

ORIGINAL RESEARCH ARTICLE

Mitigating the impacts of climate change: A case study of the city of Tshwane, South Africa

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Abstract: Climate change poses a major global challenge which affects human health and livelihood, ecosystem, critical sectors and infrastructure among others. The objective of this research is to investigate and mitigate the impacts of climate change in the City of Tshwane. A combination of quantitative and case study approaches was employed, with datasets obtained from the South African Weather Service, the City of Tshwane, and the Auditor-General. The data were modeled using a combination of discrete event simulation and system dynamics within the AnyLogic (version 8.2.3) environment. The results showed an increase in climate trends from 1981 to 2022, suggesting a growing frequency of heat waves, heavier rainfall, and more frequent floods, among other phenomena. The study recommends the use of simulation approaches to assess the impacts of climate change on the city's infrastructure during the planning process. The findings can assist the City of Tshwane in planning for future climate scenarios, enabling stakeholders to develop sustainable strategies for climate change adaptation and mitigation, with the goal of creating a climate change-resilient city. If the suggested climate change policies are implemented, there would be a 15% annual decrease in extreme events (including excessive temperature, flooding, and drought), a 3% reduction in greenhouse gas emissions, and a 25% decrease in gross domestic product loss, alongside a 15% improvement in infrastructure performance.

Keywords: Adaptation; Climate change; Infrastructure; Simulation

1. Introduction

Climate change refers to changes in the average temperature and weather patterns of a region or the

planet over time. The City of Tshwane recognizes climate change as a significant challenge, as failure to address its impacts over the years could have severe consequences.¹ Roads and stormwater infrastructures are

important for economic development, as they facilitate access to markets, local communities, and opportunities in South Africa. The impacts of climate change have an influence on the specifications for designing road and stormwater infrastructure. In the City of Tshwane, the service life of road and stormwater infrastructure is diminishing, and a large proportion of the City's budget is allocated to maintenance caused by climate change. The City of Tshwane Metropolitan Municipality was established on December 5, 2000, by merging several municipalities and councils that were previously part of the Pretoria regime and its surrounding areas.²

Infrastructure such as roads and drainage systems are essential elements of a reliable, effective, and functional transport system; without them, the economy cannot function. These infrastructures also impact public health, the economy, and disaster management policies. However, roads and stormwater infrastructure are simultaneously exposed to climate change and, in some cases, contribute to it. For example, construction activities in the road sector involve energy-intensive materials, such as bitumen (derived from fossil fuels), which contribute to carbon emissions.

The widespread flooding in South Africa in February 2023 resulted in the pronouncement of a national state of disaster in line with the Disaster Management Act. This followed significant flooding that affected homes, caused dam overflows, and damaged road infrastructure across the country.³ The adverse effects of climate change in South Africa have resulted in considerable loss of life, damage to livelihoods, and a decline in the gross domestic product (GDP).^{4,5}

There is growing concern about the vulnerability of infrastructure due to previous occurrences and the predicted increase in extreme weather events.⁶⁻⁸ As a result, developing a flexible physical network solution is still challenging for engineers and designers.⁹ Therefore, a modeling and simulation approach may be helpful in assessing the impacts of climate change in South Africa and exploring possible mitigation strategies.

Schweikert *et al.*¹⁰ investigated the effect of climate change on road infrastructure in South Africa using a stressor-response approach. The study projected that the cost incurred due to climate change may range between 116.8 and 228.7 million United States dollars (USD) in the 2050s if no adaptation policy measures are implemented. However, with the implementation of adaptation policies, these costs could be reduced to 55.7 million USD. The policies include the construction of modern roads with secondary pavements. Dube and Nhamo,¹¹ whose findings align with those of Anekwe

et al.,¹² identified a declining temperature trend in South Africa. Employing a mixed-methods research design, they investigated the impacts of climate change on the Kruger National Park in South Africa and found high inter-annual variability in rainfall, with an overall decreasing trend. This variability has led to increased costs related to environmental and wildlife management, as well as government expenditures. They also reported significant losses of flora and fauna and damage to key infrastructure within the park, attributing these impacts to climate-related events, such as floods, droughts, and extreme weather, highlighting the need for the development of adaptation measures. Chersich and Wright¹³ investigated the impacts of climate change on the health sector in South Africa through a systematic literature review and found that, although various climate change policy frameworks exist in the country, only a few address the impacts of climate change on the health sector. The review also reported that while the country has established systems for forecasting extreme weather events, there is little evidence of adaptation measures. Botai *et al.*¹⁴ examined the spatial-temporal variability of precipitation patterns in South Africa using satellite precipitation data from 1998 to 2015. The study indicated significant variation in precipitation across the country. For instance, the precipitation distribution was found to be uniform in the southern and central parts of South Africa, while the western and northeastern parts showed extreme irregularity. Between December to February, precipitation distribution was more uniform, while it was moderate between September and November, with extreme irregularity observed between June and August. The study by Jovanovic *et al.*¹⁵ on evapotranspiration in South Africa revealed a slight reduction in evapotranspiration rates in South Africa from 2000 to 2012 in all climatic regions, except in the southern part of the country. This outcome corroborates Botai *et al.*'s¹⁴ conclusion that the southern part of the country continues to experience more regular climatic conditions. Ndlovu and Demlie¹⁶ investigated drought and rainfall patterns across the KwaZulu-Natal (KZN) province of South Africa over a period of 48 years (1970 – 2017). It was found that the frequency of drought is increasing, with rainfall frequency decreasing.

However, the results obtained by Orimoloye *et al.*,¹⁷ who assessed drought conditions in South Africa using Terra MOD13Q1 data from the satellite in the Free State province, indicated that drought is less prevalent during the winter season but more severe in the summer in this region.

Climate change has significant negative impacts on the transport sector, especially road infrastructure,

exposing people to various risks. Some studies indicate that inadequate drainage systems are one of the major causes of the destruction of road and stormwater infrastructure.^{18,19} Nevertheless, climate change also contributes significantly to the destruction of road and stormwater infrastructure, leading to increased rainfall intensity, flooding, and loss of ecosystems and biodiversity. The impact of climate change further extends to the destruction of runoff that reaches roads and drainage systems, thereby causing flooding of highways.¹⁸ Another area of concern is the scarcity of water resources due to climate change and poor management.²⁰ Anekwe *et al.*¹² investigated the impacts of climate change variability on water resources in the Jozini municipality, South Africa, using conventional and machine learning approaches on precipitation and temperature datasets. The results indicated that variations in rainfall and temperature have serious consequences on water levels in the dam, negatively affecting water availability in the municipality. These findings may assist stakeholders in formulating and implementing policies to promote water availability, particularly in the construction of modern dams.

Ray²¹ stated that climate change negatively affects Africa's economies, leading to a decline in GDP, loss of business and livelihoods, and increased investment in the repair of damaged infrastructure and the development of countermeasures.

The costs associated with infrastructure repair and recovery from heavy rainfall in Cape Town in 2011 exceeded rand (R) 20 million.⁴ In 2022, the flooding in KZN resulted in the loss of 440 lives and the destruction of road infrastructure worth R5.6 billion.⁵ Comins⁵ noted that KZN would lose 1.8% of its annual GDP due to the flooding. Existing studies highlight the need for integrated climate impact modeling, as it allows for a detailed understanding of the interactions between climate change, human life, the physical environment, and socio-economic activities. These models also suggest possible adaptation and mitigation approaches that could help policymakers reduce risks and vulnerabilities.^{22,23} Ciscar and Dowling²⁴ emphasized that existing integrated climate impact models have been implemented in only a few countries to capture a limited scope of climate change impacts, underscoring the need for empirical studies on the application of these models, especially in developing economies with increasing energy demands. Ciscar and Dowling²⁴ further pointed out that the effects of extreme weather events, such as floods, require more attention and the use of different modeling techniques to capture their impacts.

