1.96 \times \sqrt{\hat{V}_{t+h}} \quad (7)$$

This approach explicitly accounts for both parameter and innovation uncertainties, providing realistic bounds for future infrastructure failure projections under continuing climate variability.

4. Results

4.1. Descriptive Statistics

The descriptive statistics in Table 1 summarise climate events and infrastructure performance metrics from 1980 to 2023. These results reflect significant variability in climate and infrastructure performance over time, with evidence of a clear upward trend in failures and water loss. Annual flood ranged from 9 to 22 incidents (mean = 15.4, SD = 3.2), while drought incidents varied between 4 and 13 (mean = 8.7, SD = 2.8). The rate of pipe failures ranged from 85 to 180 per 100 km annually (mean = 125, SD = 24), with supply interruptions between 65 and 140 events per year (mean = 98, SD = 18). Economic losses ranged from USD 1.1 million to USD 4.2 million per year, with a mean of USD 2.4 million (SD = 0.9).

Table 1. Descriptive statistics of climate events and infrastructure failures (1980–2023).

Variable	Mean	SD	Min	Max
Flood Events	15.4	3.2	9	22
Drought Events	8.7	2.8	4	13
Total Pipe Failures/100 km	125	24	85	180
Supply Interruptions	98	18	65	140
Economic Loss (Million USD/year)	2.4	0.9	1.1	4.2

These statistics provide the baseline for assessing relationships between extreme weather events and infrastructure performance.

4.2. Correlation Analysis

Pearson correlation coefficients were calculated to highlight the relationship between climate events (floods and droughts), infrastructure failures, and economic loss. Table 2 shows these associations.

The results show strong positive correlations, all statistically significant ($p < 0.05$ or $p < 0.01$). The strongest correlation exists between flood incidents and economic losses ($r = 0.81$, $p < 0.01$), indicating that flooding events have substantial financial implications. While these results demonstrate strong statistical associations, they do not establish causality. Factors such as ageing infrastructure and governance quality may also influence

Table 2. Correlation between weather events and infrastructure failures.

Variable	Pipe Failures	Supply Interruptions	Economic Loss
Flood Incidents	0.78 ($p < 0.01$)	0.72 ($p < 0.01$)	0.81 ($p < 0.01$)
Drought Incidents	0.64 ($p < 0.05$)	0.69 ($p < 0.01$)	0.74 ($p < 0.01$)

failure rates and economic losses. The relationship between floods and pipe failures is similarly robust ($r = 0.78$, $p < 0.01$), suggesting that flooding significantly increases the likelihood of physical infrastructure breakdowns. Supply interruptions show slightly lower, though still strong, correlations with both flood ($r = 0.72$, $p < 0.01$) and drought incidents ($r = 0.69$, $p < 0.01$), reflecting the dual impact of both extreme weather types on service continuity.

Drought incidents demonstrate consistently positive correlations with all infrastructure performance metrics, though generally at slightly lower magnitudes than flood correlations. The strongest drought-related correlation is with economic losses ($r = 0.74$, $p < 0.01$), highlighting the significant financial impact of water scarcity. While still significant, the correlation between droughts and pipe failures ($r = 0.64$, $p < 0.05$) is the lowest among the examined relationships, suggesting that flooding events may have more immediate and pronounced effects on physical infrastructure integrity than drought conditions. These results indicate that floods and droughts exert measurable and statistically significant pressure on urban water distribution and drainage systems, although the nature and magnitude of impacts differ.

4.3. Multiple Regression Analysis

Regression analysis allowed us to estimate how much additional pipe failure is expected for each extra drought or flood event. At the same time, ARIMA forecasting projected these failures into the future under current climate trends.

