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Presented by

Elie Katya Muyali

THE CURRENT STATE AND FUTURE PERSPECTIVE OF URBAN WATER SECURITY IN KINSHASA, DEMOCRATIC REPUBLIC OF CONGO (DRC)

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PAN AFRICAN UNIVERSITY FOR WATER AND ENERGY SCIENCES
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THE CURRENT STATE AND FUTURE PERSPECTIVE OF URBAN WATER SECURITY IN KINSHASA, DEMOCRATIC REPUBLIC OF CONGO (DRC)

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

By

Elie Katya Muyali (BSc with honours in Civil Engineering)

PAUWES/2023/MWP08

Supervisor: Professor Ronny Berndtsson

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March 2025

Tlemcen, Algeria

DECLARATION

STUDENT'S DECLARATION

I, Elie Katya Muyali, hereby declare that this thesis titled "The Current State and Future Perspective of Urban Water Security in Kinshasa, Democratic Republic of Congo (DRC)" is my original work and that it has not been wholly or in part presented for an award of any degree in any university known to me.

Signature: ___________________

Name: Elie Katya Muyali **Date:** 28/03/2025

SUPERVISOR'S DECLARATION

This thesis is the candidate's original work and has been prepared with our guidance and assistance. It is presented for examination with our approval as official University Supervisors.

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DEDICATION

This work is dedicated to my family for their constant support.

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LIST OF ABBREVIATIONS AND ACRONYMS

AFD	: Agence Français du Développement
AHP	: Analytical Hierarchy Process
BCC	: Banque Centrale du Congo
CCKP	: Climate Change Knowledge Portal
CRED	: Centre for Research on the Epidemiology of Disasters
DPSIR	: Driving Force-Pressure-State-Impact-Response
DRC	: Democratic Republic of Congo
EM-DAT	: Emergency Events Database
FAO	: Food and Agriculture Organization
GDP	: Gross Domestic Product
IFRC	: International Federation of Red Cross and Red Crescent Societies
MDGs	: Millennium Development Goals
RCP	: Representative Concentration Pathway
REGIDESO	: Régie de Distribution d'Eau
SD	: System Dynamics
SDGs	: Sustainable Development Goals
SPA	: Set Pair Analysis
SPAN	: Service Path Attribution Network
UN	: United Nations
UNICEF	: United Nations Children's Fund
USAID	: United States Agency for International Development
USD	: United States Dollar
UWSI	: Urban Water Security Index
WHO	: World Health Organization
WSS	: Water Security System

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ABSTRACT

Low water security is widely recognized by policymakers and academics as a global risk and policy challenge especially in rapidly urbanizing cities. Kinshasa, the capital and largest city of the Democratic Republic of Congo, faces significant, yet paradoxical challenges to achieve urban water security. This study evaluates the present and future urban water security in Kinshasa, across seven key dimensions: availability, accessibility, health, and sanitation, affordability, environment, water-related disaster and governance. The mini-max approach is used to normalize indicators to a scale of 1 to 5, and the weighted sum approach to calculate both dimensional and overall, the urban water index from 2015 to 2024. Furthermore, a scenario-based approach was applied to evaluate the future water state of Kinshasa considering the business-as-usual scenario and an improvement scenario up to 2040. Results revealed that the overall urban water security from 2015 to 2024 remained fair security with an overall index fluctuating between 1.69 and 2.09. In the seven dimensions of urban water security, water-related disasters exhibited a good security range fluctuating between 4 to 4.4, followed by the affordability dimension which showed improvement rising from 1.87 in 2019 to 3.94 in 2020, and slightly increasing to 3.97 in 2024 falling in the range of good security. In contrast, all remaining dimensions revealed weakness and fell in fair security in 2024 except the governance dimension which presented poor security with a security index of 1 from 2015 to 2024. Looking into the future, under the business-as-usual scenario, estimations revealed a gradual increase of 2.05 within the fair security range in 2030, reaching satisfactory security with a 3.38 range in 2040. However, under an improvement scenario considering targeted improvements are made in weak dimensions, Kinshasa could achieve a satisfactory water security level by 2030 (3.38) and a good level (3.95) by 2040. This study provides both a retrospective and prospective evaluation of water security in Kinshasa, highlighting the necessity for policymakers to take immediate, informed, and targeted actions.