The use of system dynamics (SD) modeling for climate change simulations has also been reported. For example, Gohari *et al.*²⁵ employed the SD simulation technique to assess climate change adaptation strategies for water conservation in Iran. The study found that improvements in infrastructure, effective water management, and regulation of the ecosystem could reduce water stress in the country. Existing studies have also applied the SD technique to investigate the impacts of climate change on water resource systems and to model complex systems.²⁶⁻²⁹

Unlike the singular SD technique employed in previous studies,²⁵⁻²⁹ the present research goes beyond using a single approach and demonstrates the applicability of an integrated modeling and simulation approach for investigating the impacts of climate change. This represents advancement in methodological approaches by enabling time- and cost-effective modeling and simulation of complex phenomena, such as the impact of climate change, which can facilitate better policy formulation and informed decision-making.

However, the combination of the discrete event simulation (DES) and SD to investigate climate change impacts has not been sufficiently reported in existing literature. Thus, the novelty of this study lies in its use of an integrated DES and SD approach to model and simulate climate change activities and mitigation strategies in South Africa (specifically the City of Tshwane) over the next 10 years. The findings of this study can assist the City of Tshwane in planning for future climate scenarios and enable stakeholders to develop sustainable means of climate change adaptation or mitigation in the pursuit of a climate-resilient city.

Although some studies have been conducted on the effects of climate change in South Africa, the investigation of its impacts using modeling and simulation approaches has not been sufficiently discussed. Thus, the objectives of this study are to investigate and mitigate the effects of climate change in South Africa, using the City of Tshwane as a case study, and to examine the impacts of climate change policy frameworks on the city's infrastructure management.

The following research questions underpin this study: (i) What are the potential climate change risks and possible mitigation strategies? (ii) What are the effects of climate change policy implementation on the city's infrastructure management? (iii) How can the impacts of climate change on roads and stormwater infrastructure in South Africa be effectively mitigated?

This research contributes to a better understanding of the impacts of climate change on roads and stormwater

infrastructure in South Africa infrastructure and offers insights into how to effectively mitigate these effects.

2. Methodology

2.1. Research design

The study is exploratory, quantitative, and descriptive in nature, aimed at gaining a deeper understanding of a persistent phenomenon. Climate change is considered a persistent challenge, and the exploratory aspect seeks to answer questions, address phenomena, or identify general principles to explain the phenomenon, utilizing the inductive method. In exploratory research, primary or secondary data are collected and organized for synthesis.³⁰ In this study, secondary data were collected and analyzed.

The quantitative method was employed because it allows for the representation of measured variables numerically in terms of amount, quantity, frequency, or rate. These variables' associations with other factors can be determined via systematic measurement and statistical analysis.^{31,32}

Figure 1 shows the research methodology of the study and the steps followed during the research, summarizing the approach employed in the study. As discussed in the literature section, variables such as the amount of rainfall, GDP, greenhouse gas (GHG) emissions, extreme events, and infrastructure performance are related to climate change. Therefore, secondary quantitative data on these variables were collected and compared using regression graphs, Microsoft Excel, and AnyLogic software to answer the research questions.

The methods applied in this study quantified and analyzed variables to obtain results. These include:

- (i) Inductive reasoning: Collection and analysis of historical data (temperature and rainfall) to identify trends related to climate change impacts and to draw conclusions.
- (ii) Data collection: Historical quantitative datasets on rainfall, temperature, and capital expenditure on infrastructure in the City of Tshwane were obtained from the South African Weather Service (SAWS) and the City of Tshwane.

(iii) Data analysis: The datasets were analyzed using charts and pie charts to visualize the trends in temperature, rainfall, and the cost implications of climate change. In addition, the analysis explored how the absence of adaptation would impact the economy.

(iv) Modeling and simulation: A combination of DES and SD was employed to model and simulate the effects of variables classified as extreme events (such as GHG emissions, extreme temperatures, drought, rainfall, and flooding) on the city's road and stormwater infrastructure and GDP performance. These extreme events are considered the effects of climate change. The goal of the modeling and simulation was to ascertain the effects of these extreme events on the city's infrastructure and economic activities (reflected in the GDP) to facilitate appropriate policy recommendations for effective climate change mitigation and adaptation. Finally, conclusions were drawn, and recommendations were made to support climate change mitigation and adaptation efforts.

Figure 2 illustrates the conceptual framework, linking the key variables derived from the literature related to climate change. These variables include the amount of rainfall, GDP, the greenhouse effect, extreme events, and infrastructure performance. The major threats are the greenhouse effect and extreme events, such as rainfall, flooding, drought, and extreme temperatures.

2.2. Case study

For the purpose of this study, a case study was employed to gain an in-depth understanding of the complex issue of climate change impacts. Existing studies indicate the suitability of the case study approach for investigating multifaceted and complex issues, making it extensively applicable across different fields.^{33,34} This approach allows researchers to explore and understand intricate issues by analyzing past reports or studies. It is considered a suitable research method, especially when a holistic, in-depth investigation is conducted. The case study method transcends quantitative statistical results

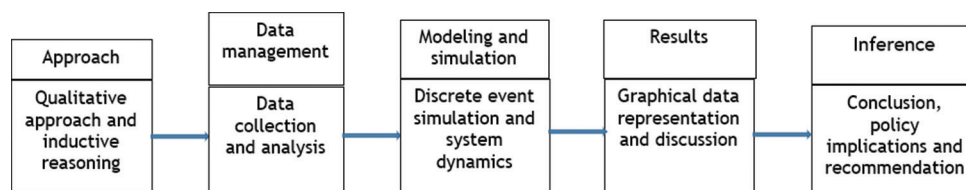


Figure 1. A comprehensive guide to the quantitative research methodology employed in this study

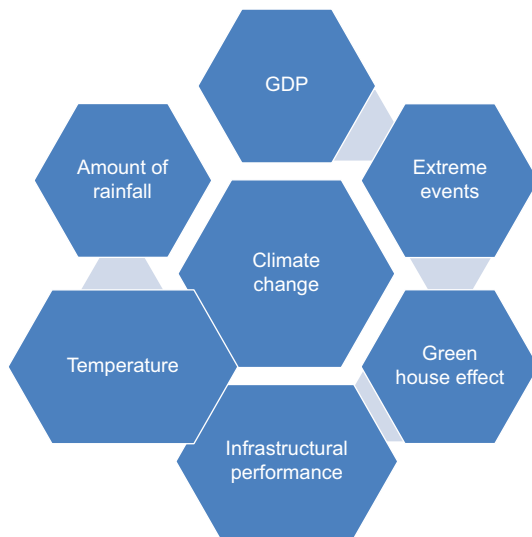


Figure 2. A conceptual framework linking the key variables derived from the literature

Abbreviation: GDP: Gross domestic product.

to provide insights that aid in understanding behavioral patterns from the perspective of the actors involved.³⁴⁻³⁶ The City of Tshwane was chosen as the case study for this research. In this case study, the researchers examined the impact of climate change on the City's roads and stormwater infrastructure, and the findings were analyzed accordingly.

The study specifically investigated climate change events in the City of Tshwane, including the Mamelodi floods and Centurion floods.

At the beginning of the research, several observations were made, and field trips were conducted to assess the flood damage and the broader effects of climate change. Although the case study is limited to the City of Tshwane, it is important to note that areas outside the city also experience different climatic conditions.

2.3. The City of Tshwane context

The city is located at 25° 40'S, 28° 20'E in the Gauteng province of South Africa. It covers a total area of 6,299 km² and had a population of 4,040,315 as of 2022. Tshwane's road network consists of 60 roads, which are grouped into three classes: national routes, provincial roads, and municipal roads.² The stormwater drainage system, with a flow rate of 15.93 m³/s, combines surface drainage from paved roads and underground pipe systems, with pipe sizes ranging from 1,500 mm by 1,200 mm to 1,800 mm to 1,800 mm. This system collects stormwater from the city and includes field inlets that are connected to the stormwater pipeline, which receives stormwater runoff. Outlet structures

are constructed at the end of the stormwater pipeline to prevent erosion. The climate change policy proposes an increase in the capacity of the drainage system, with pipe sizes ranging from 2,100 mm in height by 3,800 mm in width to 3,600 mm by 3,800 mm, and a flow rate of 36.0 m³/s. The city falls within the summer rainfall region of eastern South Africa, receiving an annual average rainfall of 670 mm.³⁷

Figure 3 depicts maps of South Africa, Gauteng province, and the City of Tshwane.