The multiple regression analysis quantified the relationship between climate variability (floods and droughts) and pipe failures from 1980 to 2023. The regression model estimating pipe failures as a function of flood and drought incidents produced Equation (8) as formulated in Equation (4), where Y represents the predicted number of pipe failures per 100 km, X_1 is the number of annual flood incidents, and X_2 represents drought incidents:

$$Y = 72.63 + 4.21(X_1) + 6.19(X_2) \tag{8}$$

The intercept (72.63) represents the expected baseline number of pipe failures with no recorded flood or drought incidents. The coefficient for flood incidents (4.21) shows that each additional flood event is associated with approximately 4.21 additional pipe failures, holding drought incidents constant. Similarly, the coefficient for drought incidents (6.19) indicates that each additional drought event corresponds to approximately 6.19 additional pipe failures, holding flood incidents constant. The model achieved a coefficient of determination (R^2) of 0.86, indicating that floods and droughts together explain 86% of the variance in pipe failures during the study period. Both predictors were statistically significant ($p < 0.01$), confirming their strong contribution to infrastructure failures. Notably, the coefficient for drought incidents (6.19) is about 47% higher than for floods (4.21), suggesting droughts may impose greater stress on urban water systems than flooding.

4.4. ARIMA Forecasting

The ARIMA model analysis identified ARIMA (1,1,1) as the optimal specification for modelling pipe failures based on minimum AIC and BIC values compared to alternative specifications. This model incorporates a first-order autoregressive term, first-order differencing for stationarity, and a first-order moving average component. The fitted ARIMA (1,1,1) model demonstrated good historical fit with the data from 1980 to 2023. Residual diagnostics confirmed model adequacy, with the Ljung-Box test showing no significant autocorrelation in residuals ($p > 0.05$) and the Shapiro-Wilk test confirming approximate normality of residuals ($p > 0.05$). These diagnostic results validate the statistical appropriateness of the selected model for the pipe failure data. The 20-year forecast (2024–2044) suggests a steady increase in pipe failures of approximately 4.5 failures per 100 km per year. The 95% confidence intervals widen progressively with the forecast horizon, reflecting the increasing uncertainty inherent in long-term projections. This expanding uncertainty is a natural characteristic of time series forecasting, where prediction accuracy diminishes as the forecast extends further into the future, as shown in Figure 1.

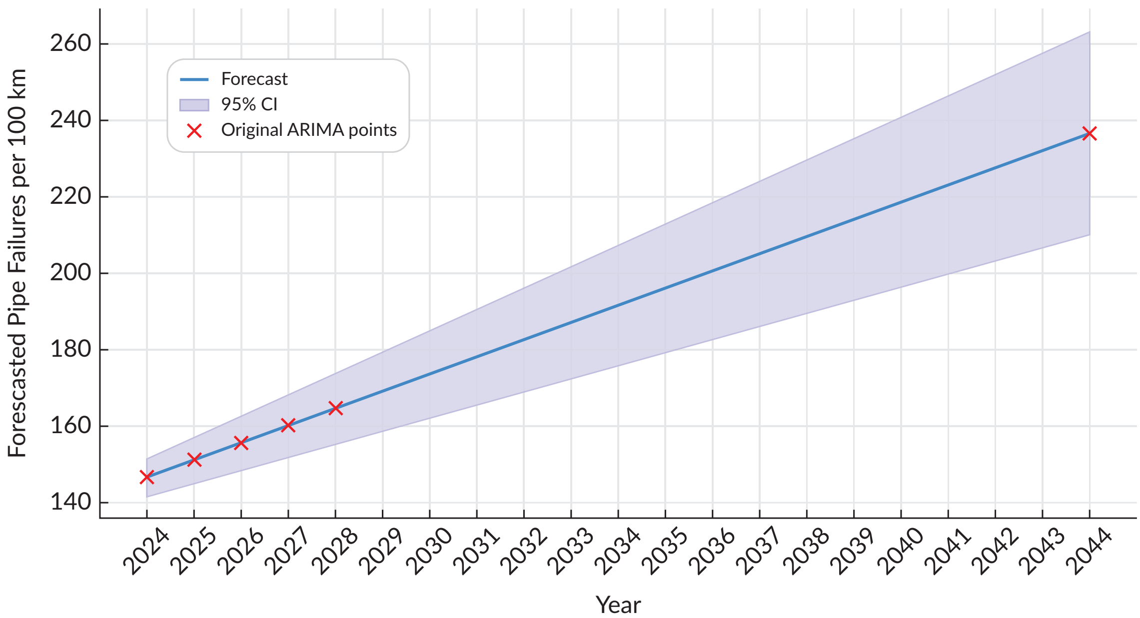

Figure 1. ARIMA (1,1,1) forecast of annual pipe failures per 100 km (2024–2044).