Keywords: Water Security Index**,** Business-as-usual Scenario, Mini-max approach

RESUME

Kinshasa, la capitale et la plus grande ville de la République Démocratique du Congo, fait face à des défis significatifs pour atteindre la sécurité urbaine de l'eau. Cette étude évalue l'état actuel et futur de la sécurité urbaine de l'eau à Kinshasa à travers sept dimensions clés : disponibilité, accessibilité, santé et assainissement, abordabilité, environnement, catastrophes liées à l'eau et gouvernance. L'approche mini-max a été utilisée pour normaliser les indicateurs sur une échelle de 1 à 5, et l'approche de somme pondérée pour calculer l'indice de sécurité de l'eau à la fois par dimension et globalement entre 2015 et 2024. En outre, une approche basée sur des scénarios a été appliquée pour évaluer l'état futur de l'eau à Kinshasa en considérant un scénario de statu quo et un scénario d'amélioration jusqu'en 2040. Les résultats ont révélé que la sécurité urbaine globale de l'eau entre 2015 et 2024 est restée dans la catégorie de sécurité passable, avec un indice global fluctuant entre 1.69 et 2.09. Parmi les sept dimensions, les catastrophes liées à l'eau a demontré une bonne sécurité, fluctuant entre 4 et 4.4, suivie de la dimension d'abordabilité qui a montré une amélioration, passant de 1.87 en 2019 à 3.94 en 2020, augmentant légèrement à 3.97 en 2024, entrant ainsi dans la catégorie de bonne sécurité. En revanche, toutes les autres dimensions ont révélé une faiblesse et sont restées dans la catégorie de sécurité passable en 2024, à l'exception de la dimension de gouvernance qui a présenté une sécurité faible, avec un indice de 1 en 2024. Sous le scénario de statu quo, les estimations indiquent une augmentation progressive jusqu'à 2.05 en 2030, maintenant ainsi la ville dans la catégorie de sécurité passable, et atteignant une sécurité satisfaisante avec un indice de 3.38 en 2040. Cependant, sous un scénario d'amélioration où des actions ciblées sont mises en place dans les dimensions faibles, Kinshasa pourrait atteindre une sécurité satisfaisante dès 2030 (3.38) et une bonne sécurité en 2040 (3.95). Cette étude fournit une évaluation rétrospective et prospective de la sécurité de l'eau à Kinshasa, mettant en évidence la nécessité pour les décideurs politiques d'agir immédiatement de manière informée et ciblée.

Mots-clés: Indice de sécurité de l'eau, Scénario de statu quo, Approche mini-max

1. INTRODUCTION

1.1. Background

Water resources are vital for both ecological and socioeconomic systems, serving as the foundation for sustainable development (Zhang & Wang, 2015). In the twenty-first century, water resources have become increasingly scarce, leading to growing concerns about water security (Shao et al., 2012). Stress over water resources is increasing in urban areas due to the overexploitation of the available water supplies. Furthermore, climate change has intensified this challenge. Cities worldwide experience extreme weather events including floods and droughts, significantly impacting water availability and human well-being (Marçal et al., 2024).

Water security and urbanization are two interconnected global phenomena with significant consequences for humans and the environment (Jensen & Wu, 2018). Achieving water security is challenging due to continuously increasing population, urbanization, and ongoing climate change leading to socioeconomic and environmental consequences (Roth et al., 2019). Over the past century, the global population has more than quadrupled, and freshwater withdrawal has increased approximately six times (Flörke et al., 2013). Unprecedented urbanization and poor governance have led to various water challenges in many countries. These challenges stem from a lack of access to safely managed water and sanitation to failing flood management, and environmental degradation (Aboelnga et al., 2020).