2.4. Description of the datasets

Data were collected from the records of the City of Tshwane,² the SAWS,³⁷ and from grey literature.

Historical data may omit important factors, which can lead to inaccurate analysis and forecasts. Moreover, such data may be subjected to bias, incompleteness, and loss of relevance over time. To overcome these limitations, the researchers gathered data from multiple sources, such as the SAWS, the City of Tshwane, and grey literature, and analyzed the various datasets. Furthermore, critical thinking and the SD simulation approach were employed to provide some future insights and projections for the data analysis.

Figure 4 presents the average rainfall of the City of Tshwane from 1981 to 2022 (42 years), showing variations in rainfall patterns.³⁷ The line representing average rainfall indicates years of heavy rainfall, as well as periods of drought. For instance, since 2015, rainfall has been above average (except for 2018), causing flooding in some areas.

Figure 5 shows the average monthly rainfall in the City of Tshwane from 1981 to 2022. The plot reveals that high rainfall typically occurs between January and March, as well as in November and December. In contrast, April and October experience moderate rainfall, while May through September generally see low rainfall.

Table 1 presents the seasonal rainfall for the City of Tshwane's temperature. The highest rainfall occurs in summer, while the lowest is observed in winter.

Figure 6 presents the average temperatures in the City of Tshwane from 1981 to 2022.³⁷ The average temperature over the 12-month period from 1981 to 2022 is 18.78°C. Temperatures are typically lower in June and July, while January and December experience higher summer temperatures. As a result, the rainfall and temperature graphs exhibit nearly identical parabolic shapes.

Table 2 presents the minimum, maximum, and average temperatures on a seasonal basis.

Mitigating climate change in city of Tshwane

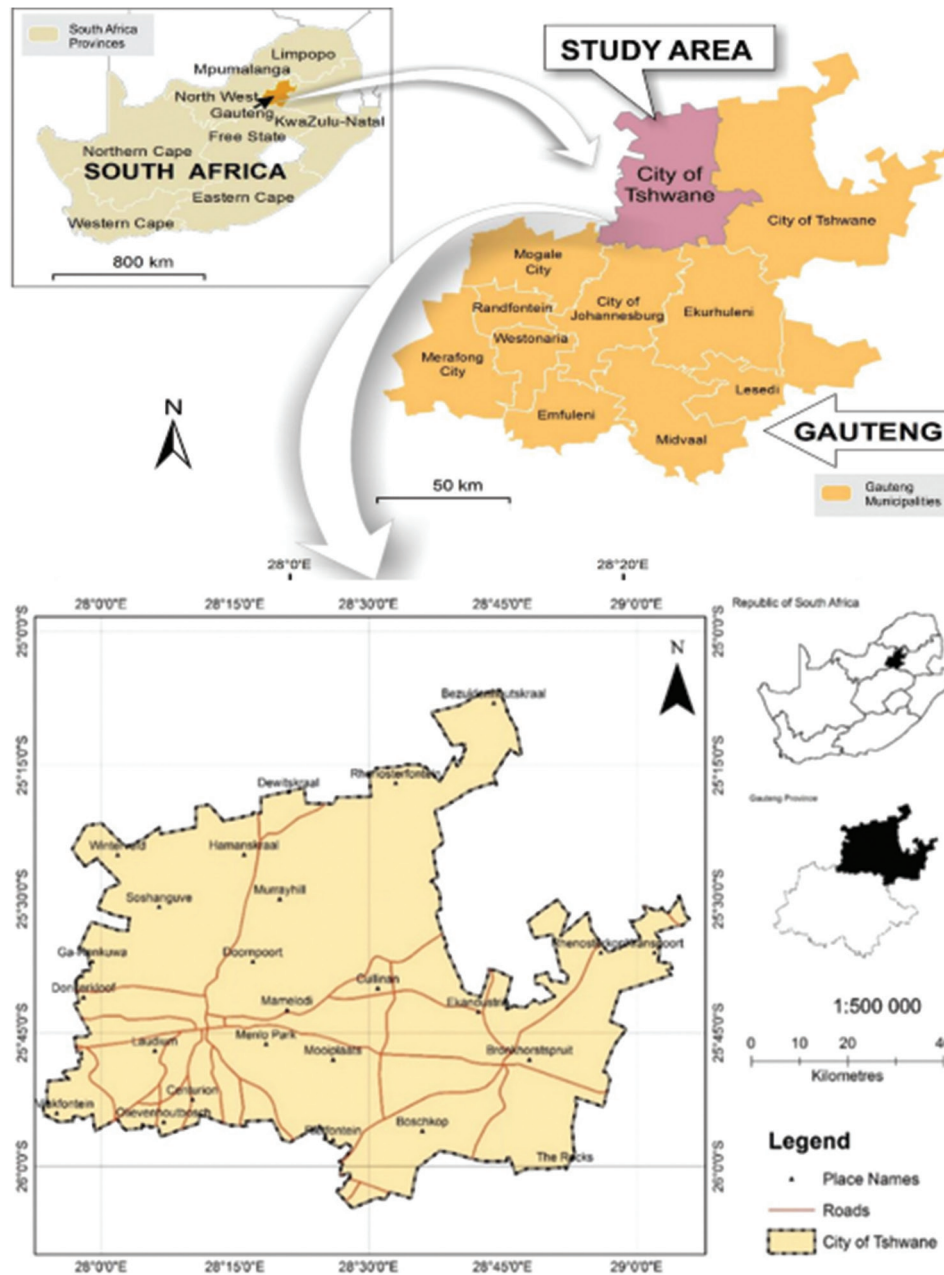


Figure 3. Maps showing South Africa, Gauteng province, and the City of Tshwane. Adapted from^{38,39}.

The average temperature from 1961 to 1990 (17.85°C) shown in Table 2 is lower than the average temperature from 1981 to 2022 (18.78°C), indicating a rising temperature trend. This increase contributes to global warming and climate change.

Datasets related to environmental variables, such as the GHG effect, the number of extreme events (including extreme temperatures, heavy rainfall, floods, and droughts), as well as the environmental variable of GDP loss, were obtained from the SAWS.³⁷ GDP loss here refers to the reduction in the total market value

of products and services produced in the city due to the effects of climate change. In South Africa, rainfall is considered normal if the total amount is <75 mm, heavy if it exceeds 75 mm, and extreme if it exceeds 115 mm in a specific area on a given day.^{40,41} A flood is considered a situation in which water overflows beyond the capacity of watercourses and drainage systems, thereby submerging dry land. The average temperatures in South Africa range from 15°C to 36°C in summer and -2°C-26°C in winter.⁴¹ According to a South African government report on geography and climate,⁴² the

country is relatively dry, with an annual average rainfall of about 464 mm, compared to the global average rainfall of 990 mm. In addition, according to Writer,⁴³ a drought in South Africa is defined as a period when an area experiences precipitation or rainfall lower than the

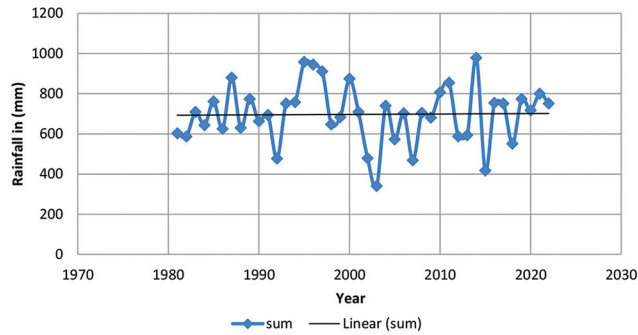


Figure 4. Average rainfall in the City of Tshwane from 1981 to 2022³⁷

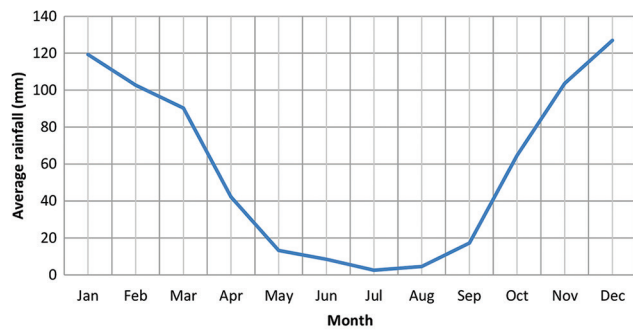


Figure 5. Average monthly rainfall in the City of Tshwane from 1981 to 2022³⁷

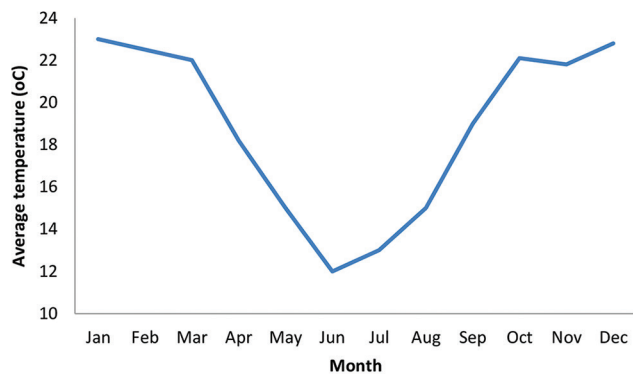


Figure 6. Average temperature variations in the City of Tshwane (from 1981 to 2022)³⁷

average, characterized by a reduction in soil moisture and groundwater levels.

