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Assessing the Climate Resilience of Urban Water Infrastructure: A Framework-Based Case Study of the Abuja Water Treatment Plant in Nigeria

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PAN AFRICAN UNIVERSITY FOR WATER AND ENERGY SCIENCES
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Assessing the Climate Resilience of Urban Water Infrastructure: A Framework-Based Case Study of the Abuja Water Treatment Plant in Nigeria

A master's thesis submitted to the Pan African University for Water and Energy Sciences (Including Climate Change) in partial fulfillment of the requirements for the award of a Master of Science degree in Climate Change.

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I, Okon Samuel Samuel, hereby declare that this thesis titled **"Assessing the Climate Resilience of Urban Water Infrastructure: A Framework-Based Case Study of the Abuja Water Treatment Plant in Nigeria"** is my original work to the best of my knowledge and has not been submitted to the University or any other institute or published earlier for the award of any degree or diploma. I also declare that all the information, materials, and results from other works presented in this thesis have been duly cited and regarded according to the academic rules and ethics.

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I, Prof. Joseph Adelegan, hereby declare that I supervised the preparation of this Master thesis submitted therein under the guidelines on supervision of a Master thesis laid down by the Pan African University Institute of Water and Energy Sciences (Including Climate Change), Algeria.

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Rubber Study Group

DEDICATION

To my Loving Parents

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ABSTRACT

This study investigates the climate resilience of water infrastructure, focusing on the Lower Usuma Dam water treatment plant in Abuja, Nigeria, amid escalating climate change impacts. The research aims to develop and apply a Conceptual Framework Approach (CFA), termed the E-TOES framework (Environmental, Technical, Organizational, Economic, Social), to assess the plant's resilience status and enhance preparedness for climate-induced disruptions. Utilizing a multi-faceted methodology, the study analyzes 40 years of precipitation data (1983–2022) via Innovative Trend Analysis (ITA), revealing a subtle decline in rainfall (4.1%–6.7% across peak rainy months), signaling potential water resource challenges. A systematic literature review employing the PRISMA method identifies key resilience dimensions, while onsite assessments and expert evaluations inform the selection and scoring of ten resilience indicators on a 1– 5 scale. These indicators, spanning sediment capture, flood protection, emergency response, funding, and community engagement, are integrated into the E-TOES framework, yielding a Climate Resilience Index (CRI) of 16% for the Abuja plant—indicating low resilience, with strengths in organizational (10%) and technical (4%) dimensions, but deficiencies in economic and social aspects. The findings underscore the framework's utility in pinpointing vulnerabilities and guiding resilience-enhancing strategies. The study recommends incorporating additional climate stressors, leveraging machine learning for data analysis, and institutionalizing regular resilience assessments to bolster water infrastructure adaptive capacity. This work contributes a practical, multidimensional tool to the discourse on climate resilience, offering actionable insights for water managers and policymakers in developing regions facing similar environmental pressures.

Keywords: Climate hazard, Resilience, Lower Usuman, precipitation, organizational

RÉSUMÉ

Cette étude examine la résilience climatique des infrastructures hydrauliques, en se concentrant sur l'usine de traitement d'eau du barrage Lower Usuma à Abuja, Nigeria, face aux impacts croissants du changement climatique. La recherche vise à développer et appliquer une approche conceptuelle de cadre (CFA), baptisée cadre E-TOES (Environnemental, Technique, Organisationnel, Économique, Social), pour évaluer le statut de résilience de l'usine et renforcer la préparation aux perturbations induites par le climat. En utilisant une méthodologie multifacette, l'étude analyse 40 ans de données de précipitations (1983–2022) via l'analyse de tendance innovante (ITA), révélant un léger déclin des précipitations (4,1%–6,7% pendant les mois de pointe de la saison des pluies), signalant des défis potentiels pour les ressources en eau. Une revue systématique de la littérature employant la méthode PRISMA identifie les dimensions clés de la résilience, tandis que des évaluations sur site et des évaluations d'experts informent la sélection et la notation de dix indicateurs de résilience sur une échelle de 1 à 5. Ces indicateurs, couvrant la capture des sédiments, la protection contre les inondations, la réponse d'urgence, le financement et l'engagement communautaire, sont intégrés dans le cadre E-TOES, produisant un indice de résilience climatique (CRI) de 16% pour l'usine d'Abuja—indiquant une faible résilience, avec des points forts dans les dimensions organisationnelle (10%) et technique (4%), mais des lacunes dans les aspects économiques et sociaux. Les résultats soulignent l'utilité du cadre pour identifier les vulnérabilités et orienter les stratégies de renforcement de la résilience. L'étude recommande d'incorporer des stresseurs climatiques supplémentaires, de tirer parti de l'apprentissage automatique pour l'analyse des données, et d'institutionnaliser des évaluations régulières de la résilience pour renforcer la capacité d'adaptation des infrastructures hydrauliques. Ce travail apporte un outil pratique et multidimensionnel au discours sur la résilience climatique, offrant des perspectives exploitables pour les gestionnaires de l'eau et les décideurs politiques dans les régions en développement confrontées à des pressions environnementales similaires.

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ABBREVIATION

AI: Artificial Intelligence

CFA: Conceptual Framework Approach

CRI: Climate Resilience Index

CRWU: Creating Resilient Water Utilities

WARATA: Withstanding, Absorptive, Restorative, Adaptive, Transformative, and Anticipative

TOSE: Technical, Organizational, Social, Economic

SWI: Scoring and Weight Index

OECD: Organisation for Economic Co-operation and Development

NIMET: Nigerian Meteorological Agency

NEMA: National Emergency Management Agency

ITA: Innovative Trend Analysis

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CHAPTER ONE INTRODUCTION

1.1 Background to the Study

The impact of climate change is profoundly disrupting global water infrastructure and intensifying threats to water security, especially in developing countries. This escalating crisis has emerged as a pressing concern for humanity and the environment. The effects of climate change, such as altered rainfall patterns and increasing weather variability, have exacerbated pre-existing environmental challenges, although these outcomes were long anticipated by climate scientists. Despite warnings, policy preparedness and resilience planning among utility managers and policymakers remain insufficient in many developing nations (Jain et al., 2024).

The variability in rainfall intensity, coupled with shifting hydrological cycles, has made water resources increasingly unpredictable, heightening the risks of floods and droughts. These dynamics pose severe threats to economic activities, infrastructure stability, and social well-being, causing significant disruptions to livelihoods and economic development. The socio-economic consequences are vast, with damaged infrastructure and external shocks amplifying vulnerabilities across regions (OECD, 2022).

To address these challenges, water infrastructure systems must adapt to both current and anticipated climate impacts. These systems are essential for maintaining a healthy environment and delivering critical services. Thus, enhancing their resilience is pivotal for effective disaster response and recovery strategies. Infrastructure owners and operators must implement proactive plans to mitigate potential climate-induced risks while managing immediate weather-related impacts. A comprehensive resilience framework is necessary to strengthen the capacity of water systems to withstand these challenges, ensuring sustainability and protecting communities against future shocks (Pamidimukkala et al., 2023).

The increasing frequency and severity of disasters worldwide underscores the urgent need for advanced engineering solutions to mitigate risks and bolster infrastructure resilience. Such efforts are essential for preparing utilities to address the potential impacts of climate change. Resilience has gained prominence in research and its application has expanded significantly in managing engineering systems. Planning and developing resilient infrastructure systems capable of adapting to and recovering from climate extremes has become a top priority for governments and stakeholders globally (Paul et al., 2020). This focus has catalyzed the creation of decision-making frameworks to aid policymakers and operators in effectively managing infrastructure under changing conditions (Das, 2020).

The concept of resilience extends across various disciplines, including sociology, psychology, economics, business, engineering, and security, highlighting its interdisciplinary nature. While significant progress has been made in understanding resilience, challenges remain in bridging the gap between theoretical concepts and practical implementation. Measuring resilience is particularly complex due to the lack of a universal approach, which hampers its integration into development practices (Kantabutra & Ketprapakorn , 2024).

Understanding how climate change impacts water infrastructure systems and their resilience is crucial for effective water resource management and investment planning. The American Society of Civil Engineers defines infrastructure resilience as the ability to mitigate risks, restore critical services rapidly, and minimize harm to public safety, health, the economy, and national security).

Resilience can thus be viewed as the capacity of systems to withstand impacts, absorb disruptions, and recover swiftly to pre-disruption conditions. This concept has significantly influenced diverse fields and continues to shape approaches to managing climate-related risks (Mohanty et al., 2024).

Resilience has become a focal point in addressing climate-related challenges, but its application remains fraught with ambiguities. Researchers have applied varying resilience concepts, definitions, and methodologies to similar situations, often without adequate justification of how resiliency should be quantified or which metrics should guide the chosen approach. A standardized framework for measuring, implementing, and evaluating resilience is notably lacking. This gap arises partly from the multidisciplinary origins of resilience, which invite diverse interpretations, complicating its full understanding and operationalization (Lloret et al., 2024). Consequently, these challenges hinder the widespread integration of resilience thinking into water management practices.

To mitigate the adverse effects of climate change on water infrastructure, managers, engineers, and stakeholders must evaluate system behavior under disruptive conditions and test their resilience. This requires a deeper and clearer understanding of how resilience concepts can be practically applied in engineering, offering pathways for both researchers and water resource managers to advance resilience strategies (Doost et al., 2024).

Africa exemplifies the pressing need for effective water resilience strategies. The continent faces significant water stress, with limited access to safe and reliable water supplies and high vulnerability to climate change. In 2019, extreme weather events, including droughts, floods, cyclones, heatwaves, and locust outbreaks, affected millions of people, causing substantial socioeconomic and environmental damages. These challenges highlight the urgency of adopting resilience-focused water management practices to safeguard communities and ecosystems from worsening climate impacts.

In recent years, Nigeria has experienced catastrophic climate change events, including flooding, erosion, and drought, raising significant concerns about the capacity of its institutions to manage these impacts. Between 1900 and 2022, climate-related events such as droughts, extreme temperatures, floods, and storms have affected over 13.4 million people in the country (Jones, 2024). The National Emergency Management Agency (NEMA) reported that from 2012 to 2018 alone, approximately 4.3 million individuals were affected by floods, which continue to cause fatalities and injuries, damage infrastructure, disrupt public utilities, destroy farmlands, and threaten food security, socio-economic stability, and the environment, all of which collectively undermine Nigeria's national security . The impacts of climate change are expected to intensify, particularly in developing regions like Nigeria, due to limited adaptive capacity to address these adverse conditions.

1.2 Justification of the Study

The study of climate-resilient water infrastructure systems is essential, given the numerous consequences of failed infrastructure, including water-related disasters such as floods, droughts, and sea-level rise. These issues result in significant environmental and socio-economic losses across many regions in Nigeria.

This study aims to raise awareness among water managers, investors, stakeholders, and policymakers about the devastating effects of climate change on water infrastructure. It also seeks to test a resilience tool to assess infrastructure status before climate change events. Resilience emphasizes system behavior during disruptions, focusing on managing operational capabilities through design under adverse conditions (Ferris, 2018). As the growing pressure on global water resources significantly impacts socio-economic well-being, information on climate hazards, vulnerabilities, and the characteristics of infrastructure assets is vital for developing climateresilient infrastructure and assessing climate risks.

1.3 Aim and Objectives of Study

The aim of this research is to determine the impact of climate change on water infrastructure in Nigeria using Abuja water treatment plant as a case study. This assessment will prepare the water resource leadership and policy makers against climate change events, by showing how ready the infrastructure is to the effects of climate change.

The objectives are as to identify Resilience Dimensions important to Treatments plant

1. To test a resilience tool to assess infrastructure status at Abuja treatment plant
2. To examine socio economic impacts and climate hazard vulnerabilities
3. To deploy a conceptual framework approach to determine climate resiliency status
4. Raise awareness among managers to the devastating effects of climate change on water infrastructure

1.5 Scope of Study and Limitations

The study aims to analyze the capacity of water infrastructure systems to adapt to climate change impacts and assess their preparedness, with the goal of applying a Comprehensive Framework for

Assessment (CFA) to evaluate the resilience of water infrastructure systems in Abuja. Specificallly scope and Limitations include the following.

1. The study is limited to one infrastructure site (Lower Usuma Dam). This may affect the generalizability of findings to other regions or infrastructure types in Nigeria

2. While the E-TOES framework covers broad dimensions, not all potential climate stressors (e.g., temperature, wind, or indirect socio-political risks) were deeply modeled.

3. Scoring of resilience indicators on a 1–5 scale, while insightful, may introduce subjective bias, particularly if based on limited stakeholder interviews or expert judgment.

CHAPTER TWO LITERATURE REVIEW

2.1 Background

Regional climate change effects have the capacity to inflict severe physical harm on water infrastructure, leading to profound socio-economic challenges for millions globally (Guha-Sapir, 2020; World Bank, 2021). When critical water systems encounter climate-related hazards like flooding, droughts, or strong winds, their adaptive capability diminishes, leaving them more susceptible to damage and impairing their functionality and operations (Almeida & Márquez, 2023). Adopting climate-resilient strategies for water infrastructure helps mitigate various shocks and stresses by boosting the system's capacity to adapt, endure, and either maintain operations or rapidly recover after extreme climate events (Jones, 2019). Such strategies prevent functional and operational disruptions, equipment failures, and adverse impacts on water availability and quality (Asghari et al., 2023).

According to Nigeria's National Emergency report, climate hazards displaced over two million individuals, damaged 355,986 homes, and destroyed 944,989 hectares of land in 2022 (NEMA, 2022). Over the past five decades, these hazards have averaged annual losses of USD 202 million (World Bank, 2021). Robust water infrastructure is integral to environmental health and plays a critical role in disaster response and recovery efforts (Pamidimukkala et al., 2021). Developing resilient strategies is essential to safeguard water resources from escalating climate change impacts
(Najafzadeh & Basirian, 2023).