The projected upward trend underscores the increasing vulnerability of the existing water distribution network under current climate variability trajectories. If no adaptive interventions are implemented, the frequency and severity of failures are expected to rise significantly, with corresponding increases in economic losses and service disruptions.

5. Discussion

The findings of this study provide strong empirical evidence that climate variability manifested through floods and droughts has a measurable and statistically significant effect on the performance of urban water distribution and drainage infrastructure in South Africa. The correlation analysis demonstrated that flood incidents have the strongest relationship with economic losses ($r = 0.81$) and pipe failures ($r = 0.78$), while droughts, although less immediately destructive, were shown through regression analysis to have a 47% greater impact on pipe failures than flooding events (regression coefficients 6.19 vs. 4.21). The ARIMA forecast indicates that, without intervention, annual pipe failures will continue to increase by approximately 4.5 failures per 100 km per year over the next two decades. These results confirm that sudden-onset and prolonged climate events can undermine infrastructure resilience, though they operate through different mechanisms and require tailored adaptation strategies.

5.1. Climate Variability and Infrastructure Resilience

The strong correlations between climate events and infrastructure failures (flood-pipe failure $r = 0.78$; drought-pipe failure $r = 0.64$) demonstrate the vulnerability of current water systems to climate variability. More significantly, the regression analysis reveals that drought incidents have a 47% greater impact on pipe failures than flood events (regression coefficients 6.19 vs. 4.21), challenging the common assumption that flooding poses the primary threat to urban water distribution and drainage infrastructure. These include pluvial flooding, riverine overflow, and in some instances, minor coastal storm surges. This study excludes coastal storm surges and sea-level rise-related flooding, focusing exclusively on inland flood hazards. These findings align with ecological and engineering resilience frameworks (Sinha et al., 2023). The time-series forecasting, which projects an annual increase of 4.5 pipe failures, on average, over the next two decades, indicates that current infrastructure lacks sufficient engineering resilience to withstand increasing climate pressures. The correlation analysis (drought-economic loss $r = 0.74$) suggests that water systems lack the adaptive capacity necessary for ecological resilience, particularly during prolonged drought conditions. The combination of high R-squared values (0.86) in the regression model and consistent upward trends in the ARIMA projections underscores the urgent need for interventions that enhance both dimensions of resilience. Without such measures, the forecast indicates infrastructure failures will continue to increase, threatening water security for millions.

5.2. Infrastructure-Specific Adaptation Strategies

For distribution networks, the regression results indicate that each additional drought event is associated with approximately 6.19 more pipe failures per 100 km. Targeted material upgrades from traditional metal and concrete to high-density polyethene or ductile iron could reduce vulnerability to soil movement and stress fractures (Mehvar et al., 2021). Though not the primary focus of the modelling, treatment facilities are indirectly implicated in resilience planning. The correlation between drought incidents and supply interruptions ($r = 0.69$) indicates that reduced raw water availability can limit treatment capacity, a phenomenon well-documented in other semi-arid regions (Al-Saidi & Elagib, 2017; Radcliffe, 2015). Decentralised treatment solutions such as neighbourhood-scale recycling and dual reticulation systems can mitigate these effects by diversifying sources and distributing operational risks. Stormwater and drainage systems face particular challenges under intensified precipitation events. The correlation analysis revealed that floods have strong relationships with pipe failures and economic losses, consistent with evidence that drainage systems designed for historical rainfall intensities often fail under current climate extremes (Depietri & McPhearson, 2017; Nhamo et al., 2025). Failure in drainage infrastructure can lead to cascading disruptions across the water network, including backflow contamination and treatment plant overloads (Ferdowsi et al., 2024). Integrating nature-based solutions such as bioswales, permeable pavements, and constructed wetlands can reduce peak hydraulic loads while delivering ecological co-benefits. Copenhagen's post-flood blue–green infrastructure initiative is a case in point, achieving reductions in flood-related pipe failures while enhancing urban biodiversity (Depietri & McPhearson, 2017).