2.5. Analysis, modeling, and simulation of the datasets

The data were analyzed descriptively as follows:

- (i) Creating themes such as “evaluation of bias in the dataset,” “annual rainfall in the City of Tshwane,” and “modeling and simulation of the climate change and the mitigation strategy,” and categorizing data accordingly.
- (ii) Elaborating on the meaning and significance of these themes as they relate to climate change and its effect on road and stormwater infrastructure in the City of Tshwane.
- (iii) Using graphs and plots, such as regression plots, pie charts, and simulation software, to interpret the data collected from the SAWS and the City of Tshwane on weather and climate change.
- (iv) Utilizing regression analysis to compare the relationships between variables (GHG emissions and extreme events, GHG emissions and GDP loss, rainfall, and infrastructure performance). Regression analysis employs data from two variables to make future projections. This method will allow the City of Tshwane to develop specific strategies, enabling meaningful predictions regarding extreme events, loss of GDP, infrastructure performance, heavy rainfall, and increases in GHG emissions.

The consideration of GHG emissions as a variable stems from the fact that they may contribute to temperature increases. The more GHGs are emitted, the higher the likelihood of an increase in atmospheric temperature, as the gases trap heat, leading to global warming. Furthermore, as indicated in the literature, extreme events due to climate change can disrupt lives, businesses, and livelihoods, thereby resulting in a reduction in GDP.

AnyLogic software was used in the study because it is suitable for modeling and simulating events and business applications. AnyLogic simulation models enable engineers and managers to gain deeper insights and optimize complex systems and processes across various industries.⁴⁴ The AnyLogic modeling and simulation technique allows researchers to set the

Table 1. Average seasonal and annual rainfall (mm) in the City of Tshwane from 1961 to 1990

Variable	Winter	Spring	Summer	Autumn	Average
Rainfall (mm)	13	192	325	141	671

Source: City of Tshwane².

Table 2. Seasonal and annual daily temperatures in the City of Tshwane from 1961 to 1990

Temperature (°C)	Winter	Spring	Summer	Autumn	Average
Minimum	3.9	12.5	16.1	10.7	10.80
Maximum	20.5	26.5	28.2	24.6	24.90
Average	12.2	19.5	22.2	17.6	17.85

Source: City of Tshwane².

model’s starting state and apply selected rules to simulate the evolution of the system over time.⁴⁵

A combination of SD and DES was used in this study. The SD method is best known for its high level of abstraction, requiring few details, and is typically deterministic with continuous time modeling. Its coupled first-order differential equations are solved by numerical methods. In contrast, DES focuses on systems where a sequence of operations or tasks needs to be performed.^{44,45}

The choice to combine SD and DES arose from the fact that SD offers an opportunity to precisely evaluate and model the impact of climate change on road and stormwater infrastructure. On the other hand, DES can be useful in the development and testing of new policies, as it helps understand how changes in systems (such as variation in weather conditions) can affect overall outcomes (such as the impact on road and stormwater infrastructure, as well as the proposed mitigation strategies). DES is a powerful and comprehensive paradigm capable of modeling almost any system that changes over time through events, provided these changes can be reasonably approximated within the events or important occurrences. Thus, the abstract simulation used in SD is more suited for long-term, strategic modeling and simulation.^{44,45} Hence, the combination of SD and DES was found to be suitable for investigating and representing the impact of climate change on road and stormwater infrastructure, including the proposed mitigation strategies. The integrated approach enables the simulation of climate-related events, such as temperature changes, rainfall, and GHG emissions that occur at specific times. Meanwhile, SD enables these activities to be tracked continuously over time. DES focuses on understanding the changes in the state and events, while SD tracks the activities to capture the system’s state at different points in time without any gaps.

The combined use of DES and SD modeling was carried out sequentially. DES was used to simulate the behavior of the City of Tshwane’s stormwater infrastructure, representing two scenarios (with and without policy implementation). Thereafter, the models

Table 3. Parameters of the drainage system (with and without policy implementation)

Drainage parameter	Drainage system without policy intervention	Drainage system with policy intervention
Height (mm)	-1,800	-3,600
Width (mm)	-1,800	3,800
Designed flow rate (m ³ /sec)	3	36.0

were used to predict the behavior over a 10-year period under the SD modeling framework.

The methodology focuses on the development of two drainage system models: one based on the “business-as-usual” approach (i.e., without policy implementation) and the other incorporating dynamic factors, such as forecasted changes in environmental policies. These models are compared to the present drainage network design, which relies solely on historical data. The performances of the drainage systems are evaluated by comparing their designed flow rate values to the simulated flow rate values (expressed as percentages) to determine whether the systems operate within the expected range of design values, particularly in relation to flood occurrences, as assessed by the DES. [Table 3](#) presents the parameters of the drainage system (with and without policy implementation) used for the DES.

The DES was conducted in four steps:

- (i) Observation of the system’s real dynamics. The model’s input parameters comprise the following: the rainfall dataset (derived from [Table 1](#)), the temperature dataset (derived from [Table 2](#)), and the drainage system’s parameters ([Table 3](#)). The model’s outputs include the GHG effect, GDP loss, number of extreme events, and drainage system performance. The performance of the drainage systems was evaluated by comparing their designed flow rates with the simulated values to determine the lifespan and quality of roads and stormwater in the model.
- (ii) Modeling the relationship between GDP loss and GHG emissions. The relationship between GDP

loss and GHG emissions was modeled using the equation derived from the regression graph (Equation I):

$$y = 0.0083x - 2.4587 \quad (\text{I})$$

where y represents GDP loss (%) and x represents GHG emissions (expressed in tCO₂e).

(iii) Modeling the relationship between GHG emissions (x) and temperature (t). The relationship between GHG emissions and temperature was modeled and observed using Equation II:

$$x = 0.0254t - 6.5745 \quad (\text{II})$$

where t represents temperature (°C).

(iv) SD simulation. The important moments in the system's lifecycle were considered instantaneous, indivisible events. All changes in the system were associated with these climate events. The system was observed for 10 years into the future using the SD simulation.

The SD steps are summarized into five phases:

- (i) Problem definition: This phase involves tracking climate events or activities (such as temperature, rainfall, and GHG emissions) and capturing the state of infrastructure performance and the average loss of GDP at different points in time without any gap over a period of 10 years. This phase helps to define and formulate the policies required to address the identified problem.
- (ii) Dynamics hypothesis: In this phase, a theory is formulated regarding the emergence of the problem, and a causal loop diagram is created to provide insight into the causal relationships between variables. The causal loop diagram is then converted into a level and rate (stock and flow) diagram. For example, heavy rainfall causes flooding, while extreme weather events (such as an increase in temperature) lead to an increase in the emission of GHGs.
- (iii) Formulation: This phase presents the equations that define the relationships between the variables, including the estimation of parameters and the determination of initial conditions (Table 4). The equations that define the relationships between the variables were obtained from regression analysis.
- (iv) Testing: This phase involves validating the developed model by observing its behavior and determining whether the model behavior accurately represents real systems. The model's behavior and outputs were visualized over time to ensure consistency with real-world observations.