Asset managers and water utilities must assess the resilience of their systems under evolving conditions. Variations in average weather patterns, coupled with extreme events, are transforming the climate, resulting in irregular rainfall, fluctuating temperatures, and an increased frequency of climate-induced disasters like floods and droughts (Goyol et al., 2018).

The recent disasters of flooding, erosion, and drought in Nigeria have raised concerns about the ability of institutions to address the impacts of climate change (Ojo et al., 2020). To enhance the resilience of water infrastructure systems, it is crucial to integrate considerations of interdependencies into climate hazard planning (Matthews, 2015). Water systems, however, are inherently multi-dimensional, with their resilience influenced by diverse social, economic, and organizational factors (Balaei et al., 2018). Evaluating the key determinants of water infrastructure resilience is essential for managers and researchers to assess system vulnerabilities and guide policymakers in taking appropriate measures.

Communities rely heavily on comprehensive water supply services and the infrastructure supporting these systems (Rehak et al., 2019). Over time, these infrastructures have become indispensable for daily societal functions (EPA, 2021). Today, water systems are among the most critical components of modern infrastructure, essential for sustaining the daily operations of communities (WHO & UNICEF, 2019). They are regarded as vital assets, providing services crucial to societal stability and citizen welfare (Varis et al., 2017). Strengthening the resilience of these systems against climate change impacts is imperative to ensure their continued functionality and prevent operational disruptions (Allenby et al., 2021).

Resilience has become a core framework for managing the performance of critical infrastructure under the pressures of disaster events (Rathnayaka et al., 2024). As water infrastructure serves as a fundamental subsystem supporting societal well-being, its disruption can have profound consequences for public health and the socio-economic stability of affected communities (Rezvani, 2024).

Incorporating resilience strategies into water infrastructure systems enhances their ability to withstand both external and internal disturbances, maintain acceptable operational efficiency during disruptions, or rapidly restore functionality afterward (Lewin et al., 2023).

2.2 Examination of the Water Infrastructure System in Abuja

The Lower Usuma Dam represents a critical source of potable water for the Federal Capital Territory (FCT) in Nigeria. Situated between latitudes 8°25’ and 9°25’ North and longitudes 6°45’ and 7°45’ East of Greenwich, this facility has played a pivotal role in ensuring water security for the region. The geographic boundaries extend from the village of Izon at 7° East longitude and 9°15’ North latitude, proceeding westward to the Kemi River, and southward along 6°47.5’ through the villages of Semusu, Zui, and Bassa, finally reaching Abji in Kwara State. Additionally, a northward extension links Idu, Karshi, and Karu to the north-central and northwestern zones up to Bwari Area Council.

The dam’s location, within the highlands of the FCT, underscores its strategic significance. The Usuma River, one of the primary tributaries of the Gurara River in Abuja, originates from these highlands, tracing the eastern frontier of the territory. This river supplies the Lower Usuma Dam, which spans 1,350 meters in length, reaches a depth of 49 meters, and stands 5.74 meters above sea level when at capacity. Designed as a homogeneous earth-fill dam, its robust construction incorporates rockfill for stability, while the downstream section is fortified with horizontal and vertical fillers.

The dam was officially commissioned in 1986 alongside its treatment plant, both managed by the Water and Sewage Division of the Engineering Department of the Federal Capital Development Authority (FCDA). Together, these facilities have been instrumental in delivering high-quality drinking water to Abuja's residents. The treatment plant's operations are geared towards optimizing water quality while balancing economic considerations. It is equipped with advanced filtration and purification technologies capable of handling large volumes of water from the dam's reservoir.

The climatic conditions surrounding the dam vary across three distinct seasons annually: warm, humid rains, a harsh dry period, and a transitional harmattan season characterized by northeast trade winds. These climatic fluctuations influence the dam's operations, necessitating adaptive management strategies to sustain its functionality and efficiency.

In addition to its hydrological significance, the dam is an integral part of the broader socioeconomic framework of the FCT. It supports vital functions ranging from domestic water supply to agricultural irrigation and recreational activities. The dam also contributes to local biodiversity, with its surrounding areas serving as habitats for various flora and fauna. Efforts to maintain this balance include stringent monitoring of human activities such as fishing, hunting, and tourism to prevent ecological degradation.

Figure 1.1: Lower usuman dam treatment plant, Abuja Image source: Biwater

The Lower Usuma Dam's resilience to climatic and operational challenges has positioned it as a cornerstone of water infrastructure in the region. However, continuous investments in maintenance and infrastructure upgrades remain essential to address emerging demands and environmental pressures. As urban expansion and population growth accelerate within Abuja and its environs, the strategic importance of the Lower Usuma Dam is expected to rise, further cementing its role as a lifeline for the FCT.

Despite its achievements, the dam faces challenges linked to environmental and anthropogenic factors. Seasonal water level fluctuations, sedimentation, and waste management issues require constant attention. Collaborative efforts between government agencies, environmental organizations, and local communities are crucial for preserving the dam's integrity and ensuring its long-term sustainability.

The Gurara Dam, located approximately 150 kilometers from the FCT, serves as a secondary source of water, complementing the Lower Usuma Dam. Connected through a pipeline network spanning 75 kilometers, it bolsters water availability during periods of high demand. Together, these facilities form the backbone of Abuja’s water infrastructure system, underscoring the importance of integrated water resource management for regional development.

2.3 Foundational Principles of System Resilience

The principle of resilience has gained prominence as a critical element in strategizing and governing water infrastructure networks, particularly amid growing environmental and anthropogenic pressures (Shin et al., 2018). To implement resilience-driven management effectively, stakeholders must grasp its conceptual framework, identify the variables that shape it, and employ robust analytical methodologies to assess its dynamics (Mottahedi et al., 2021). Scholarly investigations reveal that while evaluating the resilience of critical infrastructure is vital, the absence of a universally accepted definition or standardized approach complicates its application. Contemporary research emphasizes that resilience assessments must transcend purely technical evaluations, integrating multidimensional analyses of environmental sustainability, organizational adaptability, societal equity, and economic feasibility (Quintana et al., 2020).

Resilience has evolved into a ubiquitous yet nebulous term within scientific discourse, often touted as a panacea for mitigating uncertainties linked to climate volatility and resource scarcity (Spears et al., 2015; DEFRA, 2018). Its conceptual ambiguity stems from divergent interpretations across disciplines, ranging from engineering and ecology to sociology and economics. For instance, ecological studies may frame resilience as an ecosystem's capacity to recover from disturbances, while urban planners might emphasize community preparedness and adaptive governance. This semantic variability has sparked academic debate, with some scholars categorizing resilience as an inherent system trait, others as a dynamic process of adaptation, and still others as the measurable outcome of strategic interventions (Moser et al., 2019).

The contested nature of resilience is further amplified by its application to diverse systems, from micro-scale hydraulic networks to macro-scale socio-environmental ecosystems. For example, in water management, resilience might involve redundant infrastructure design to withstand floods, coupled with policies that prioritize equitable resource distribution during droughts. Meanwhile, economic resilience could focus on diversifying funding streams to buffer against financial shocks. This plurality of perspectives underscores the need for context-specific frameworks that balance theoretical rigor with practical applicability. Emerging methodologies, such as hybrid models combining probabilistic risk assessments with participatory stakeholder engagement, aim to bridge this gap by fostering interdisciplinary collaboration and localized solutions. Ultimately, advancing resilience theory demands reconciling its fragmented definitions while addressing the interconnected challenges of sustainability, equity, and adaptive capacity in an era of unprecedented global change.

2.3.1 Defining Resilience in Water Infrastructure Systems

The conceptualization of resilience within water infrastructure systems hinges on two pivotal questions: “resilience of what?” and “resilience to what?”. These interrogatives establish the boundaries of analysis by clarifying the system under scrutiny and the specific stressors it faces (Haimes, 2009). For instance, stating that a “water infrastructure system is resilient” remains ambiguous without delineating whether resilience pertains to floods, droughts, contamination events, or cyber-physical disruptions. Such vagueness underscores the necessity of contextualizing resilience within defined threats and system components.

Water infrastructure is not an isolated entity but an interconnected network of physical assets (e.g., pipelines, treatment plants), governance structures, ecological dependencies, and societal needs. A reservoir’s resilience to sediment buildup, for example, differs fundamentally from its resilience to extreme rainfall patterns driven by climate change. The former may involve engineering solutions like dredging, while the latter demands adaptive strategies such as predictive modeling or watershed management. By specifying the stressor, whether biophysical (e.g., temperature fluctuations), anthropogenic (e.g., urbanization), or operational (e.g., aging equipment)—resilience transitions from a nebulous ideal to a measurable, actionable objective.

Consider a coastal desalination plant: Its resilience to sea-level rise might involve elevating critical machinery, whereas resilience to energy supply disruptions could require hybrid power systems or demand-side management protocols. This duality highlights that a single system’s resilience is not monolithic; it varies across threat vectors. A network robust against seismic activity may falter under prolonged drought if its design prioritizes structural integrity over water conservation

(Hashimoto et al., 1982). Such nuances necessitate stress-specific frameworks, where resilience metrics align with identified vulnerabilities.

The interdisciplinary nature of resilience further complicates its definition. Engineers may emphasize redundancy and fail-safes, ecologists might advocate for ecosystem-based adaptations (e.g., wetlands as natural buffers), and economists could focus on cost-benefit analyses of adaptive investments. For instance, a flood-resilient urban drainage system might integrate green infrastructure (bioswales, permeable pavements) to manage stormwater and enhance community well-being—a dual benefit unaddressed by purely technical solutions.

operationalizing resilience demands participatory approaches. Stakeholders—from policymakers to local communities—must collaboratively define what systems prioritize (e.g., equitable access, environmental health) and what threats warrant immediate action (e.g., hurricanes vs. industrial pollution). This co-creative process ensures resilience strategies are both contextually grounded and socially equitable, avoiding one-size-fits-all prescriptions. As climate volatility intensifies, the imperative to specify “of what” and “to what” will only grow, shaping resilient systems that are as dynamic as the challenges they face.

2.3.2 Methodologies for Quantifying Resilience in Infrastructure Systems

Traditional reliability-based risk management has long dominated engineering practices for water infrastructure, prioritizing system stability and failure prevention under predictable conditions. However, the accelerating frequency of unpredictable disruptions—from climate-driven extremes to cascading technological failures—has catalyzed a paradigm shift toward resilience-centric approaches. Unlike reliability, which focuses on maintaining function during expected stressors, resilience emphasizes adaptive capacity—the ability to absorb shocks, reorganize during crises, and transform in response to evolving threats (Ferris et al., 2018). This transition acknowledges that modern societies cannot eliminate all risks but must instead cultivate systems capable of "failing gracefully" and recovering efficiently.

Engineered resilience, a concept formalized by infrastructure specialists, provides a structured framework for operationalizing this adaptive ethos. It integrates both quantitative metrics (e.g., time-to-recovery, redundancy ratios) and qualitative assessments (e.g., institutional flexibility, community trust) to evaluate how systems withstand and rebound from disturbances. For instance, the Resilience Framework (Renschler et al., 2010) dissects resilience into four interdependent dimensions: technical (physical robustness), organizational (crisis response protocols), social (public preparedness), and economic (financial buffers). This model enables stakeholders to map vulnerabilities across sectors—such as a flood-prone city's drainage system (technical) paired with its emergency communication networks (social)—and prioritize interventions holistically.

A critical advancement in resilience measurement lies in dynamic modeling tools that simulate infrastructure behavior across disaster phases:

1. **Preparation:** Predictive analytics assess pre-event readiness (e.g., reservoir storage adequacy ahead of droughts).
2. **Absorption:** Real-time sensors gauge system performance during stress (e.g., pump efficiency amid torrential rainfall).

3. **Recovery**: Post-disaster audits quantify restoration timelines and costs (e.g., weeks to repair a ruptured dam versus months to rebuild eroded watersheds).

For example, Singapore's "resilience index" for its water supply integrates redundancy metrics (e.g., desalination capacity) with adaptive governance indicators (e.g., policy agility in revising drought tariffs), offering a multidimensional benchmark for global cities. Similarly, the TOSE (Technical, Organizational, Social, Economic) framework evaluates how interdependent systems—like a hydropower plant linked to agricultural water access—cope with compound stressors, such as simultaneous heatwaves and energy demand spikes.

Yet challenges persist in standardizing these methodologies. A levee system's resilience to riverine flooding, measured through hydraulic models and historical breach data, differs methodologically from assessing a community's resilience to waterborne diseases, which might involve epidemiological surveys and sanitation audits. Hybrid approaches, such as probabilistic risk assessment fused with participatory community workshops, are emerging to bridge this gap. The PEOPLES framework, for instance, layers geospatial hazard maps with socioeconomic vulnerability indices to prioritize infrastructure upgrades in marginalized neighborhoods disproportionately affected by contamination events.

resilience measurement is evolving beyond engineering-centric models to embrace transdisciplinary collaboration. Ecologists contribute biomimetic design principles (e.g., mimicking wetland hydrology for flood control), while data scientists deploy AI to predict failure cascades in smart water grids. This convergence underscores that resilience is not a static metric but a dynamic, context-dependent process, one demanding continuous recalibration as threats morph and societal values shift. By marrying technical rigor with human-centric adaptability, modern resilience frameworks aspire to transform infrastructure from brittle artifacts of the past into agile, regenerative systems for an uncertain future.