5.3. Balancing Prevention, Adaptation, and Acceptance

The statistical evidence from this study suggests that neither prevention nor adaptation alone is sufficient to address the dual challenges posed by floods and droughts. Adaptive strategies that improve flexibility, redundancy, and responsiveness must complement engineering-focused prevention measures such as infrastructure hardening. At the same time, strategic acceptance of certain risks may be the most cost-effective option for non-critical infrastructure components, provided robust contingency and emergency response plans are in place (Bani et al., 2024). Given the average annual economic loss of USD 2.4 million identified in this study, cost–benefit analyses should prioritise interventions where the potential for avoided damage is most significant. For example, replacing high-risk pipeline segments in flood-prone and drought-affected areas can yield outsized benefits relative to investment costs. Similarly, diversifying water sources and enhancing localised treatment capacity can reduce dependency on vulnerable centralised infrastructure during climate extremes.

5.4. Governance and Community Engagement

Resilience planning is as much a governance challenge as an engineering one. The significant correlation between flood events and economic losses ($r = 0.81$) reflects physical vulnerability and institutional readiness. Adaptive governance structures that can mobilise resources rapidly and integrate new data into decision-making are essential for managing the evolving risks identified by this study (Akamani, 2023; Bani et al., 2024). Community engagement is also critical. Participatory planning approaches can reveal localised vulnerabilities and adaptation opportunities that may be overlooked in purely technical assessments. As demonstrated in post-flood resilience planning efforts, incorporating community knowledge into project design can enhance both legitimacy and effectiveness (McEwen & Jones, 2012). In South Africa, where service delivery protests often signal dissatisfaction with infrastructure performance, early and meaningful stakeholder involvement can help align adaptation investments with community priorities, improving both uptake and sustainability of resilience measures.

6. Conclusion

This study examined the relationship between climate variability and the resilience of urban water distribution and drainage infrastructure in South Africa by integrating 43 years of climatic and infrastructure performance data into correlation, multiple regression, and ARIMA time-series forecasting analyses. The results provide clear empirical evidence that floods and droughts exert significant pressure on water infrastructure, though their impacts differ in magnitude and mechanism. Flood incidents were found to have the strongest association with economic losses and acute infrastructure failures. In contrast, drought events, while less immediate in their damage, exerted a 47% greater influence on pipe failures than flooding. The regression model's explanatory power ($R^2 = 0.86$) and the ARIMA projection of an average increase of 4.5 pipe failures per 100 km per year over the next two decades underscore the urgency of proactive resilience planning. Without targeted interventions, the vulnerability of South Africa's water distribution network is likely to increase, resulting in escalating service disruptions and economic losses. This study offers infrastructure managers and policymakers actionable insights by grounding resilience strategies in empirical evidence. The findings highlight the need for targeted material upgrades in drought-prone areas, decentralised treatment systems to reduce supply interruption risks, and nature-based stormwater solutions to alleviate hydraulic stress during floods. Balancing prevention, adaptation, and strategic acceptance guided by cost-benefit considerations emerges as a pragmatic approach to enhancing resilience.

Beyond its practical recommendations, the study contributes to the broader resilience literature by demonstrating that empirical, long-term, climate-linked infrastructure performance data can and should inform adaptation planning. This integrated analytical framework, combining engineering and ecological resilience perspectives with statistical modelling, offers a replicable methodology for other regions facing similar climate pressures. Future research should expand the scope to explore mechanisms linking drought stress to pipeline failures in greater detail and assess the long-term cost-effectiveness of specific adaptation measures in diverse socio-climatic contexts. Strengthening the evidence base in these areas will be critical for building urban water systems capable of withstanding the accelerating challenges of climate change. Further, while this study focused on inland flood and drought hazards, coastal storm surges and sea-level rise pose increasingly urgent risks for cities such as Durban and Cape Town. Future studies should integrate these compound risks to provide a comprehensive national resilience assessment. Addressing inland and coastal challenges will be critical for safeguarding South Africa's water infrastructure under climate change.

Conflict of Interests

The author declares no conflict of interests.

Data Availability

Data will be made available on request.

LLMs Disclosure

To prepare this work, the author used ChatGPT 4.0 and Grammarly tools strictly for grammar and editing purposes.

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About the Author

Joy Tuoyo Adu is a senior lecturer and researcher in the Discipline of Civil Engineering at the University of KwaZulu-Natal, Durban, South Africa. She is dedicated to advancing water sustainability through research and evidence-based practice.