Table 4. Equations defining the relationship between the variables

Equation	Description
$\frac{\Delta A_{it}}{A_{it}} = g_{it} + \delta_1 T_{it} + \delta_2 R_{it} + \delta_3 SPT_{it} + \delta_4 SPR_{it}$	Economic Modeling Equation
$y = 0.0083x - 2.4587$	GDP loss versus GHG emission
$x = 0.0254t - 6.5745$	GHG emission versus temperature

Abbreviations: GDP: Gross domestic product; GHG: Greenhouse gas.

- (v) Policy formulation and evaluation: In this phase, decisions are made regarding the redesign of the model or the adjustment values of parameter values to improve the performance of the system.

The DES and SD models were implemented in the AnyLogic software environment (version 8.2.3). The software employed the stock-and-flow diagram as the visual modeling language, with the input variable being the City of Tshwane's climate change policy. The model variables influenced by this policy included: (i) Average rainfall, (ii) infrastructure performance, (iii) average loss of GDP, (iv) GHG effects, and (v) the number of extreme weather events in the City of Tshwane.

The model was simulated using the policy implementation serving as a mitigation strategy. Multiple simulation runs were conducted, which resulted in improvements in GHG emissions and GDP performance. Two SD models were developed: the first, without climate change policy implementation (Figure 7), and the second, with policy implementation (Figure 8).

To assess the effect of climate change policy implementation in the SD model, the first model (Figure 7) was modified by incorporating a feedback loop and a policy parameter. This modification produced a scenario different from the one generated without the climate change policy implementation. The resulting scenario enabled an understanding of potential future conditions by evaluating simulated forecasts. The main objective of the scenario was to examine the impact of climate change policy on the performance of road and stormwater infrastructure, GHG emissions, amount of rainfall, and the number of extreme events, to effectively mitigate the impacts of climate change. The DES model advanced in increments of 0.5-time units to balance computational efficiency and simulation accuracy by

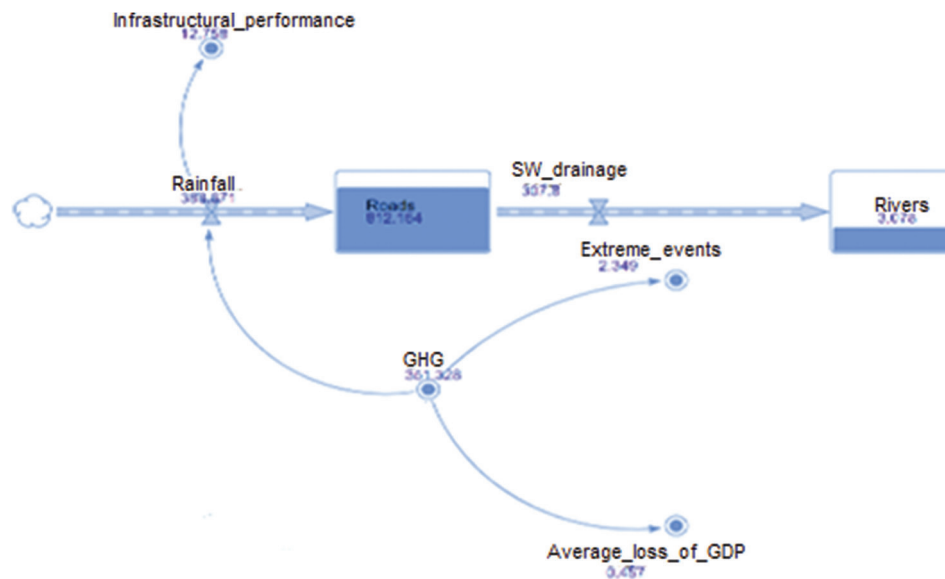


Figure 7. AnyLogic model depicting the scenario without policy implementation
 Abbreviations: GDP: Gross Domestic Product; GHG: Greenhouse gas; SW: Surface water.

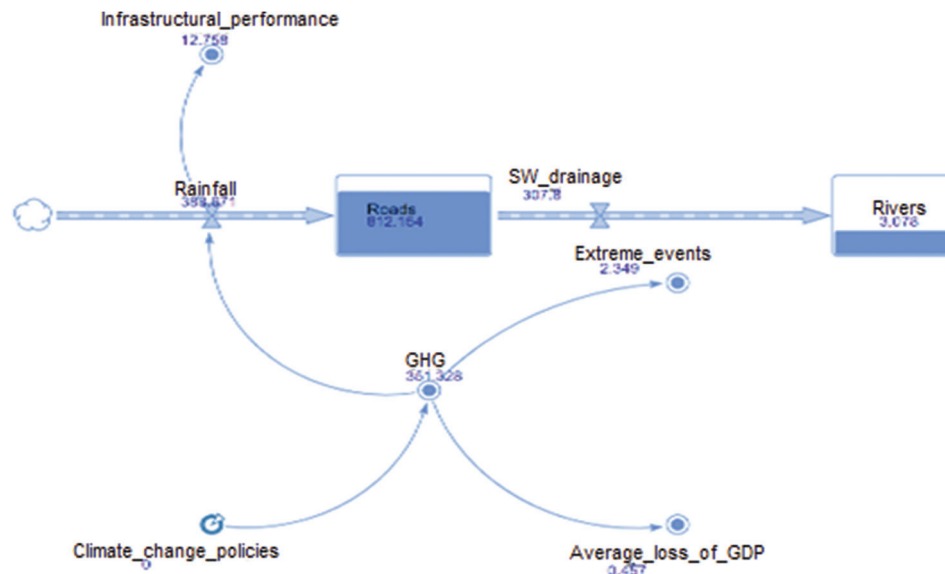


Figure 8. AnyLogic model depicting the scenario with policy implementation
 Abbreviations: GDP: Gross domestic product; GHG: Greenhouse gas; SW: Surface water.

reducing approximation errors, while the SD model ran continuously. Overall, the combined DES and SD model required a total simulation time of 5.05 minutes.

The models simulated the temporal and spatial application of the climate change policy under two scenarios: Without policy implementation (Figure 7) and with policy implementation (Figure 8).

The South African climate change policy actions, as outlined in the Climate Change Act 2024,⁴⁶ aim to coordinate and integrate climate change responses.

These actions align with the National Climate Change Response Policy, which emphasizes both adaptation and mitigation strategies over short-, medium-, and long-term horizons to support the transition to a low-carbon economy. This policy encompasses carbon taxation, smart agriculture, renewable energy initiatives, integrated resource plans, and the Just Energy Transition Partnership, among others.

The following are the assumptions underlying the DES and SD modeling and simulation:

- (i) Discrete-time: The DES assumes that time progresses in discrete steps, with events occurring at specific points in time.
- (ii) State change: The DES assumes that the system's state changes dynamically as events occur, and the system behavior is primarily driven by events.
- (iii) Stochastic behavior: The DES model also assumes that the time between events, as well as the behavior of entities and resources, are subjected to random variability.
- (iv) Aggregation: One of the assumptions in the SD model is that extreme events – including excessive temperature, flooding, and drought – are modeled as a single event or entity. This approach reduces the complexity of the model and reflects the interrelated nature of these variables. For instance, temperature can influence precipitation patterns, leading to either heavy rainfall (and flooding) or drought. High temperatures may increase the rate of evaporation, causing dry conditions and droughts, while also increasing the amount of atmospheric water vapor, which can intensify precipitation and lead to heavy rainfall and flooding. Given this cause-effect relationship between temperature, heavy rainfall, flooding, and drought, these variables were aggregated and modeled as a single event or entity.
- (v) Continuous time: The SD assumes a continuous progression of time, representing modeling system changes as ongoing processes over time.
- (vi) Closed system: The SD model is treated as a closed system, meaning that no external factors influence

the system's behavior unless they are explicitly included in the model.

3. Results and discussion

3.1. Evaluation of bias in datasets

Harman's one-factor test was conducted to evaluate the presence of common bias. For the climate change dataset, the total variance extracted was 6.253, with the corresponding sum of squares accounting for 31.835% of the variance. Similarly, the financial dataset showed a total extraction of 6.850 and a sum of squares of 34.122%.