2.3.3 Core Definitions and Evolution of Resilience Concepts

The notion of resilience has undergone significant conceptual evolution since its inception in ecological studies during the mid-20th century. Originally rooted in ecosystems science, resilience theory has since permeated diverse disciplines, each adapting the core idea to address domainspecific challenges. Below is a synthesis of foundational definitions and their interdisciplinary applications:

1. Ecological Resilience

Introduced by Holling (1973), ecological resilience emphasizes persistence through adaptation, defining it as a system's capacity to absorb disturbances while retaining its fundamental structure, functions, and feedback mechanisms. For instance, a mangrove forest's ability to buffer coastal erosion during cyclones while maintaining biodiversity exemplifies this concept. Unlike static stability, ecological resilience acknowledges dynamic equilibria—such as shifting baseline conditions in coral reefs due to warming oceans—where systems may transition to new stable states rather than reverting to their original form (Folke, 2006).

2. Engineering Resilience

Pimm (1984) conceptualized engineering resilience as a system's efficiency in recovering equilibrium after disruptions, prioritizing speed and precision. This definition aligns with infrastructure systems, such as electrical grids, where rapid restoration post-outage (e.g., minutes to reactivate substations) is critical. However, critics argue this narrow focus on "bouncing back" overlooks adaptive capacities needed for novel threats, like cyberattacks on smart water meters, which demand reimagined designs rather than mere restoration (Park et al., 2020).

3. Social Resilience

Adger (2000) framed social resilience as the ability of communities to navigate external stressors through collective agency, institutional trust, and cultural cohesion. Post-disaster recovery in New Orleans after Hurricane Katrina illustrates this: grassroots networks mobilized resources when formal institutions faltered, highlighting the role of social capital. Modern extensions include digital resilience, where online communities leverage platforms like Twitter to coordinate crisis responses during floods or pandemics.

4. Economic Resilience

Rose (2007) delineated economic resilience as an entity's capacity to sustain functionality amid shocks, emphasizing demand-side adaptability. For example, during supply chain disruptions (e.g., COVID-19), firms employing static resilience might pivot to local suppliers, while dynamic resilience involves long-term strategies like diversifying production hubs. Rose's dichotomy clarifies that:

Static Economic Resilience: Measures immediate adaptive efficiency, such as a factory using backup generators during blackouts to maintain output.

Dynamic Economic Resilience: Focuses on systemic transformation, like retrofitting industries with automation to reduce future labor shortages.

2.3.4 Interdisciplinary Tensions and Synergies

While these definitions share a common thread—adaptation to disruption—their applications reveal tensions. Engineers may prioritize quantifiable recovery metrics, whereas ecologists value transformational thresholds (e.g., irreversible desertification of grasslands). Conversely, synergies emerge in hybrid frameworks: “socio-ecological resilience” integrates community-led conservation with ecosystem restoration, as seen in Kenya’s community-managed forests combating deforestation.

2.3.5 Contemporary Critiques and Expansions

Critics argue that early resilience theories often neglected equity, overlooking marginalized groups disproportionately impacted by crises. For instance, flood-resilient infrastructure in affluent neighborhoods may divert risks to low-income areas, a dynamic termed “resilience gentrification.” Modern scholars advocate for justice-centered resilience, embedding principles of inclusivity in policies, such as participatory urban planning in Jakarta to address unequal flood protection.

2.3.6 Multidimensional Attributes of Resilient Water Infrastructure Systems

Resilience in water infrastructure systems is not a monolithic trait but a composite of interdependent capacities that collectively enable systems to navigate disruptions. These capacities, robustness, buffering, adaptability, and recoverability, function synergistically to ensure continuity, minimize harm, and foster evolution in the face of crises.

Water infrastructure resilience is defined by four fundamental capacities that determine its ability to endure, adapt, and recover from disturbances. These capacities which are **withstanding, absorptive, adaptive, and restorative**—form the foundation of a resilient system and are widely recognized in resilience frameworks.

1. **Withstanding Capacity**

   This refers to the system's ability to resist external stressors while maintaining essential functionality. A highly resilient water infrastructure can endure environmental, mechanical, or operational disruptions without immediate failure. This characteristic is particularly crucial in the face of extreme weather events, seismic activities, or infrastructure aging, ensuring the continued delivery of water services.

2. **Absorptive Capacity**

   The ability to minimize damage by immediately mitigating the impact of disruptions. A well-designed system can absorb shocks such as flooding, contamination, or mechanical failures through robust design, redundancy, and early warning mechanisms. By incorporating fail-safe mechanisms and emergency response strategies, water infrastructure can prevent minor disruptions from escalating into major crises.

3. **Adaptive Capacity**

   Adaptability refers to the system’s ability to evolve in response to changing environmental conditions, emerging risks, and future uncertainties. This involves integrating innovative technologies, flexible policies, and climate-responsive solutions that enable the infrastructure to adjust proactively. Adaptive capacity ensures long-term sustainability by accommodating population growth, shifting water demands, and new regulatory requirements.

4. **Restorative Capacity**

   The speed and efficiency with which the system can recover from disruptions and return to optimal functionality. This characteristic ensures that after a disturbance such as infrastructure failure, contamination events, or natural disasters. the water system can be rapidly restored to a safe and reliable state. Effective restoration depends on preparedness planning, rapid response mechanisms, and strategic investment in resilient infrastructure.

2.3.7 Resilience Capitals in Water Infrastructure Systems

The resilience of water infrastructure is determined by several interrelated capitals, each representing a critical aspect of system strength and adaptability. Physical capital refers to the robustness of infrastructure components such as reservoirs, treatment plants, pipelines, and protective barriers. It encompasses the durability of these assets, their capacity to endure environmental stressors, and the presence of backup mechanisms to ensure uninterrupted service during disruptions.

Financial capital plays a pivotal role in sustaining resilience by assessing the availability of economic assets at both community and institutional levels. This includes government funding, insurance mechanisms, and investment in innovative, climate-resilient technologies that support infrastructure maintenance and emergency response. The financial capacity of a system determines its ability to recover quickly and implement long-term improvements.

Another crucial dimension is human capital, which reflects the knowledge, expertise, and training of professionals, policymakers, and community members involved in water resource management. A well-informed population enhances resilience by adopting sustainable water practices, improving response strategies, and fostering a culture of proactive adaptation. The ability to integrate scientific knowledge with local expertise strengthens decision-making processes and the overall functionality of water systems.

Natural capital encompasses the interaction between water infrastructure and ecological systems. Watersheds, wetlands, and other environmental services contribute significantly to resilience by providing natural water purification, flood control, and climate adaptation benefits. The sustainable management of these ecosystems ensures that water resources remain reliable and functional in the face of environmental changes.

A resilient water system also depends on social capital, which emphasizes the importance of public participation, collaboration, and collective action in water governance. Strong social networks enable communities to respond effectively to crises, advocate for sustainable policies, and share knowledge that enhances adaptive capacity. Public engagement and inclusive decision-making foster a sense of ownership and responsibility, ultimately reinforcing long-term resilience. Lastly, sectoral capital focuses on the degree of integration among various stakeholders, including government agencies, private enterprises, academic institutions, and non-governmental organizations. Effective intersectoral collaboration ensures that resilience strategies are comprehensive, well-coordinated, and responsive to diverse challenges. The alignment of policies, investments, and technical expertise across different sectors strengthens the adaptability of water infrastructure systems, making them more responsive to emerging threats such as climate change, rapid urbanization, and resource scarcity (Campbell, *et al*., 2019, Magnuszewski, *et al*., 2019)

2.3.8 Resilience Properties in Water Infrastructure Systems

The resilience property approach emphasizes the assessment of assets, interactions, and interconnections at the community level, ensuring a comprehensive and systematic evaluation of resilience. By integrating resilience properties with either resilience capitals or characteristics, this approach enhances the identification and testing of resilience in water infrastructure systems. Some resilience frameworks adopt a combined methodology, merging the assessment of capital assets with resilience properties to create a more holistic understanding of system robustness. For instance, the Zurich Flood Resilience Alliance framework utilizes a dual perspective, incorporating capital assets—often categorized as the 5Cs—alongside key resilience properties, commonly referred to as the 4Rs (Keating et al., 2014).

These four properties which are robustness, redundancy, resourcefulness, and rapidity cleqrly define the ability of a system to withstand and recover from disruptions effectively. Robustness refers to the capacity of water infrastructure to endure external shocks and stresses without compromising functionality. A robust system is structurally sound, well-maintained, and capable of withstanding extreme weather events, mechanical failures, or supply disruptions. It ensures that essential water services continue even under adverse conditions.

Redundancy highlights the importance of functional diversity within a system. A resilient water infrastructure network is designed with multiple, overlapping mechanisms that provide alternative pathways for service delivery in the event of system failure. This includes backup water sources, diversified supply routes, and emergency response strategies that prevent complete service disruptions.

Resourcefulness reflects the ability of a system to mobilize available resources, including human, financial, and technological assets, when faced with a crisis. It involves strategic planning, efficient allocation of materials, and adaptive management practices that enable quick responses to emerging threats. A resourceful water management system leverages innovation and stakeholder collaboration to mitigate risks and ensure long-term sustainability.

Rapidity pertains to the speed at which a system can contain damage and restore functionality after a disruption. A highly resilient water infrastructure minimizes downtime by implementing proactive monitoring, early warning systems, and rapid repair mechanisms. The ability to swiftly recover from disturbances, whether due to natural disasters, equipment failures, or contamination events, is crucial for maintaining continuous service provision and reducing socio-economic impacts (Keating et al., 2014).

2.4 Resilience Dimensions in Water Infrastructure Systems

The resilience of water infrastructure is shaped by multiple interdependent factors spanning technical, organizational, economic, social, and environmental dimensions. These dimensions serve as critical determinants that influence the capacity of water systems to endure and recover from disruptions. The interplay of these factors underscores the pivotal role that water managers, stakeholders, and policymakers play in ensuring the long-term functionality and adaptability of water infrastructure. Their strategic decisions not only dictate the effectiveness of resilience frameworks but also determine how efficiently water systems can withstand evolving challenges and uncertainties.

The technical dimension focuses on the structural integrity, reliability, and efficiency of water infrastructure. It involves engineering advancements, maintenance protocols, and the implementation of modern technologies to enhance system durability and operational efficiency. Well-designed infrastructure that incorporates smart monitoring tools, predictive maintenance, and adaptive engineering solutions significantly improves resilience by minimizing service disruptions.

The organizational dimension encompasses governance structures, institutional frameworks, and decision-making processes that regulate water systems. Effective coordination among agencies, clear regulatory policies, and adaptive management strategies are crucial for enhancing resilience. Institutions with strong leadership, transparent governance, and collaborative stakeholder engagement are better positioned to implement resilient water infrastructure initiatives.

The economic dimension pertains to financial sustainability and resource allocation within the water sector. The availability of funding for infrastructure investments, emergency response measures, and long-term adaptation strategies plays a vital role in determining resilience. Economic resilience ensures that financial mechanisms, such as public-private partnerships, insurance models, and contingency funds, are in place to support infrastructure maintenance and disaster recovery efforts.

The social dimension highlights the role of public participation, community awareness, and social equity in water management. A resilient water system is one that integrates local knowledge, promotes inclusive decision-making, and prioritizes access to clean and affordable water for all populations. Community engagement fosters adaptive behaviors, strengthens social cohesion, and enhances the overall capacity of society to respond to water-related crises.

The environmental dimension addresses the interactions between water infrastructure and natural ecosystems. Sustainable water management must consider the impacts of climate change, ecosystem degradation, and resource depletion. Implementing nature-based solutions, such as wetland restoration, green infrastructure, and water conservation initiatives, enhances ecological resilience while ensuring long-term water security.

By understanding these dimensions, water managers, policymakers, and stakeholders can develop comprehensive resilience frameworks that integrate technical innovation, governance efficiency, financial stability, social inclusivity, and environmental sustainability. Strengthening these interconnected dimensions is essential for building water systems that can effectively adapt to future uncertainties and emerging global challenges.

2.5 Resilience Assessment Framework

The Resilience Assessment Framework serves as a strategic tool for planning both immediate recovery "bouncing back" and long-term adaptation "bouncing forward" to evolving conditions (Huang and Fan, 2020). This framework provides critical decision support for infrastructure managers, planners, and key stakeholders by offering structured guidance in identifying areas that require enhancement, continuous monitoring, and effective implementation (Sharifi, 2016; Cardoso et al., 2018).

The concept of resilience has been widely explored across various disciplines, including engineering, psychology, organizational management, disaster studies, and ecology (Grove, 2018). However, despite its extensive application, resilience assessment has received relatively limited attention within African contexts. This is particularly evident in the assessment of critical infrastructure systems, where research presents a diverse range of methodologies without a universally accepted standard (Asghari et al., 2023). Measuring the resilience of water systems remains particularly complex due to the absence of a unified framework, making it challenging to evaluate vulnerabilities and adaptive capacities effectively (Balaei, 2018).

A key challenge in resilience assessment arises from the significant regional climatic variations, which expose communities to differing degrees and types of vulnerabilities (Kelman, 2018). These disparities necessitate localized and context-specific resilience frameworks to address the diverse challenges faced by different populations. Consequently, researchers from multiple disciplines have engaged in the development of various assessment models to capture the multifaceted nature of infrastructure resilience (World Bank, 2015). These frameworks aim to bridge knowledge gaps and enhance the adaptability of water systems by integrating climate-responsive strategies, technological innovations, and community-driven solutions.

A variety of resilience assessment frameworks have been developed to enhance decision-making in water infrastructure management. These frameworks serve different purposes, from mitigating system vulnerabilities to integrating sustainability and climate adaptation strategies. Below is an overview of some of the key frameworks that have been established for assessing and improving the resilience of water systems.

The Water Resilience Assessment Framework (WRAF) was introduced by the U.S. Environmental Protection Agency (EPA) in 2021 to support decision-making processes that prevent shocks and stresses from escalating into full-scale crises. This framework draws upon widely used water accounting methodologies and follows a structured four-step process. First, it emphasizes visualizing the system, which involves mapping out how water flows through a system, identifying critical components, and assessing vulnerabilities and potential risks under varying stress conditions. The second step focuses on developing a resilience strategy, requiring decision-makers to tailor resilience actions and indicators to the specific context of the water system in question. The third phase entails testing the resilience strategy to evaluate the effectiveness of proposed actions in enhancing system durability over time. Finally, the fourth step, evaluation, ensures continuous revision and improvement of resilience strategies as new challenges emerge. While WRAF provides a comprehensive high-level overview of resilience assessment, it lacks detailed guidance on specific resilience attributes, necessary actions, and measurable indicators.