The Democratic Republic of Congo (DRC), despite its abundant water resources, faces similar challenges. In 2015, only 52% of its population had access to a safe drinking water supply and 29% to safe sanitation. With a population of approximately 71.25 million, the urban population accounted for 42% with 81% of access to improved drinking water sources and 29% to improved sanitation (WHO/UNICEF, 2015). Thus further, the DRC's government set a goal in 2017 to completely eradicate open defecation and guarantee universal access to drinking water and basic sanitation by 2021. The government's goal was to ensure that 45% of people had access to a well-managed sanitation system and 65% of people to a safely managed water supply by 2021 (USAID, 2017).

While these ambitious targets represent the DRC's strong commitment to meet an improved level of water security, the country is far from an acceptable level of urban water security. In

2022, WHO/UNICEF (2023) reported that the population reached approximately 99.01 million, with the urban population accounting for 47%. The report revealed that the urban population's access to an improved drinking water source decreased to 24%, while access to improved sanitation decreased to 15%. Additionally, the effects of climate change worsen the crisis. According to the World Bank Group (2021), from 1900 to 2020, flash floods and river floods affected 95,400 and 547,600 people, respectively, while drought affected 800,000 people. By the 2100s, the overall trend suggests that runoff and drought will occur more frequently, seriously affecting water availability (USAID, 2021).

Notably, effective management of water resources has a significant impact on several facets of human life, which is why governments worldwide prioritize maintaining high water security (Babel & Shinde, 2018). Low water security is widely recognized by policymakers and academics as a global risk and policy challenge that threatens national security, the health and livelihoods of vulnerable communities, and affects global security (World Economic Forum, 2020). In view of this, the present thesis analyses the current and future state of urban water security in Kinshasa, the capital and largest city of the DRC, to inform the government, policymakers, and different stakeholders about the key areas that require attention and action.

1.2. Statement of problem

Kinshasa, the capital and largest city of the DRC, faces significant, yet paradoxical challenges to achieve urban water security. Despite having an abundance of water resources in the country, Kinshasa is struggling to access safe water. Rapid urbanization and population growth have led to increased water demand and stress on water resources, while poor water management, lack of access to safe water and sanitation, and ageing infrastructure have left a large segment of the city without access to water. Although there have been government efforts in the past, the situation is still alarming.

Access to piped water decreased from 90% of households in 2014 to 72% in 2018 due to high demand and insufficient infrastructure capacity. Most of the connections were off-premises and the supplied water was of inadequate quality. Furthermore, access to basic sanitation decreased from 65% in 2014 to 55% in 2018 (World Bank, 2020). Additionally, the impacts of climate change, including floods and drought, strain water availability and destroy infrastructure. In

2022 Kinshasa experienced a flash flood that affected approximately 84,600 people and destroyed several pieces of infrastructure (IFRC, 2023).

Notably, the water crisis coupled with climate change represents a growing concern for city administrators and regional and national governments. A new long-term solution to addressing the water crisis and reducing water-related hazards is needed. Grey & Sadoff (2007) defined water security as “access to a sufficient and satisfactory quantity and quality of water for health, sustenance, and productivity, along with an acceptable level of water-related hazards." This thesis provides a comprehensive assessment of urban water security from an interdisciplinary perspective covering the dimensions of water safely availability and accessibility, sanitation and health, water affordability, the environment, water-related disasters and governance.

1.3. Research objectives

The main objective of this thesis is to analyse the current and future state of urban water security in the DRC to inform the government and important stakeholders about the key issues and areas that need attention and action. The specific objectives of this thesis are:

1. To evaluate and present the current state of urban water security in Kinshasa, DRC, across multiple dimensions.
2. To analyse and present the future state of urban water security in Kinshasa under a business-as-usual scenario and an improvement scenario.
3. To compare the outcome of future urban water security under the two future scenarios.