According to the rule of thumb, if the total variance extracted by one factor exceeds 50%, common method bias may be present. In this study, there is no evidence of such bias for both the rainfall and temperature datasets, as the total variance explained by one factor is below the 50% threshold—31.835% for rainfall and 34.122% for temperature.³¹

3.2. Descriptive statistics and analysis of variance

Table 5 presents the descriptive statistics for average monthly rainfall in the City of Tshwane from 1981 to 2022. Descriptive statistics are used to numerically describe and summarize the dataset. The mean represents the central tendency, that is, the rainfall, while the standard deviation measures the variations within the dataset. The large standard deviation values observed in Table 5 indicate significant variability in rainfall over the 42-year period (1981 – 2022). This variability may be attributed to the effects of climate change, as

Table 5. Descriptive statistics of average monthly rainfall in the City of Tshwane from 1981 to 2022

Month	N	Range	Minimum	Maximum	Sum	Mean		Standard deviation
						Statistic	Standard error	
January	42	457.00	8.00	465.00	5473.60	130.3238	11.14551	72.23114
February	42	331.50	20.90	352.40	4314.40	102.7238	10.37460	67.23511
March	42	317.80	0.10	317.90	3793.60	90.3238	10.65665	69.06299
April	42	133.20	0.00	133.20	1772.00	42.1905	4.87410	31.58779
May	42	87.60	0.00	87.60	552.50	13.1548	3.11226	20.16978
June	42	68.90	0.00	68.90	354.40	8.4381	2.07840	13.46959
July	42	30.30	0.00	30.30	105.60	2.5143	0.87653	5.68054
August	42	54.40	0.00	54.40	235.90	5.6167	1.58145	10.24900
September	42	116.10	0.00	116.10	740.10	17.6214	3.74341	24.26005
October	42	176.70	0.00	176.70	2711.40	64.5571	6.42257	41.62303
November	42	271.80	0.00	271.80	4352.40	103.6286	8.60268	55.75175
December	42	172.80	43.00	215.80	5332.10	126.9548	6.80836	44.12323

Table 6. Descriptive statistics of average yearly temperature in the City of Tshwane from 1981 to 2022

Variable	N	Range	Minimum	Maximum	Sum	Mean		Standard deviation
						Statistic	Standard error	
Rainfall	42	53.13	28.32	81.44	2439.84	58.0915	1.85334	12.01104

Table 7. Confidence interval and component variance for rainfall

Model	Standard deviation	Standard error	95% confidence interval for mean		Between-component variance
			Lower bound	Upper bound	
Fixed effects	6.10233	1.76159	35.5685	80.3348	-
Random effects	-	15.25579	23.9596	91.9437	2361.97017

Table 8. Analysis of variance results for rainfall

Comparison	Sum of squares	df	Mean square	F	Significance
Between groups	25960.395	10	2596.039	69.714	0.023
Within groups	37.238	1	37.238	-	-
Total	25997.633	11	-	-	-

it suggests significant fluctuations in monthly rainfall patterns over time.

Table 6 presents the descriptive statistics of average yearly temperature in the City of Tshwane from 1981 to 2022. The large standard deviation value (12.01104), indicates significant variations in the dataset. This finding further implies significant variation in the amount of rainfall over the 42-year period (1981 – 2022), which may be attributed to the effect of climate change.

A one-way analysis of variance was conducted using the *F*-distribution at a 95% confidence interval to determine whether the means of the temperature and rainfall differ significantly. In this analysis, average monthly rainfall (1981 – 2022) was taken as the dependent variable, while average monthly temperature over the same period was taken as the independent variable. The mean temperature for the 12 months (January – December) was 57.9517, which falls within the 95% confidence interval range, from a lower bound of 35.5685 to an upper bound of 80.3348.

The confidence interval for a mean provides a range of possible values for the population mean. As the confidence interval presented in Table 7 does not include zero, it suggests that the difference is statistically significant, and that the observed mean is a true reflection of the rainfall dataset. The “between-component variance” estimates the differences in average monthly rainfall, treating each month (January – December) as a group. The result indicates statistically significant variations in the average rainfall among the

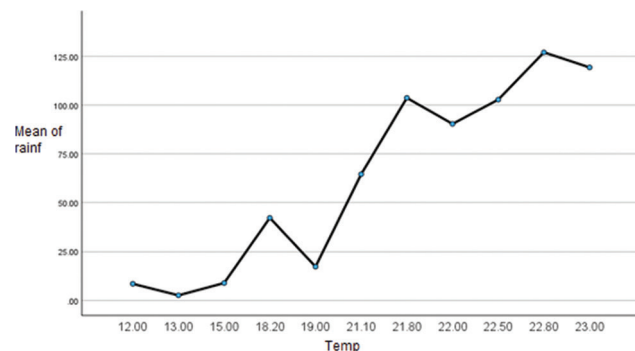


Figure 9. Mean plot for the temperature (temp) and rainfall (rainf) datasets

months, as indicated by the high component variance value (2,361.97017). This finding provides evidence of changing rainfall patterns across months during the 1981 – 2022 period, likely influenced by climate change. Table 8 presents the analysis of variance results. The *F*-value represents the ratio of between-group variance (temperature and rainfall) to within-group variance. A high *F*-value (69.714), as shown in Table 8, suggests a significant difference between the groups. Furthermore, the $p < 0.05$, (0.023), indicating that the variation in the pattern of average monthly temperature and rainfall in South Africa is statistically significant.

Figure 9 displays the mean plots used to visualize the differences between group means for temperature and rainfall. Each data point in the plot represents the mean of a specific group, further illustrating the existence

of statistically significant differences or variations between the groups. This finding is an indication that notable changes in temperature and rainfall patterns occurred during the study period, likely as a result of climate change.

3.3. Annual rainfall in the City of Tshwane

As shown in Figure 4 in Section 2.4 (rainfall data from 1981 to 2022 in the City of Tshwane), rainfall has not been uniform, leading to periods of droughts and floods.

Figure 10 illustrates the relationship between the annual rainfall and infrastructure performance. Equation III, derived from the regression graph, demonstrates that the relationship between rainfall and infrastructure performance is inversely proportional:

$$Y = -0.0923x + 48.632 \tag{III}$$

This indicates that as rainfall increases, the performance of infrastructure – specifically its durability and safety – decreases. The R-squared value for the regression line is 0.818, which is a statistical measure of how well the data fit the regression model (goodness of fit). A value closer to 1 indicates higher reliability of the regression equation, while a value closer to 0 indicates lower reliability.³¹

Figure 11 depicts the relationship between GDP loss and GHG emissions. Equation IV, derived from the regression graph, shows that the relationship between GDP loss and GHG emissions is directly proportional:

$$Y = 0.0083X - 2.4587 \tag{IV}$$

The R-squared value for the regression line is 0.878.

The forecast for GDP growth can be derived from the economic modeling Equation V.

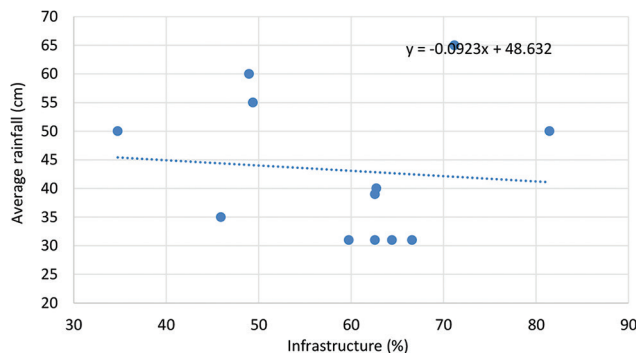


Figure 10. The relationship between rainfall data and infrastructure performance

Source: Functional relationship derived from the regression plot based on the data obtained from the South African Weather Service³⁷.

$$\frac{\Delta A_{it}}{A_{it}} = \delta_1 T_{it} + \delta_2 R_{it} + \delta_3 SPT_{it} + \delta_4 SPR_{it} \tag{V}$$

where T is temperature, R represents rainfall, and the spatial effect terms (standard penetration test [SPT] and soil penetration resistance [SPR]) affect total factors and productivity exponentially.