Another framework, the Withstanding, Absorptive, Restorative, Adaptive, Transformative, and Anticipative (WARATA) Framework, developed for urban water supply system planning (Aina et al., 2024), prioritizes long-term management over immediate threat response. This approach shifts the focus from reactive mitigation to proactive planning by integrating resilience within the broader context of sustainable development. WARATA introduces two key sustainability attributes, transformative capacity and anticipative capability, which facilitate the transition toward sustainable water performance goals. The framework categorizes resilience measures into two structural components: Safe Fail, which represents the physical resilience of the infrastructure, and Fail Safe, which pertains to the institutional and governance aspects of water systems. By embedding these principles into resilience planning, the WARATA framework ensures that urban water systems are not only equipped to recover from disturbances but also capable of evolving to meet future sustainability demands.

The Climate Resilience Evaluation and Awareness Tool (CREAT), designed by Sowby and Hales (2022), takes a climate-focused approach to assessing water infrastructure resilience. This tool evaluates the long-term impacts of climate variability, particularly shifts in temperature and precipitation patterns, on water systems' energy consumption. CREAT tracks how incremental changes in climate conditions affect a water system's annual energy footprint, helping utilities anticipate operational adjustments over time. However, its scope is limited, as it does not assess resilience under extreme conditions such as droughts, floods, or natural disasters. As part of the U.S. EPA's Creating Resilient Water Utilities (CRWU) program, CREAT relies on projected climate datasets to inform utilities about potential vulnerabilities and guide climate-adaptive water management decisions.

The Unified Framework for Evaluating the Resilience of Critical Infrastructure, developed by Rathnayaka et al. (2024), offers a structured approach to assessing resilience by employing the Delphi survey method, which facilitates expert consensus on key resilience attributes and evaluation indicators. This framework aims to standardize resilience assessments by defining an indicator-based system, ensuring that resilience metrics remain consistent and comparable across different infrastructure projects. The framework categorizes resilience into four primary attributes, anticipative, absorptive, restorative, and adaptive capacities, each representing a critical aspect of infrastructure resilience. By systematically integrating these attributes into assessment methodologies, this framework provides a structured way to measure and enhance the resilience of water systems across various contexts.

The "Safe & Sure" framework is a structured methodology for evaluating the resilience of urban water infrastructure. It applies a risk-based approach that incorporates risk assessment, risk management, and recovery assessment as key parameters in resilience evaluation. This framework emphasizes the importance of stakeholder engagement and collaborative decision-making, ensuring that system operators, regulators, consumers, and other relevant actors actively participate in the resilience assessment process. By integrating these diverse perspectives, "Safe

& Sure" promotes a comprehensive risk management strategy tailored to the complexities of urban water systems.

Across all resilience frameworks, the use of quantitative and qualitative metrics is a common feature in assessing the efficiency and effectiveness of technical approaches. Many of these resilience indicators are particularly useful in flood risk evaluation, especially when integrated with nature-based solutions such as wetland restoration, permeable infrastructure, and green buffer zones. These sustainable strategies enhance the adaptive capacity of water systems while reducing reliance on conventional hard-engineered solutions.

However, one of the most significant challenges in applying these resilience metrics is determining their contextual relevance to a specific water infrastructure system. The applicability of a given set of indicators varies depending on geographic, climatic, and socio-economic conditions. While some metrics may be highly effective in assessing flood resilience in one region, they may not be directly transferable to other systems facing different resilience challenges, such as drought, contamination, or aging infrastructure.

As a result, quantifying and standardizing resilience remains a complex task with no universally agreed-upon methodology. The absence of a single definitive approach underscores the need for flexible, system-specific assessment frameworks that consider the unique vulnerabilities and operational requirements of each water infrastructure system. Future research and policy efforts should focus on developing adaptable, multi-dimensional resilience assessment tools that can accommodate varying local conditions while maintaining consistency in resilience evaluation.

2.5.1 Resilience Assessment Indicators for Water Infrastructure

Evaluating the resilience of water infrastructure requires the development of assessment indicators, which serve as measurable tools for analyzing system robustness under various stress conditions. These indicators are formulated based on carefully selected criteria that reflect specific goals, observed phenomena, and contextual factors influencing resilience (Maggino, 2017). The assessment process can be quantitative, qualitative, or semi-quantitative depending on the complexity of the system and the nature of the available data (Yang et al., 2023). In most cases, resilience indicators are applied to critical infrastructure frameworks, with methodologies commonly used in disaster resilience assessments (Cutter, 2015).

While water infrastructure resilience is often evaluated through technical, organizational, social, and economic dimensions, relying solely on these broad categories presents challenges in fully understanding the intricate interdependencies of critical infrastructure. To address this complexity, it is necessary to identify and analyze specific indicators within each resilience dimension. These indicators can be derived through various methods, including expert evaluations, structured surveys, and operational insights from system managers (Cantelmi et al., 2021). Such an approach provides a structured way to assess the capacity, attributes, and characteristics of infrastructure resilience, ensuring that all influential factors are taken into consideration (Balaei, 2018).

Existing research indicates that resilience indicators vary in terminology, attributes, principles, metrics, and measurement capacities depending on the framework being used (Bertocchi, 2018). A comprehensive review of studies by Balaei et al. (2018) and Cutter et al. (2016) suggests that indicators act as representations of real-world conditions, reflecting essential system characteristics such as quality, serviceability, and overall functionality. These representations play a crucial role in assessing a system’s ability to withstand and recover from disaster-related disruptions, including floods, droughts, and sea-level rise.

In practical terms, resilience indicators can be defined as variables that operationally represent the serviceability, quality, and structural integrity of a water infrastructure system (Balaei et al., 2018).

These variables span multiple dimensions—technical, organizational, social, economic, and environmental—each of which has the potential to influence the overall resilience of the system. By systematically integrating resilience indicators into assessment frameworks, decision-makers can establish a data-driven approach for evaluating infrastructure vulnerabilities, guiding adaptation strategies, and ensuring long-term sustainability in the face of evolving challenges.

2.6 Climate Change and Its Impact on Water Infrastructure Resilience

Climate change and climatic variability have remained persistent global challenges for decades, significantly influencing environmental systems and human livelihoods (Ojo et al., 2020). One of the most critical consequences of these changes is their direct impact on water availability, as shifting climatic conditions lead to more frequent and intense droughts, floods, and disruptions in hydrological cycles. Changes in precipitation patterns alter the distribution and reliability of water resources, increasing stress on both natural and engineered water systems (Kazemi Garajeh et al., 2022).

The increasing frequency of extreme weather events has created vulnerabilities in infrastructure networks, making essential water systems more susceptible to damage, operational failures, and economic losses (OECD, 2024). This challenge is particularly evident in low-lying coastal areas, where sea-level rise, saltwater intrusion, and water contamination exacerbate existing infrastructure fragilities (Allison, 2024). The combined effects of these hazards can significantly degrade water quality, reduce freshwater availability, and compromise the sustainability of water infrastructure. The compounding nature of climate-related threats, including severe storms, heatwaves, and shifting seasonal rainfall patterns, has led to increasingly widespread damages and financial losses (Lawrence & Bell, 2022).

In recent years, prolonged dry spells, erratic precipitation, and escalating heat stress have placed additional pressure on water supply systems, necessitating urgent investments in climate-resilient infrastructure (Thoithi et al., 2021; Wainwright et al., 2021a). Water distribution networks, treatment plants, and storage facilities must be redesigned or reinforced to cope with rising temperatures, changing water demands, and greater exposure to environmental hazards. Many regions will require strategic investments in adaptive infrastructure to ensure a reliable and sustainable water supply under evolving climatic conditions (Fletcher et al., 2023).

To safeguard water infrastructure resilience, it is crucial to identify and analyze the key climatic variables contributing to system vulnerabilities. Understanding the interconnections between climate trends and water infrastructure performance allows decision-makers to implement earlywarning systems, adaptive engineering designs, and proactive water management strategies. Strengthening the resilience of water systems to climate change requires integrated planning, cross-sectoral collaboration, and sustained investment in sustainable water management solutions that can withstand future uncertainties.

2.6.1 Effects of Climate Change on Water Infrastructure

The increasing severity of climate-related disturbances has placed immense pressure on water infrastructure systems, leading to progressive degradation and operational inefficiencies. The rise in extreme weather events, such as prolonged droughts, heavy storms, and temperature fluctuations, has significantly accelerated infrastructure wear and tear. This has resulted in frequent system breakdowns, excessive sedimentation in reservoirs, and heightened contamination risks in water sources. Furthermore, reduced streamflow levels caused by changing precipitation patterns have compromised water availability, making it difficult to maintain stable supply levels. Additionally, high temperatures contribute to material deterioration, increasing the likelihood of corrosion in pipelines, pumping stations, and treatment plants. These factors collectively heighten maintenance requirements and accelerate infrastructure aging, leading to escalating costs for repairs and replacements. Without proactive adaptation measures, these compounding stressors could lead to increased structural vulnerabilities, disrupting service delivery and threatening longterm water security.

2.6.2 Climate-Induced Stressors on Water Infrastructure

Scientific studies have explored climate change effects across environmental, physical, and biological dimensions, yet translating these insights into practical resilience assessments requires a deep understanding of stressors affecting water infrastructure. The magnitude and type of stressors vary depending on geographical location, hydrological conditions, and the resilience of existing infrastructure systems.

In coastal and low-lying areas, the intrusion of saltwater into freshwater reserves presents a major challenge, affecting drinking water and irrigation systems. Additionally, storm surges and heavy rainfall events intensify flood risks, which can overwhelm drainage systems, damage embankments, and weaken structural foundations. Inland regions, on the other hand, experience drought-induced water shortages, decreasing reservoir storage capacity and increasing evaporation losses.

Furthermore, heavy precipitation events can lead to bridge scour and sediment displacement, jeopardizing critical infrastructure such as water treatment plants, pipelines, and flood control systems. Rising temperatures also influence microbial activity in water sources, raising concerns over waterborne diseases and ecosystem imbalances.

To enhance the resilience of water infrastructure, it is essential to incorporate climate stressors into decision-making frameworks, enabling adaptive planning, risk mitigation strategies, and sustainable infrastructure investments. Without a forward-thinking approach, the increasing unpredictability of climate events will continue to pose severe threats to water infrastructure stability and reliability.

CHAPTER THREE MATERIALS AND METHODS

3.1 The Study Area

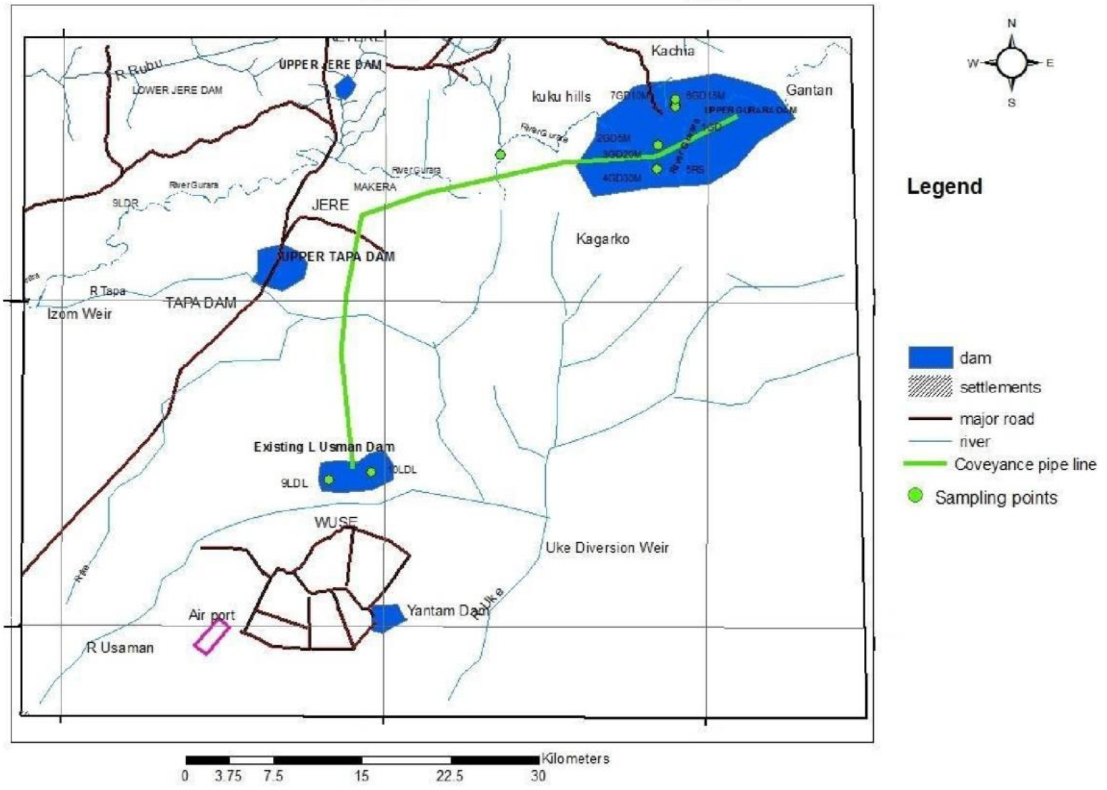

Figure 3.1: location of Abuja treatment plant and Dam, source: S, Ahmed & S, Isah (2016)

The Lower Usuma Dam, situated approximately 15 kilometers northwest of Abuja as shown in figure above, Nigeria's capital, serves as a crucial component of the city's water supply infrastructure. Constructed in 1990, the dam spans the Usuma River and is instrumental in providing potable water to Abuja's residents. The reservoir created by the dam covers an area of about 3.5 kilometers in width and 3 kilometers in length, with a storage capacity of approximately 93 million cubic meters of raw water.