1.4. Research questions

The research questions are the following:

1. What is the current state of urban water security in Kinshasa, based on water availability and accessibility, health and sanitation, economic value of water, environment and water governance?
2. What is the future state of urban water security in Kinshasa under a business-as-usual scenario and under an improved scenario
3. How do the outcomes of future water security under the two scenarios compare in terms of achieving urban water security?

1.5. Hypotheses

The working hypotheses in this thesis are explanatory. They aim to explore and explain how key factors, including water accessibility, water availability, health and sanitation, water affordability, the environment, water-related disasters and governance influence urban water security in Kinshasa.

H1: The current state of urban water security state in Kinshasa is significantly compromised due to inadequate water availability, poor water accessibility, insufficient health and sanitation infrastructure, environmental challenges and weak governance.

H2: Implementing targeted improvement in water availability, water accessibility, water health and sanitation, environment and governance, will ensure future urban water security in Kinshasa.

1.6. Significance of the study

As urban water security emerges as a pressing challenge for Kinshasa due to the forces of urbanization, population growth and climate change, there is an urgent need to understand the multidimensional vulnerabilities and strengths at the urban scale to effectively prioritize actions. By developing the first urban water security index for Kinshasa City based on water availability, water accessibility, health and sanitation, affordability, the environment, water-related disaster and governance dimensions, this research will fill significant knowledge gaps and support evidence-based planning and decision-making. The results of the study are expected to be highly relevant for Kinshasa's water managers and other stakeholders to develop targeted strategies to enhance the resilience of the urban water system. The findings will also add valuable insights for scholars engaged in assessing urban water security challenges in other developing nations undergoing rapid urban transitions.

1.7. Scope of the study

This thesis assesses urban water security challenges in Kinshasa, the capital and largest city of the DRC. The thesis assesses both the current state and future perspectives of urban water security in Kinshasa. The assessment is based on a framework comprising seven dimensions of water security, namely availability, accessibility, health and sanitation, affordability, environmental factors, water-related disasters and governance. The performance of Kinshasa City in each dimension was assessed in a time frame from 2015 to 2025. Additionally, the thesis presents a projection of urban water security for the future up to 2040, based on two different scenarios mainly, the business-as-usual scenario considering no change in the current state of urban water security and the improvement scenario considering improvement in the current state of urban water security. Finally, the thesis proposes targeted strategies and short and long-term policies to improve the current and future state of urban water in Kinshasa.

1.8. Organization of the thesis

The following is the organization of this thesis: Chapter 1 is an introduction presenting a comprehensive background of the study, a clear statement of the problem, research objectives and questions. Chapter 2 is a literature review that presents the state-of-art and previous scholarly published work on urban water security upon which this thesis is grounded. This chapter further provides the gap identified from the reviewed literature and provides a comprehensive theoretical review of the concepts used in this thesis. Chapter 3 is the methodology, describing the water and wastewater system of Kinshasa City, the method of data collection, and the analysis of collected data. Chapter 4 is the results and discussion, presenting the key findings of the analysis in a concise comparative manner based on the literature. Chapter 5 presents conclusions, which provide the research summary outcomes, recommendations for policymakers and the limitations of the research. This chapter further provides areas for future research.

2. LITERATURE REVIEW

2.1. Introduction to Urban Water Security

The concept of water security has been defined across different disciplines and in different lenses since the 1990s (Gerlak et al., 2018). Water security was defined by the capacity of water supply to meet the water demand and the ecological needs (Cook & Bakker, 2012). Over time, the concept extended from natural and human induced degradation of the water resources to a multi-dimensional framework comprising environmental, socio-economic and governance aspects. In recent years, water security has expanded to include health, livelihood and water-related risks to people (Grey & Sadoff, 2007). Urban water security further builds on this evolution by addressing challenges specific to urban areas, such as insufficient infrastructure, rapid urbanization and governance complexities.