From Equation V, two key parameters that directly influence climate change – namely, temperature and rainfall – are included in the economic modeling equation, along with the spatial effects terms (SPT and SPR).

The inclusion of these two variables (temperature and rainfall) in Equation III is due to their crucial role in influencing other variables and climate change. In other words, other variables may be indirectly determined by temperature and rainfall. For instance, temperature can serve as a variable to determine extreme events, such as heatwaves, while rainfall can be used to prevent extreme events, such as flooding, when its amount exceeds a certain threshold. Both temperature and rainfall can also impact infrastructure performance and GDP. For example, the lower the occurrence of extreme events due to excessive temperature and rainfall, the higher the infrastructure performance, assuming design and service requirements are met.

The inclusion of all six variables may result in a complex equation that could be challenging to resolve mathematically.

The results indicate that the effect of climate change on the South African economy is significant. This agrees with the findings of Ray,²¹ who stated that climate change negatively affects African economies through GDP

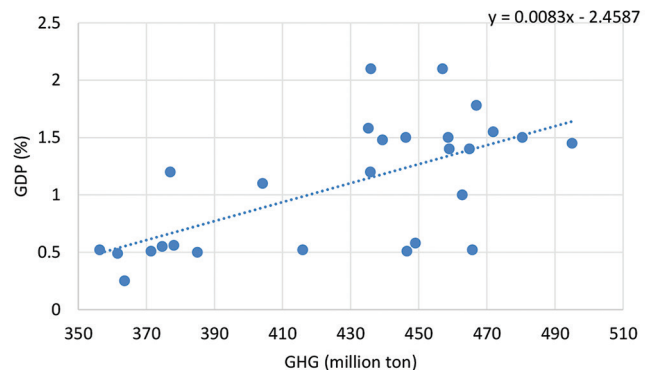


Figure 11. The relationship between gross domestic product loss and greenhouse gas emissions

Source: Functional relationship derived from the regression plot based on data obtained from the South African Weather Service³⁷.

decline, loss of business and livelihoods, and increased investment in repairing damaged infrastructure and developing countermeasures.

For example, the costs associated with infrastructure repair and recovery following heavy rainfall in Cape Town in 2011 exceeded R20 million.⁴ In 2022, the KZN flooding resulted in the loss of 440 lives and the destruction of road infrastructure worth R5.6 billion. Comins⁵ estimated that KZN would lose 1.8% of its annual GDP.

Figure 12 shows the relationship between GHG emission and temperature. Equation VI, derived from the regression graph, demonstrates that the relationship between GHG emissions and temperature is directly proportional. Higher temperatures increase the likelihood of GHG emissions. This may be due to higher temperatures accelerating the decomposition of organic matter, as increased microbial activities raise the concentration of carbon in the atmosphere. Furthermore, higher temperatures may drive an increased energy demand for cooling. In addition, higher air temperatures can hold more moisture, leading to greater amounts of trapped water vapor, which contributes to global warming. Similarly, lower temperatures may also lead to increased GHG emissions due to higher energy demand for heating, thereby resulting in carbon emissions resulting from increased energy consumption.

$$Y = 0.0254x - 6.5745 \quad (VI)$$

The R-squared value for the regression line shown in Figure 12 is 0.825. Given the R-squared values of the three regression models are close to 1, it implies that the regression models are highly reliable.³¹

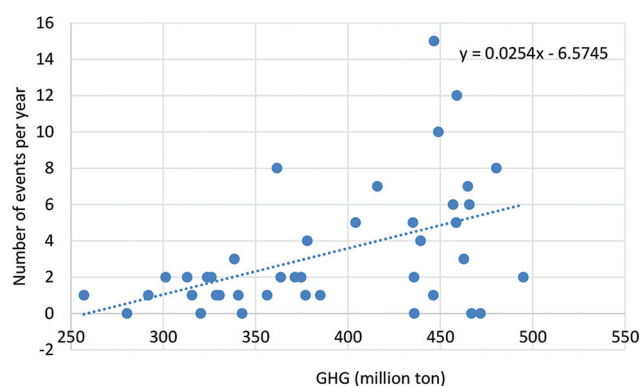


Figure 12. The relationship between greenhouse gas emissions and temperature

Source: Functional relationship derived from the regression plot based on data obtained from the South African Weather Service³⁷.

3.4. Modeling and simulation of climate change and mitigation strategies

Figure 13 illustrates the modeling and simulation of climate change and mitigation strategies for the next 10 years. The model's input variable was the climate change policy, which depends on how often it is reviewed and updated each year. The model variables included: (i) Average rainfall, (ii) infrastructure performance, (iii) average loss of GDP, (iv) GHG emissions, and (v) the number of extreme weather events in the City of Tshwane. Changes in the climate change policy affect the amount of GHG emissions, and the model then simulates the impact of average rainfall, infrastructure performance, and GDP loss as functions of GHG emissions. The green line represents infrastructure performance without the climate change policy, showing poor infrastructure performance. The blue line represents the number of extreme events due to an increase in GHG emissions. The orange line represents GDP loss resulting from GHG emissions, and the red line represents GHG emissions as a result of implementing the climate change policy. All these variables – GDP loss, GHG emissions, extreme events, and infrastructure performance – are controlled by the climate change policy. Without policy implementation, the model showed higher rainfall, decreased infrastructure performance, and more extreme events.

Figure 14 shows the results of implementing the climate change policy over the next 10 years. The model was tested multiple times by varying the number of times the climate change policy is updated and implemented each year. The more the climate change policy is implemented, the greater the decrease in GHG

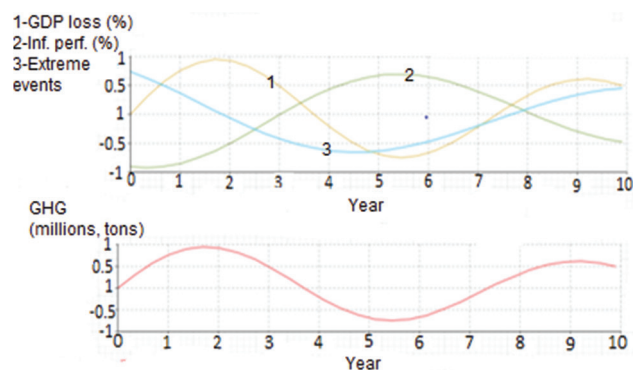


Figure 13. AnyLogic model of climate change mitigation

Abbreviations: GDP: Gross Domestic Product; GHG: Greenhouse gas; Inf. perf.: Infrastructure performance; No: Number.

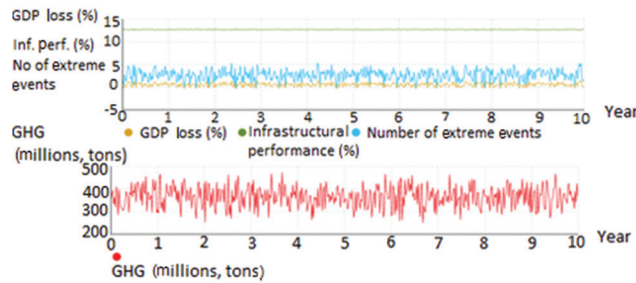


Figure 14. Mitigation results from the simulation model of climate change

Abbreviations: GDP: Gross Domestic Product; GHG: Greenhouse gas; Inf. perf.: Infrastructure performance; No: Number.

emissions, which positively impacts the reduction of the number of extreme weather events and lessens GDP loss. The green line represents infrastructure performance, which improved by 15%; the blue line represents the number of extreme events, which decreased by 15%; the orange line represents GDP loss, which improved by 25%; and the red line represents the amount of GHG emissions, which decreased by 3%.

Implementation of the climate change policy within the Department of Roads and Stormwater Infrastructure more than once a year could reduce the amount of GHG emissions, which would, in turn, reduce GDP loss due to fewer extreme weather events.

The modeling horizon was set for a period of 10 years. After running multiple simulations, where the frequency of climate change policy implementation was varied, the results showed a 15% decrease in climate trends, a 3% reduction in GHG emissions, a 25% decrease in GDP loss, and a 15% increase in infrastructure performance.