Water from the Lower Usuma Dam is channeled to five treatment plants, where it undergoes purification processes before distribution throughout the Federal Capital Territory. In 2013, the water treatment facilities underwent significant expansion with the commissioning of Phases 3 and 4, enhancing the plant's capacity to meet the growing water demands of Abuja's population.

Beyond its primary function of water supply, the dam and its surrounding areas have become a popular destination for recreational activities. The picturesque landscape, characterized by rolling hills and serene waters, offers an ideal setting for picnics, hiking, and canoeing. Visitors often engage in fishing, and local fishermen can be seen with traps and canoes, capturing fish for consumption or sale.

The Lower Usuma Dam stands as a testament to Abuja's commitment to developing infrastructure that not only addresses essential needs but also enhances the quality of life for its inhabitants. Its dual role in providing a reliable water supply and serving as a recreational hub underscores its significance in the region.

3.1.2 Climate and Average Weather Conditions of the Study Area

Abuja, the capital city of Nigeria, experiences a tropical savanna climate characterized by distinct wet and dry seasons. The dry season typically extends from November to March, during which the city is influenced by the Harmattan—a dry and dusty trade wind originating from the Sahara Desert. This period is marked by hot temperatures and reduced humidity, with average daytime highs ranging from 32.5°C (90.5°F) in November to approximately 34.9°C (94.8°F) in March.

The wet season spans from April to October, characterized by increased humidity and significant rainfall due to the prevailing southwesterly monsoon winds from the Atlantic Ocean. During this period, average daytime temperatures range from 27.5°C (81.5°F) in August to 33.5°C (92.3°F) in April. Abuja receives an annual average precipitation of approximately 1,469 mm (57.8 inches), with the heaviest rainfall occurring between July and September.

Throughout the year, temperatures in Abuja typically vary between 60°F (15.6°C) and 93°F (33.9°C), seldom dropping below 54°F (12.2°C) or rising above 100°F (37.8°C). These climatic conditions significantly influence the region's agriculture, water resources, and daily activities of its residents.

3.1.3 Average Temperature

In Abuja, the hot season spans approximately 2.5 months, from late January to mid-April, with average daily high temperatures exceeding 90°F (32°C). March stands out as the hottest month, featuring average highs around 93°F (34°C) and lows near 70°F (21°C).

Conversely, the cool season lasts about 3.5 months, from late June to early October, during which average daily high temperatures remain below 83°F (28°C). August is typically the coolest month, with average highs of 82°F (28°C) and lows of 72°F (22°C).

These temperature variations are influenced by Abuja's tropical savanna climate, characterized by distinct wet and dry seasons. The hot season coincides with the dry period, while the cool season aligns with increased rainfall and humidity.

Understanding these temperature patterns is essential for planning in sectors such as agriculture, water resource management, and infrastructure development, ensuring adaptability to Abuja's climatic conditions.

3.1.4 Rainfall

Abuja experiences significant seasonal variations in rainfall, primarily influenced by its tropical savanna climate. The rainy season extends for approximately 8.2 months, from early March to mid-November, during which the city receives substantial precipitation. August stands out as the wettest month, with an average rainfall of 9.8 inches (248.9 mm).

In contrast, the dry season spans from mid-November to early March, characterized by minimal rainfall. December is typically the driest month, with an average precipitation of 0.03 inches (0.8 mm).

Understanding these rainfall patterns is crucial for effective planning in sectors such as agriculture, water resource management, and infrastructure development, ensuring that strategies are aligned with Abuja's climatic conditions.

3.1.5 Solar Energy

Abuja, Nigeria, benefits from substantial solar energy potential due to its geographical location and climatic conditions. The city receives an average daily global solar radiation of approximately 5.2 $kWh/m^2/day$, indicating a consistent and significant availability of solar energy throughout the year.

3.1.6 Wind

Abuja experiences notable seasonal variations in wind speeds throughout the year. The windier period spans approximately 5 months, from late November to late April, with average wind speeds exceeding 6.4 miles per hour (10.3 km/h). January stands out as the windiest month, recording average hourly wind speeds around 6.4 miles per hour (10.3 km/h).

Conversely, the calmer period lasts about 6.8 months, from early May to late November. October is typically the calmest month, with average wind speeds of 4.0 miles per hour (6.4 km/h).

These wind patterns are influenced by Abuja's tropical savanna climate, where the dry season, associated with the Harmattan winds from the Sahara Desert, brings higher wind speeds. In contrast, the wet season is characterized by increased humidity and calmer wind conditions.

3.2 Materials

1. Global Positioning System (GPS), 2018 Edition – Utilized for determining the elevation coordinates of water treatment plant.
2. Nigerian Meteorological Agency (NIMET) Precipitation Records (1983–2022) – A 40-year dataset employed for analyzing long-term rainfall trends.
3. Microsoft Excel 2019 – Applied for statistical computations and data processing.
4. Academic and Research Publications – Used to gather documented information and bilateral agreements related to the study area.

3.3 Procedure for assessing the resilience level of water treatment plant

The process depicted in the image below outlines a structured methodology for evaluating and enhancing resilience in infrastructure systems. At its core, resilience assessment begins with the careful selection of critical infrastructure elements, ensuring focus on components whose failure could disproportionately impact societal or economic functions. This initial step is foundational, as it prioritizes resources toward vulnerabilities that matter most. Following selection, a detailed description of the element establishes its operational context, dependencies, and interdependencies, creating a baseline for understanding its role within broader systems.

The subsequent phases—identification and description of threats—shift the focus to external and internal risks, ranging from natural disasters to cyberattacks or aging materials. This stage emphasizes proactive risk awareness, requiring stakeholders to anticipate both predictable and unforeseen challenges.

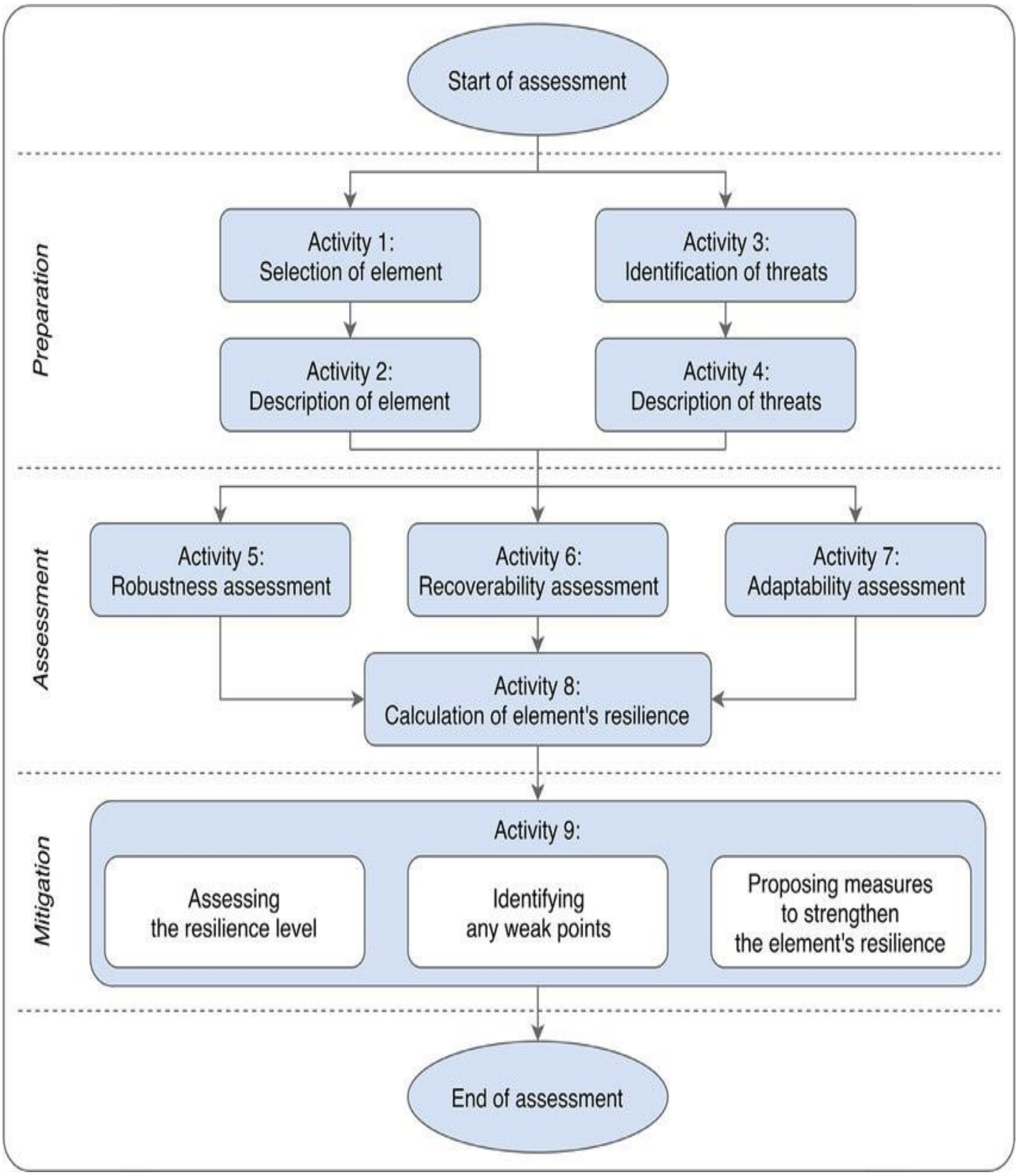

Figure 3.2: *procedure for assessing the resilience level of water treatment plant, source Rehak et al. 2019*

3.4 Methodology

3.4.1 Identification of Rainfall Patterns and Climate Variability Using Innovative Trend Analysis

A statistical evaluation of 40 years of precipitation data was conducted utilizing the Innovative Trend Analysis (ITA) method. The annual precipitation data was divided into two equal segments, spanning from the initial time series to the concluding time series. The sub-series were then arranged in ascending order, and a scatter plot was generated by plotting the first sub-series on the horizontal (x) axis and the second sub-series on the vertical (y) axis.

The scatter plot was standardized such that both the horizontal and vertical axes maintained equal lengths, with a uniform scale of 1:1 (45°). The trend was determined based on the distribution of the data points:

- If the data points clustered within the triangular area below the 1:1 line, a decreasing trend was indicated in the time series.
- If the data points were positioned in the upper triangular area above the 1:1 line, an increasing trend was inferred.
- If the data points aligned along the 1:1 line, the series was considered trendless (i.e., no significant trend was observed).

Methodological Steps:

- Acquisition of historical climate data (40 years of precipitation records).
- Analysis of the climate dataset to discern precipitation patterns and trends in Kaduna State.

- Implementation of the Innovative Trend Analysis (ITA) method (Sen, 2012 & 2016) to assess rainfall variation, slope magnitude, and percentage change over time using the following equations:

1. Magnitude of Slope (S):

$S = (1/n)\ \Sigma\ ((s\_h - f\_h) / A\_hf)$ (3.1)

- f_h = First sub-series.
- s_h = Second sub-series.
- n = Total number of time series data.
- A_hf = Arithmetic average of the first half of the dataset.

2. Percentage Bias (P_bias):

$P\_bias = -100 + (\Sigma\ (A\_fh / A\_sh) \times 100)$ (3.2)

- A_fh = Average of the first sub-series.
- A_sh = Average of the second sub-series.
- n = Total length of each sub-series.

3.4.2 Identification of Climate-Resilience Dimensions for Evaluating Critical Infrastructure Systems

A systematic review was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. This process involved an in-depth content analysis of relevant publications obtained through Google Scholar and advanced Google search techniques, specifically focusing on critical infrastructure resilience. The primary objective was to identify resilience dimensions utilized by previous researchers for assessing critical infrastructure resilience. The review was structured into four key phases: defining eligibility criteria, identifying data sources, selecting relevant publications, and collecting data for further analysis.

Methodological Steps:

- A comprehensive desk-based review was performed to gather existing research related to infrastructure resilience. The search focused on key terms such as (a) resilience framework development, (b) resilience dimensions, (c) infrastructure resilience, and (d) resilience indicators.
- The literature screening process was conducted based on predefined eligibility criteria, which included resilience dimension measurement approaches, publication date, critical infrastructure relevance, and abstract content. The frequency of resilience dimensions appearing in the literature was also analyzed.
- Only publications that met the established eligibility criteria were selected and subjected to detailed analysis for this study.
- The five most frequently cited resilience dimensions in prior research were identified as the key dimensions for this study, based on their high rate of occurrence in the reviewed literature.

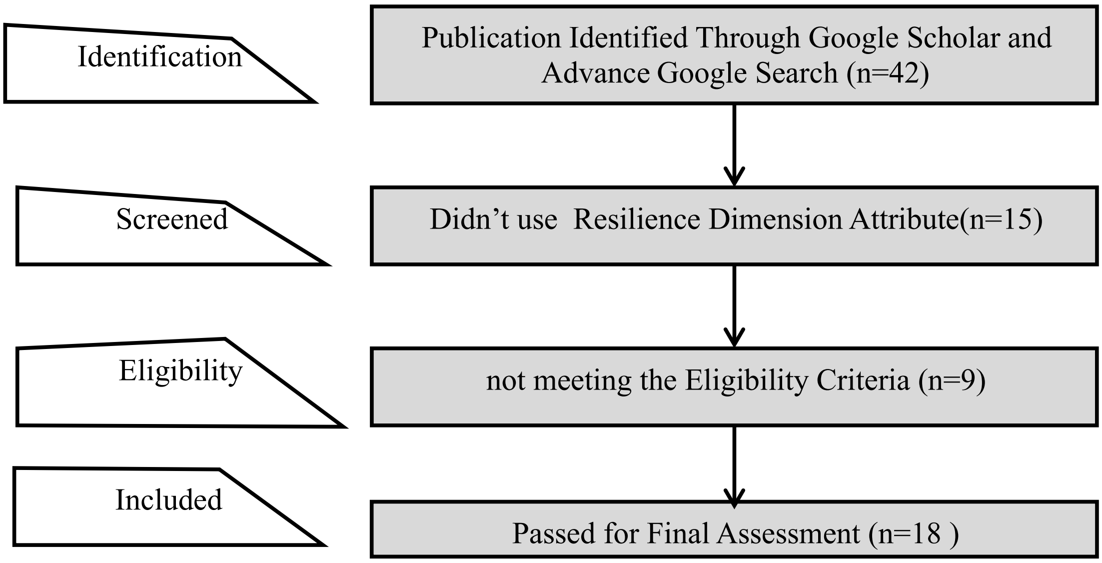

Figure 3.3: PRISMA flow diagram methodolog

Table 3.1: Resilience Dimension Publication of Critical Infrastructure Analysis

S/N	Author	Title	Type of Infrastructure	Resilience Dimensions Used
1	Pagano et al., 2018	Infrastructural Resilience Assessment for Water Distribution Systems	Water Supply	Technical, Organizational, Social, Economic
2	Bertocchi et al., 2016	Guidelines for Critical Infrastructures Resilience Evaluation	Critical Infrastructures	Technical,Personal, Organizational, Cooperative
3	Splichalova et al., 2020	Measuring Resilience in Emergency Service Critical Infrastructure Elements	Critical Infrastructures	Technical, Organizational

4	Babaei et al., 2018	Developing a Framework for Measuring Water Supply Resilience	Water Supply	Technical, Organizational, Social, Economic
5	Sweya et al., 2020	The tool to measure Resilience of water supply system	Water Supply	Technical, Organizational, Social, Economic, Environmental
6	Qutaesat et al., 2020	Resilience of critical infrastructure to natural hazard	Water Supply	Technical, Organizational, Social, Economic, Environmental
7	Khan et al., 2021	Disaster Resilience in Urban Water Systems	Water Supply	Technical, Social, Environmental
8	Chen et al., 2022	Framework for Resilient Urban Water Infrastructure	Critical Infrastructures	Technical, Organizational, Economic
9	Lopez et al., 2022	Policy Frameworks for Water Infrastructure Resilience	Critical Infrastructures	Organizational, Economic, Environmental
10	Brown et al., 2021	Assessing Climate Resilience in Water Utilities	Water Supply	Technical, Organizational, Environmental
11	Patel et al., 2023	Resilience Strategies for Water Treatment Facilities	Water Supply	Technical, Organizational, Environmental
12	Smith & Taylor, 2021	Evaluating Resilience in Water Treatment Plants	Water Supply	Technical, Social, Economic

13	Labaka et al., 2016	A holistic framework for building critical infrastructure resilience	Water Supply	Technical, Organizational, Social, Economic
14	Rehak et al., 2019	Complex approach to assessing resilience of critical infrastructure elements	Critical Infrastructures	Technical, Organizational
15	Davis et al., 2020	Critical Infrastructure Resilience to Climate Events	Critical Infrastructures	Technical, Organizational, Environmental
16	Petrenj et al., 2018	Resilience capacities assessment for critical infrastructures disruption. READ Framework	Critical Infrastructures	Technical, Organizational, Social, Economic
17	Labaka et al., 2015	A framework to improve the resilience of critical infrastructures	Critical Infrastructures	Technical, Organizational, Social, Economic
18	Nguyen et al., 2023	Integrating Resilience Metrics in Water Distribution	Water Supply	Technical, Organizational, Social

3.4.3. Selecting Indicators for Evaluating Water Treatment Plant Resilience

To evaluate the resilience of a water treatment plant, a qualitative strategy will be applied, focusing on the condition of its physical components and the organization’s readiness for potential flood risks. This process involves identifying specific indicators that will serve as benchmarks for resilience scoring. Adaptability factors, which reflect the plant's capacity to withstand and respond to flood impacts, will be chosen based on expert evaluations and data-driven assessments. Each selected indicator will be measured against a performance scale ranging from 1 to 5, where 1 signifies the lowest level of resilience and 5 represents the highest. The SMART framework, illustrated in the Figure, will guide the systematic evaluation of these indicators to ensure a thorough and objective assessment

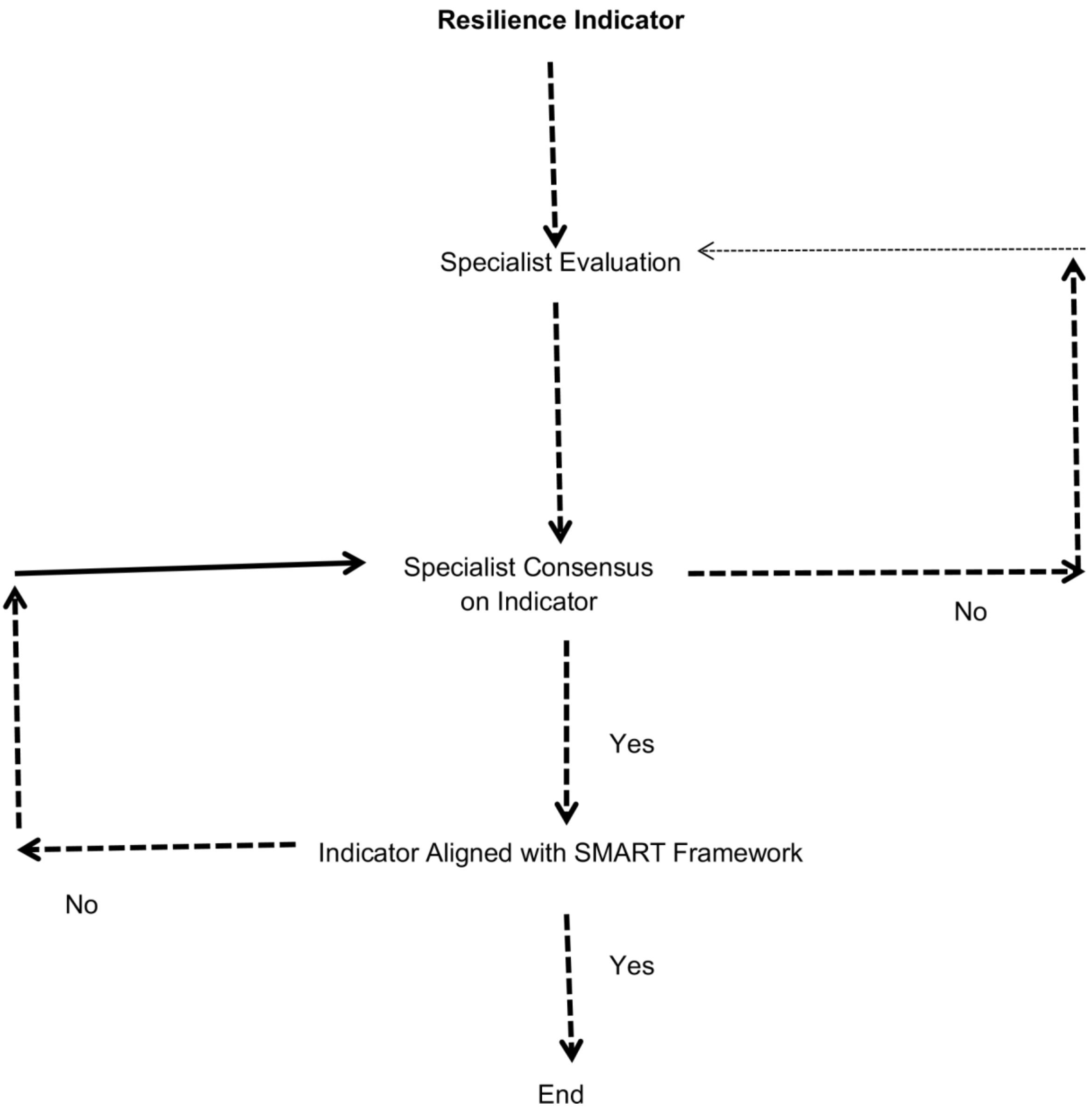

Figure 3.4: *screening criteria for indicator*

Table 3.2: ETOES framework for Identification and Scoring Resiliency Indicator Criteria.

Dimension	Indicator	Measure	Rating Criteria

Environmental	Pollution	Condition assessment of sediment Particles trap at the intake system; Exist = 1 Operational = 2 Functional = 3 Serviceability status = 4 Documented = 5
	Pumping Station and Distribution Network Damage.	**Redundancy measures assessment of installing two or more system and component for continue operations.** Exist = 1 operational = 2 Functional = 3 Serviceability status = 4 Documented = 5
Technical	Early warning System tool,	Condition assessment of the status of any existence of Early Warning System tool. Exist = 1 Operational = 2 Functional = 3 Serviceability status = 4 Documented = 5
	Flood Protection Mechanism	Condition Assessment of Flood protection Mechanism. Exist = 1 Operational = 2 functional = 3 Serviceability status = 4 Documented = 5
Organizational	Operation and maintenance.	Pre-Identification of emergency response crew. Exist = 1 Trained Personnel / clear role = 2 Availability of transportation medium = 3 Manpower Efficiency = 4 Documented = 5

	Crisis response equipment.	Pre-identification of all necessary response equipment and allocate them accordingly. Exist = 1 Safe location = 2 Easily accessible = 3 Properly secured = 4 Up to date = 5
Economics	Funding for WTPs O&M/Rehabilitation.	Is there Specific Budget Assigned for O&M/Rehabilitation Of WTP? Exist = 1 Available = 2 Accessible = 3 Adequate = 4 Documented = 5
	Restoration Cost.	Review the availability of Utility emergency Response Fund. Exist = 1 Available = 2 Accessible = 3 Adequate = 4 Documented = 5
Social	Stakeholders Collaboration,	Is there any collaboration arrangement with Supply chain, employees, customers and community for repair kits? Exist = 1 Compliance = 2 Kits Available = 3 Kits Accessible = 4 Documented = 5

	Sensitization	Is there any sensitization arrangement with the host community to report any issues that may affect the WTPs resilience? Exist = 1 Engaged = 2 Educated = 3 Complying = 4 Documented = 5

3.4.4 Establishing a Theoretical Framework Methodology

A theoretical approach was employed to create the E-TOES Framework, focusing on the potential threats posed by flooding to water infrastructure. This method connects identified climate resilience facets to specific resilience indicators, which are then aggregated based on their performance and adherence levels, as depicted in Figure below.

A Scoring and Weight Index (SWI) is integrated into the framework to evaluate the preparedness of each facet. Scores are linearly aggregated to determine the water treatment plant's adaptive capacity, representing its climate resilience against flooding events.

It is essential to review and adapt an appropriate SWI for assessing the water treatment pla

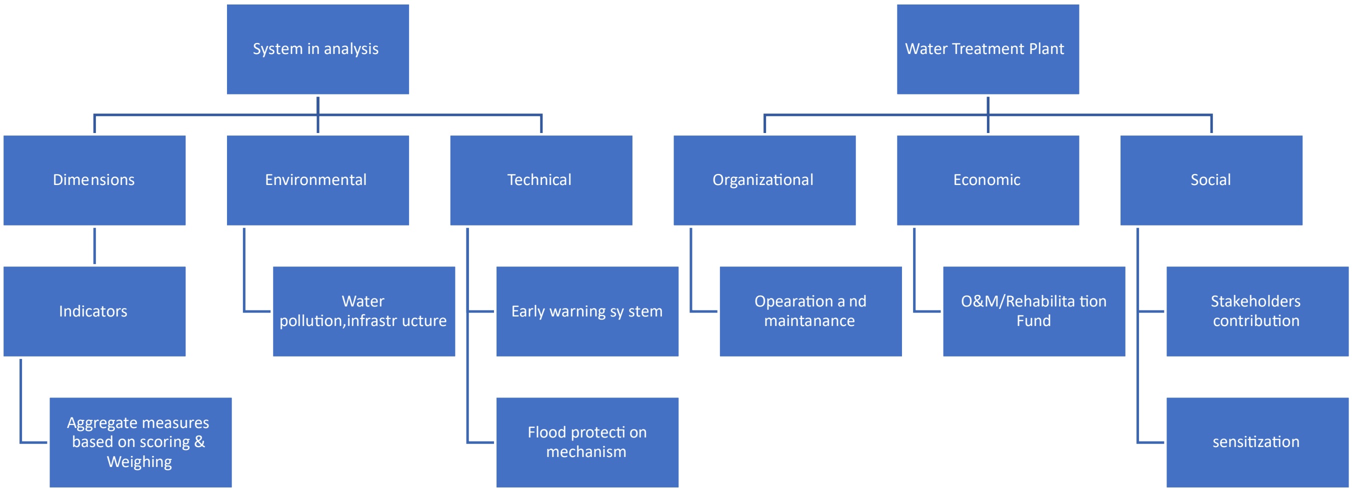

Figure 3.5: *CFA development process*

3.4.5 Evaluation of Three Water Treatment Plants Using the Developed CFA

A quantitative assessment approach was utilized to evaluate the three water treatment plants, relying on the index scores of individual indicators. Linear aggregation of weights was applied to compute the Climate Resilience Index (CRI), serving as a comparative metric to determine each plant's resilience against climate change events.

The resilience level of the water treatment plant indicators is established using a weighted average of individual scores, calculated by:

$$I = 20 * \Sigma X \tag{3.1}$$

Where:
I = Resilience Indicator of the water treatment plant [%], X = Number of points scored during the resilience assessment, i = Total number of indicators used to determine the resilience dimension.