4. Discussion

During the period covered by this study, the City of Tshwane operated with an infrastructure budget of R33.038 billion (2018/2019).² The population of Tshwane continues to grow annually, with its growth rate exceeding that of Gauteng and South Africa as a whole.⁴⁷

Based on the latest data, Tshwane's high population growth is primarily driven by urbanization, which is creating challenges, as people are building in high-risk areas. Tshwane is exposed to numerous hazards, such as wildfires, floods, droughts, and extreme temperatures. Climate change has a direct impact on the frequency and intensity of these climate hazards, while factors include population growth, urbanization, adaptation

interventions, and land use planning play key roles in the number of residents and the vulnerability of infrastructure to these hazards.

The simulation conducted in this study was able to predict the situation over the next 10 years, considering whether or not the climate change policy is implemented.

The simulation results indicated a significant occurrence of extreme events, such as extreme temperatures, droughts, rainfall fluctuations, and GHG emissions, which had a notable negative impact on economic activities, as reflected in the city's GDP, especially when climate change policies were not implemented. However, with the implementation of climate change policies, the magnitude of these extreme events was reduced, resulting in a decrease in GDP loss. Hence, the climate change policy in the Gauteng Department of Roads and Stormwater Infrastructure should be implemented in every project. This approach could also be extended to the National Department of Roads and Stormwater Infrastructure to achieve better outcomes. It is critical for local government bodies to implement climate change policies to reduce the amount of GHG emissions.

The rainfall observed from 1981 to 2022 was not consistent; periods of heavy rainfall and droughts were experienced. The rainfall projections suggest more extreme climate trends in the future, including severe floods and droughts, if climate policies are not implemented. Anekwe *et al.*¹² also found that variations in rainfall and temperature have serious consequences for water resources in South Africa.

The findings of this study are supported by the works of Anekwe *et al.*¹² and Dube and Nhamo,¹¹ who noted significant variations in weather and temperature patterns in South Africa. Furthermore, Botai *et al.*¹⁴ observed substantial variations in precipitation concentration across the country, while Ndlovu and Demlie¹⁶ found an increasing frequency of droughts and a reduction in rainfall frequency in South Africa between 1970 and 2017 in the KZN province. However, a report from the University of Witwatersrand⁴⁸ indicated that flooding in Durban (KZN) has been catastrophic. This suggests that KZN alternates between two extreme events – drought and flooding. These extreme events of drought and flooding have been included in South Africa's climate risk profile, according to the World Bank Group,⁴⁹ further supporting the findings of this study. This underscores the need for timely intervention and the implementation of climate change policies.

According to the data gathered and analyzed, it is recommended that the road and stormwater

infrastructure be redesigned for effective climate change mitigation. Furthermore, simulation and modeling tools should be integrated into the planning and decision-making processes of climate adaptation plans and policy development. In this technology- and data-driven era, data is crucial for forecasting and decision-making,^{50,51} especially rainfall data. Hence, rainfall data, runoff coefficients, and runoff data for the past three decades should be critically analyzed to identify trends in the area. This analysis will inform both structural and non-structural solutions for stormwater management in South Africa. At present, there is no climate change legislation in South Africa, as the draft climate change bill published in June 2018 has yet to be implemented. Thus, the implementation of South Africa's climate change laws and policies is strongly recommended. This recommendation aligns with the view of Averchenkova *et al.*,⁵² who emphasized that, despite South Africa's sophisticated governance systems, the country faces challenges in implementing national climate policy.

The quality of the drainage system in the City of Tshwane also needs to be assessed. A reliable stormwater collection system should be designed with interlocking features, particularly for rural and urban areas that require protection from flooding, given the economic implications. Stormwater must be approached as a hazard, as it can damage road structures and other infrastructure. Effective management planning will require detailed information on how and where impacts will occur, as well as data on the cost and performance of stormwater management practices, such as green infrastructure strategies. At present, stormwater management in Tshwane mainly focuses on collecting runoff and directing it to nearby watercourses. This implies that the present design of the stormwater drainage system prioritizes flow management without sufficient consideration for environmental preservation. The stormwater collection system around the City of Tshwane is full of waste, grass, and untreated sewage due to lack of maintenance and population growth, highlighting the need for a redesign.

To address variations in rainfall patterns leading to drought, the country could adopt coping strategies such as water resource conservation and distribution techniques, modern irrigation facilities, and adjustments in cropping patterns to align with rainfall trends.^{53,54} Furthermore, reservoirs with large capacities should be established in areas vulnerable to both floods and droughts to mitigate the impacts of these extreme weather events. Mechanisms can be developed to harvest the floodwater into reservoirs for storage during

periods of heavy rainfall, which can then be used during droughts. This would offer multiple benefits, such as water storage, flood prevention, and drought mitigation.⁵⁵

The findings of this study contribute to the body of knowledge by demonstrating the applicability of an integrated model for assessing the impacts of climate change. The study enhances the understanding of climate change impacts in South Africa, specifically the City of Tshwane. With the 10-year predictions of climate change and its potential effects (with or without the implementation of climate change policy), policymakers will be better positioned to prioritize climate change policy implementation and make informed decisions on developing effective adaptation and mitigation strategies.

5. Conclusion and recommendations

5.1. Conclusion

This study focused on assessing the impact of climate change on the City of Tshwane, South Africa. Based on the simulation results, the following conclusions are drawn:

- (i) The effects of climate change – particularly flooding – have significant cost implications, leading to increased expenses for the development and repair of roads and stormwater infrastructure.
- (ii) Rainfall dataset observed from 1981 to 2022 showed considerable variability, with periods of heavy rainfall and drought. Projections suggest more extreme climate trends in the future, including severe floods and droughts if climate change policies are not implemented.
- (iii) Implementing climate change policies could lead to an annual improvement in GDP by 25%, a 3% reduction in GHG emissions, and a 15% increase in infrastructure performance.

The novel contribution of this study lies in the integration of the DES and SD models to investigate the impact of climate change on roads and stormwater infrastructure in the City of Tshwane, as well as to represent mitigation strategies over a 10-year period. Thus, the study contributes both methodologically and empirically by generating data related to climate change that can assist the relevant stakeholders in making informed decisions on its mitigation. The model could be further improved by incorporating factors, such as infrastructure maintenance, for which data is limited. There is also a lack of accurate, city-specific data on

GHG emissions, as existing figures are reported at the provincial level. Furthermore, quantitative data are needed on elements, such as the annual percentage or scorecard of infrastructure constructed, the extent and measurements of flood events, and a political stability index to better inform policy and infrastructure planning.

5.2. Policy implications

Effectively mitigating the impact of climate change on roads and stormwater infrastructure requires deliberate and sustained policy implementation. The following policy implications are proposed for consideration by relevant stakeholders:

- (i) Increase public awareness and education on the impacts of climate change and promote individual, corporate, and governmental actions to mitigate its effects
- (ii) Integrate climate change adaptation and mitigation strategies into national planning and development processes to ensure coherence across sectors
- (iii) Strengthen coordination between subnational and national government plans aimed at climate change mitigation and adaptation
- (iv) Encourage human capacity development in the areas of climate change policy analysis, formulation, and implementation
- (v) Address resource constraints that hinder the development and implementation of effective climate change policies.

5.3. Limitations and directions for future study

This study is limited to the analysis and simulation of historical data on stormwater collection systems, road infrastructure, climate change, and financial datasets specific to the City of Tshwane. It does not consider the age-related issues within the lifecycle of road and stormwater infrastructure. The historical data used in this study may omit important factors, potentially leading to inaccuracies in the analysis and forecasting. Moreover, such data may be subjected to bias and incompleteness and may lose relevance over time. Although Harman's one-factor test was conducted to assess the presence of bias and to establish the reliability of the dataset, the use of primary data may offer greater accuracy and reliability due to its direct acquisition from original sources. Therefore, future works could benefit from the use of primary data and should also consider investigating the typical performance challenges associated with the lifecycle of road and stormwater infrastructure. In addition, further studies could explore the interactions between climate change and infrastructure lifecycle to

provide a more comprehensive understanding of long-term infrastructure resilience and sustainability.

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Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization: All authors

Formal analysis: All authors

Investigation: All authors

Methodology: All authors

Writing – original draft: All authors

Writing – review & editing: All authors

Availability of data

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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