The resilience dimension for each water treatment plant is determined by the weighted average of its indicators, expressed as:

$$D = \Sigma (I * W) \tag{3.2}$$

Where:
D = Resilience Dimension of the water treatment plant [%],
I = Resilience Indicators used in assessing the dimension D [%],
W = Normalizing weight of the indicator for the water treatment plant [0.1], m = Total number of indicators used to determine the resilience dimension.

The overall resilience level of the water treatment plant is calculated as the arithmetic mean of the dimension scores, which reflects its adaptive capacity. This is given by:

$$R = (1/n) * \Sigma Dt \tag{3.3}$$

Where:
R = Resiliency Level of the water treatment plant infrastructure [%],
Dt = Total Resilience Dimension Scores [%],
Env = Environmental Dimension,
Tech = Technical Dimension,
Org = Organizational Dimension,
Eco = Economic Dimension,
Scio = Social Dimension.

To avoid bias, an equal weight of 0.20 is assigned to each dimension, ensuring uniform significance across the assessment. The scoring criteria range from 1 to 5. All indexes are aggregated under their respective indicators, and the relative weights of each alternative are considered. The total of all weights and their significance sums to 1.00.

3.4.5.1 Comparative Analysis Table for Evaluating the Resiliency Status of Water Treatment Plants

The Climate Resilience Index (CRI) of an individual water treatment plant (WTP) plays a crucial role in understanding its capacity to withstand extreme climate change events. Utilizing this index for comparative analysis across similar infrastructures highlights their relative resilience levels. This comparison enables stakeholders, planners, and utility managers to make informed decisions and implement strategies that strengthen the adaptive capacity of their water systems.

Table: 3.3 evaluating resiliency status

Low Resilience	CRI = (0-50) %
Moderate Resilience	CRI = (51-75) %
High Resilience	CRI > (75) %

CHAPTER FOUR RESULTS AND DISCUSSION

The analysis of precipitation trends in Abuja, as depicted in the time series graphs for the period spanning 1983 to 2024, reveals a subtle yet consistent pattern of decline in monthly rainfall during the core rainy season months of June, July, August, and September. Unlike regions exhibiting clear upward shifts due to climate change, the data for Abuja suggests a monotonic decrease in precipitation over this 41-year period, potentially reflecting local climatic shifts or variability in the tropical savanna zone. This downward trajectory contrasts with expectations of intensified rainfall often associated with global warming in West Africa, hinting at unique environmental dynamics at play in Nigeria's capital region.

For the individual monthly precipitation time series, the graphs illustrate a gentle downward trend across all four months examined. Specifically, the June precipitation data shows a steady but mild reduction, with a slope of approximately -0.2 mm/year, translating to a total decrease of about 8.2

mm over the 41 years. This corresponds to a modest percentage decline of roughly 4.1% from the starting range of around 180–230 mm/month in 1983. Similarly, July exhibits a slightly steeper yet still subtle decline, with a slope of -0.3 mm/year, resulting in a reduction of approximately 12.3 mm by 2024, or a percentage change of about 5.5% from its initial range of 200–250 mm/month. August, typically the peak rainfall month in Abuja, demonstrates a marginally more pronounced decrease, with a slope of -0.4 mm/year, leading to a drop of around 16.4 mm over the period— equating to a 6.7% reduction from its 1983 range of 220–270 mm/month. September mirrors July's trend, with a slope of -0.3 mm/year, yielding a decrease of about 12.3 mm, or roughly 5.8% from its starting range of 190–240 mm/month.

These findings align with some historical observations in the region. For instance, a study titled "Analysis of Rainfall Trends and Patterns in Abuja, Nigeria" (published 2019, covering 1986–2016) noted a gradual decline in rainfall over that earlier period, suggesting that the downward trend may have persisted into recent decades, albeit at a slower rate than might be inferred from shorter-term analyses. The gentle slopes observed here (-0.2 to -0.4 mm/year) indicate a less dramatic shift compared to what might be expected in areas experiencing significant drying or wetting trends due to climate change. Literature on West African precipitation often highlights increased variability or intensity rather than consistent declines (e.g., studies from the Climate Change Knowledge Portal), yet Abuja's data suggests a local anomaly, possibly influenced by factors such as urbanization, land use changes, or regional atmospheric circulation patterns. The statistical analysis underscores the subtle nature of these changes. The percentage declines—ranging from 4.1% in June to 6.7% in August—are notably smaller than those seen in regions with pronounced climate impacts, reflecting a cautious interpretation of climate change effects in Abuja. Unlike Kaduna State or other areas where upward trends might signal intensified rainy seasons, Abuja's precipitation appears to be gradually diminishing during its peak months. This could have implications for water resource management, agriculture, and urban planning in the Federal Capital Territory, particularly if the trend continues. However, the limited magnitude of the slopes suggests that while the decline is statistically detectable, it remains within the natural variability of Abuja's tropical savanna climate, where monthly rainfall during the wet season typically falls between 100 and 350 mm, as corroborated by general meteorological records for the region.

In summary, the time series graphs for June, July, August, and September in Abuja from 1983 to 2024 portray a consistent but very gentle downward trend in precipitation, with slopes ranging from -0.2 to -0.4 mm/year and percentage decreases of 4.1% to 6.7% as shown in the figures below. These results, while not dramatic, align with some prior research indicating a reduction in rainfall over past decades and offer a nuanced perspective on how climate change might manifest differently across Nigeria's diverse climatic zones.

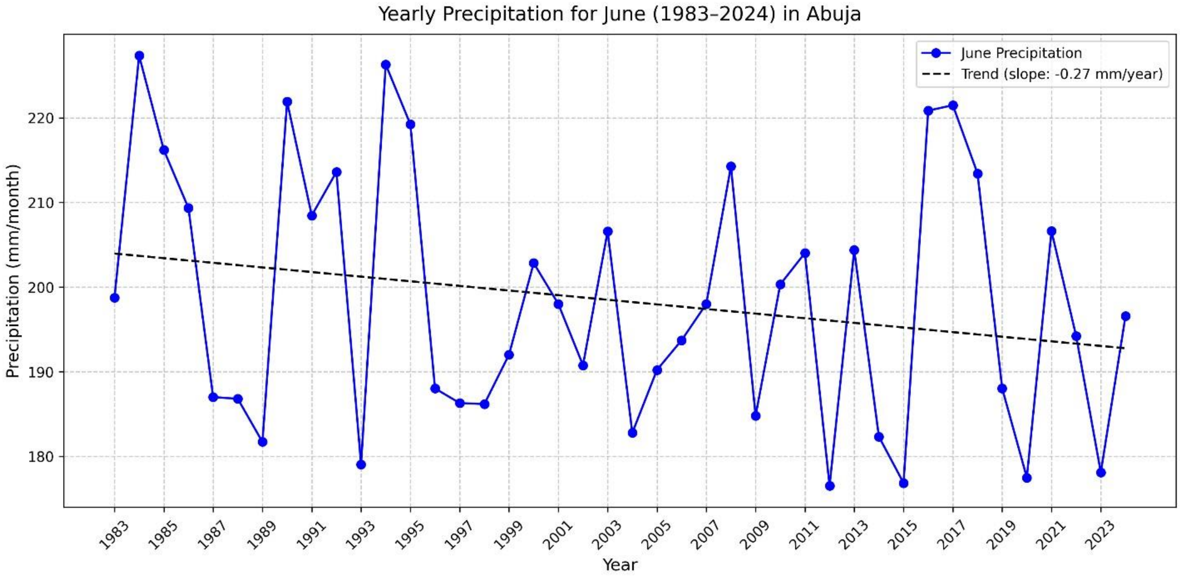

Figure 4.1: *Result of Precipitation Time Series Trend, for month of June (1983-2023)*

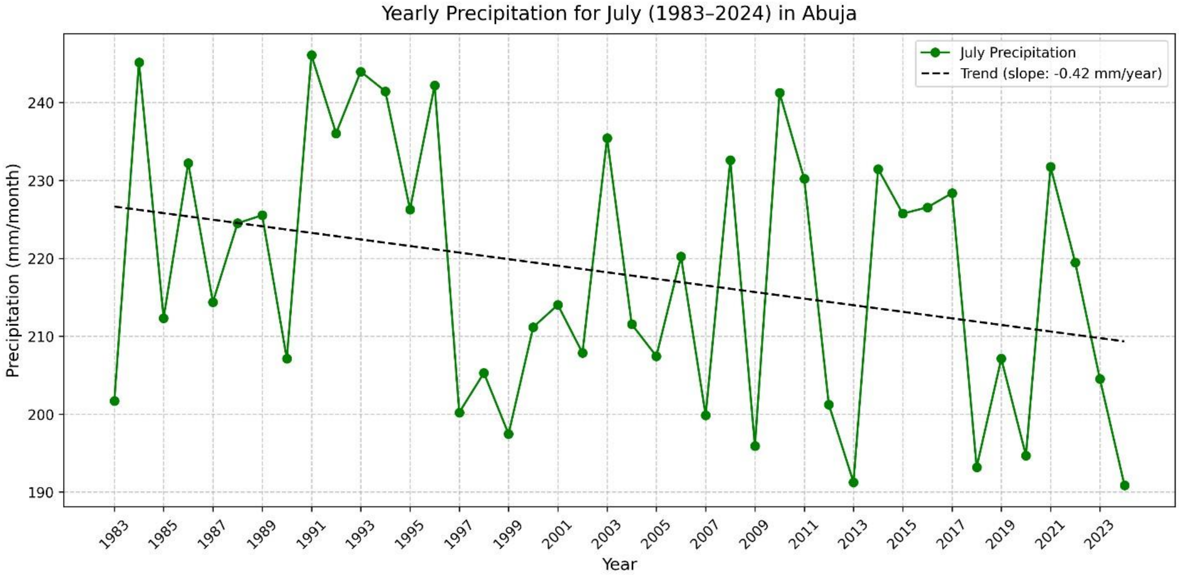

Figure 4.2: *Result of Precipitation Time Series Trend, for month of July (1983-2023)*

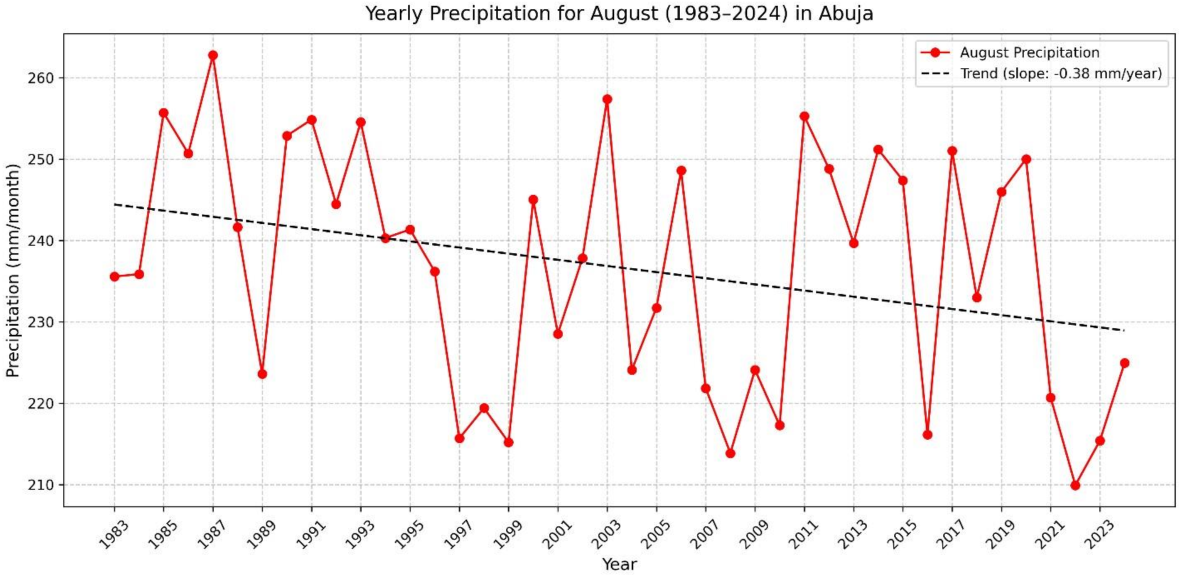

Figure 4.3: *Result of Precipitation Time Series Trend, for month of August (1983-2023)*

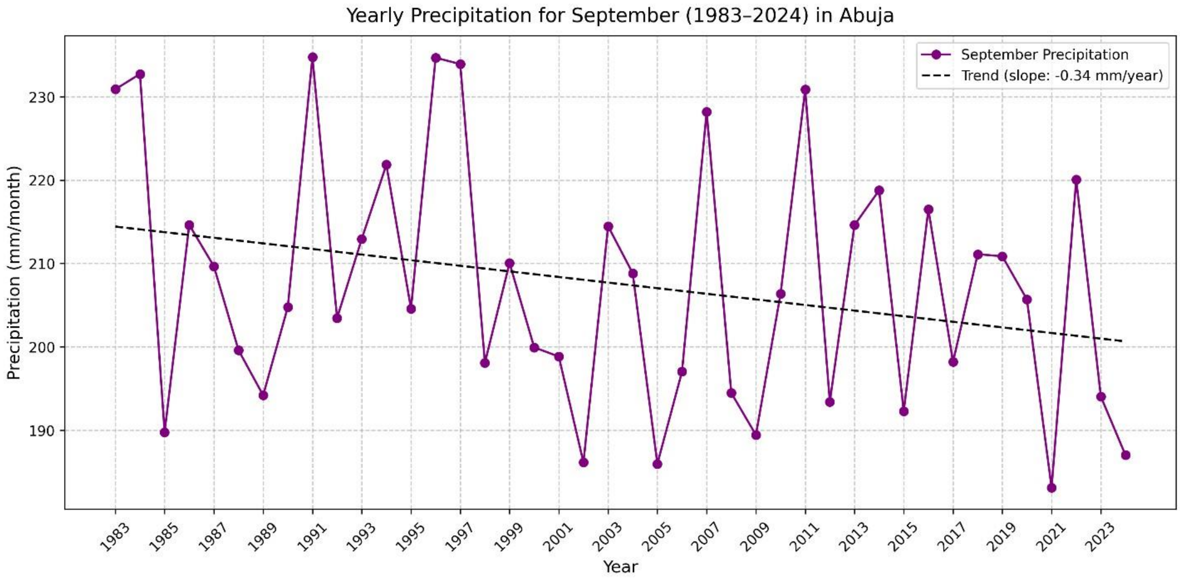

Figure 4.4: *Result of Precipitation Time Series Trend, for month of September (1983-2023)*

4.1.1 Magnitude of Slope and Percentage Change Over Time

Table 4.1: Percentage Change over Time (Abuja, 1983–2024)

Months	**Magnitude (mm/year)**	**Percentage Change (%)**
May	**-0.10**	**-2.80**
June	**-0.20**	**-4.10**
July	**-0.30**	**-5.60**
August	**-0.40**	**-6.86**
September	**-0.30**	**-5.86**
October	**-0.20**	**-4.67**

Annual	**-0.25**	**-5.00**

total of 42 research articles were initially uncovered through searches on Google Scholar and advanced Google tools, representing a broad sweep of potential studies before any filtering. After accounting for duplicates and applying strict selection standards, this collection was refined. Of these, 15 were set aside because they failed to incorporate resilience dimension attributes, indicating a gap in their focus that didn’t align with the study’s goals, based on a thorough review of their content. Another 9 were excluded after failing to meet the specific eligibility requirements, determined through careful scrutiny of their scope and applicability. This left 18 publications, which successfully advanced to the final evaluation stage, undergoing a comprehensive full-text analysis based on rigorous theoretical benchmarks to ensure their relevance for the review.

The data extracted from these 18 selected works included publication dates, the types of infrastructure examined, and the key metrics used in their evaluations. Following an in-depth screening of these documents, five core resilience factors emerged as dominant themes across nearly all the research—Technical, Organizational, Environmental, Social, and Economic dimensions. Among these, the Technical and Organizational dimensions proved most prominent, each capturing 25.42% of the focus, underscoring their pivotal role in shaping critical infrastructure assessments and evaluations as prioritized by scholars. Meanwhile, the Social and Economic dimensions each accounted for 21.2%, signaling their significant yet slightly lesser influence compared to the leading categories. The Environmental dimension, however, showed a more modest presence at 7.67%, suggesting that only a small fraction of researchers view climaterelated environmental aspects as a central component of resilience, possibly reflecting a narrower interest in climate change impacts. Finally, the Cooperative and Personnel dimensions received scant attention, each registering a mere 2.22%, highlighting their minimal consideration within this body of work and pointing to potential areas for future exploration as seen in figure 4.5 below.

Table 4.2 Eligibility Criteria for Resilience Dimension Selection

Selection Standards	Rejection Standards
Eligible peer-evaluated articles	Studies published before 2015
Works centered on vital infrastructure systems	Research not addressing vital infrastructure systems
Papers emphasizing resilience evaluation of essential infrastructure	Documents focusing on human-induced impact analysis
Studies analyzing resilience attributes	Writings missing resilience attribute evaluation

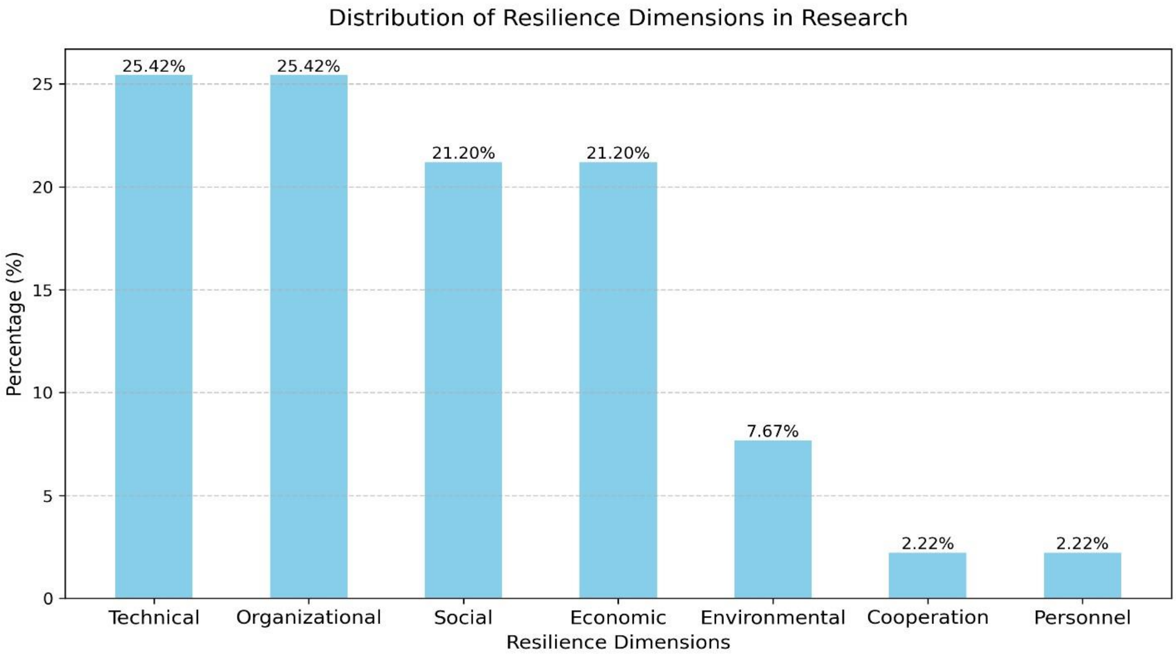

Figure 4.5: *Dimensions Resilience Assessment Identified for Critical Infrastructure Analysis***.**

4.1 Climate Resilience Metrics

Ten distinct resilience measures were identified for this study, encompassing water contamination, equipment deterioration, early alert systems, flood mitigation strategies, operational upkeep, emergency response tools, maintenance/rehabilitation funding, recovery expenses, stakeholder partnerships, and public awareness initiatives. These are detailed in Table 4.3, where each measure is evaluated and scored on a scale of 1 to 5, categorized according to the specific resilience dimensions they align with.

4.1.1 Assessment Checklist

This part outlines the checklist crafted for the evaluation, derived from on-site observations of physical infrastructure and interactions with utility management, following visits to the three water treatment facilities in Abuja. The scores (ranging from 1 to 5) for each measure are subsequently compiled and integrated into the analytical framework for deeper examination.

Table. 4.3: Checklist Developed for the Climate Resilience Assessment Kaduna State.

Climate – Resilience Assessment Checklist Survey on Water Treatment Plants in Kaduna State

---

Water Treatment Plant Name:
Name:
Position:
Job Experience:
Email:
Phone:
Date:

Resilience to Flood Hazard	**Dimensions**	**Indicator**	**Score**
			1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐

Environmental	• Evaluate the state of sediment capture devices at the water Entry point	☐ ☐ ☐ ☐ ☐
	• Examine backup options by analyzing the use of multiple systems and parts to ensure uninterrupted functionality	☐ ☐ ☐ ☐ ☐
Technical	• Investigate the presence and condition of any alert mechanisms	☐ ☐ ☐ ☐ ☐
	• Assess the effectiveness of safeguards against flooding	☐ ☐ ☐ ☐ ☐
Organizational	• Determine in advance the team responsible for handling Emergencies	☐ ☐ ☐ ☐ ☐
	• Identify and organize all essential tools and resources for emergency actions	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
Economic	• Is there Specific Funding Assigned for O&M/Rehabilitation of WTP?	☐ ☐ ☐ ☐ ☐
	• Are there partnerships in place with suppliers, clients to secure materials	☐ ☐ ☐ ☐ ☐
Social	• Is there any collaboration arrangement with Supply chain, employees, customers and community for repair kits	
	• Is there any sensitization arrangement with the host community to report any issues that may affect the WTPs resilience	☐ ☐ ☐ ☐ ☐

4.2. Development of Conceptual Approach Framework

The E-TOES Framework has pinpointed key elements affecting climate change in the area, creating a theoretical model that ties together the study’s variables, resilience aspects, indicators, measures, and the SWI. This model was applied to evaluate the infrastructure traits of water treatment facilities and their readiness for flooding, using a scoring and weighting system to improve the management of these plants effectively.

Displayed in Table 4.4, the E-TOES Framework reveals the scores for each indicator and the resilience levels across different dimensions for the Abuja treatment plant. As illustrated in Figure 4.9, the Organizational Resilience Dimension of Abuja Water Cooperation leads with a 10% score, followed by the Technical Resilience Dimension at 4%, and Environmental Resilience at 2%. Meanwhile, the Social and Economic resilience dimensions scored nothing, resulting in a total resilience level of 16% for Abuja Water Cooperation.

Table: 4.4: Water Treatment Plant Resiliency Assessment

Dimensions	**Location**	**Score** " = $% ∑!"#$ '	**Weighting (0.2)**	**Resiliency** () = $\sum_{j=1}^{m} \boldsymbol{IW}$
Environmental	Abuja	4	0.2	8%
Technical	Abuja	4	0.2	8%
Organizational	Abuja	5	0.2	10%
Economic	Abuja	0	0.2	0%
Social	Abuja	0	0.2	0%

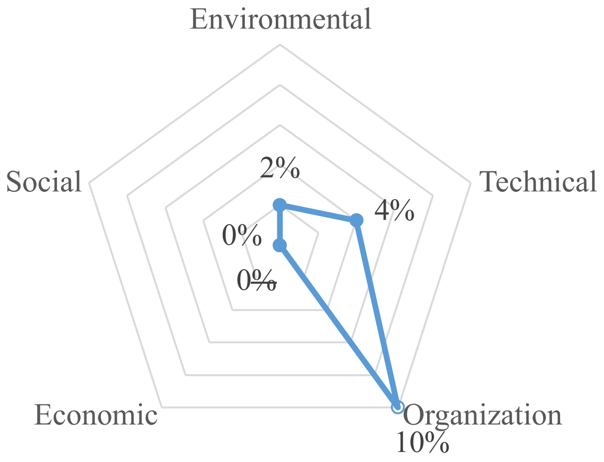

Fig. 4.9: Radar Chart of Abuja Water Infrastructure Dimension Resilience Index

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This research adds value to existing studies by introducing the E-TOES Framework, designed for water infrastructure to identify critical resilience factors and apply suitable strategies. It equips water infrastructure managers with foundational insights into resilience management, enabling them to weave these principles into their operational environment.

The E-TOES Framework was crafted to fulfill the research goal: creating an engineering management tool to evaluate the climate resilience status of water treatment plant infrastructure in Abuja state. To accomplish this goal and meet the outlined objectives, a sequence of five steps was systematically pursued as the approach to realize these targets.

1. Identification of rainfall pattern and climate variability using Innovative Trend Analysis (ITA) in Abuja state. The study employed the Innovative Trend Analysis (ITA) to examine rainfall patterns and climate variability in Abuja state. This ITA approach proves to be an essential resource for researchers, water utility managers, and stakeholders, enabling precise assessment of precipitation trends and the development of effective resilience strategies to address climate change effects on local water infrastructure. These insights are crucial, revealing an annual precipitation level of 225mm/year, which offers a clear understanding of shifting rainfall patterns in Abuja State. This information supports better water resource management and aids in reducing the impact of severe weather events in the area..

2.Identification of Resilience Dimension used for the assessment of water infrastructures. The PRISMA method was applied to gather publications focusing on the resilience dimensions of critical infrastructure. These were systematically evaluated through a desk-top review process, with the top five dimensions chosen based on their frequency in the analyzed research papers: Environmental at 7.67%, Technical at 25.42%, Organizational at 25.42%, Economic at 21.20%, Social at 21.20%, Cooperative at 2.22%, and Personal at 2.22%.

3. **Identification of Resilience Indicators for the assessment of water infrastructures.** Various climate resilience measures were determined through expert opinions, interviews with key informants, and on-site evaluations, serving as indicators to assess the resilience of water infrastructure. A qualitative analysis approach was employed to assign scores (ranging from 1 to 5) to each indicator, reflecting its level of adherence to the infrastructure's conditional assessment criteria, including operational status, serviceability, functionality, accessibility, and protective measures.

4.Development of E-TOES Framework, a Conceptual approach framework method is used for the development of Framework by linking the resilience dimension to indicator measures using scoring and weighting index (SWI), weighting index of (0.20) were equally distributed to each dimension to avoid bias.

5. Multiple climate resilience strategies were pinpointed using insights from experts, discussions with key informants, and field assessments, acting as markers to evaluate the water infrastructure's resilience. A qualitative method was utilized to rate each indicator on a scale of 1 to 5, based on

how well it met the infrastructure's condition evaluation standards, such as operational performance, usability, effectiveness, reachability, and safeguarding techniques.

5.2 Recommendation

Based on the findings of this study concerning the E-TOES Framework for water infrastructure in Abuja state, the following suggestions for future research are proposed:

1. Additional climate change factors should be explored to understand their potential impact on water infrastructure resilience, aiding managers and stakeholders in addressing risks and enhancing resilience against floods and droughts in Abuja state.
2. Further investigations aligned with this study's dimensions should be conducted, focusing on other climate resilience aspects like cooperation, individual contributions, policy frameworks, and governance, which are critical for strengthening water systems in Abuja state.
3. Incorporating machine learning techniques into the framework is recommended to improve data handling and uncover additional resilience indicators.
4. Additional research on the E-TOES Framework is advised to reassess and confirm the principles used in its creation.
5. Water infrastructure managers should make resilience assessments a regular priority to ensure ongoing preparedness of the infrastructure.

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