However, certain elements of urban water security are distinct from water security at household, state, country or global level. Urban areas, characterized by their reliance on hinterlands for natural resources, face unique challenges tied to their urbanization (Hoekstra et al., 2018). Some notable characteristics of urban areas include high population density and high exposure to climate risk and natural disasters (Roth et al., 2019). Governments often fail to keep pace with the rapid urbanization, resulting in challenges such as limited access to safely managed water and sanitation, inadequate water supply, declining water quality, poor flood management and environmental degradation (Chang et al., 2015). In recent years, studies have advanced the discourse by exploring definitions, assessment frameworks, and indicators of urban water security (Grey & Sadoff, 2007). While some of these studies adopted a disciplinary, problem-specific and goal-oriented approach, others focus on the integration and process-oriented perspectives (Hoekstra et al., 2018).

2.1.1 Disciplinary perspective

Water security is a multifaceted concept with different meanings according to different disciplines. Hoekstra et al. (2018) conclude that in engineering studies the focus of water security is about securing water supply and mitigating risks like floods and contamination while environmental research emphasizes water quality, water availability, and ecosystem support. Cook & Bakker (2012) denote that policy-oriented research highlights the nexus between water, food, energy and climate security, alongside sustainable development goals. Furthermore, they note that public health perspectives concentrate on access to safe water and contamination prevention. These different lenses show the complexity of addressing water security comprehensively emphasizing water security as an interconnected challenge linked to broader socio-economic and ecological systems (Gomez-Jaramillo et al., 2024).

2.1.2 Problem oriented Perspective

Urban water challenges are often summarized as issues of "too little, too much, or too dirty" water, reflecting scarcity, flooding, and pollution as interconnected problems (Marcal et al., 2021). Scarcity, arising from natural causes like droughts or from overuse and poor management, is often addressed through infrastructure such as dams and desalination plants (Hoekstra et al., 2018). However, Fielding et al. (2013) argue that these solutions present financial, environmental, and jurisdictional challenges. They further argue that effective demand management requires overcoming significant socio-economic and political barriers. Conversely, Di Baldassarre et al. (2013) conclude that urban flooding is intensified by urbanization in flood-prone areas due to their fertile land and transport advantages. Pollution compounds these issues, as contaminated water sources are unsuitable for consumption without costly treatment, disproportionately affecting economically disadvantaged populations. Waterborne diseases, driven by inadequate sanitation and runoff from industrial and urban activities, remain a persistent global health and economic burden (Biswas & Tortajada, 2011; Falkenmark, 2011).

The dynamic nature of urban water issues is driven by socioeconomic, environmental, and governance-related factors. Climate change, population growth, and upstream land-use changes alter hydrological patterns while evolving technologies and societal preferences shape water management approaches (Hoekstra et al., 2018). These dynamics operate across multiple scales, linking urban water challenges to global climate trends, regional basin conditions, and shifts in consumer behaviour (Wheater & Gober, 2013). Addressing these interconnected challenges requires adaptive strategies that account for their complexity and inherent uncertainties to enhance urban water security.

2.1.3 Goal-oriented perspective

Water security is frequently conceptualized as both a public good and a critical goal to be achieved. Traditional water management literature emphasizes the "functions of a water system," while environmental sciences frame these functions as "ecosystem services" or "water system services," encompassing urban water supply, sewerage, drainage, flood protection, navigation, and the provision of recreational and ecosystem values (Hoekstra et al., 2018). The prioritization of these services often reflects broader societal goals, such as those outlined in the Millennium Development Goals (MDGs) and the Sustainable Development Goals (SDGs), which focus on expanding access to safe drinking water and adequate sanitation (Larsen et al., 2016). Despite this comprehensive framing, much of the urban water security literature narrows its focus to water supply security, driven by concerns over meeting demand in rapidly urbanizing areas (Padowski et al., 2016; Grafton, 2017).

A critical aspect of this goal-oriented perspective is addressing equity, encapsulated in the question: "Water security for whom?" (Grey et al., 2013). This inquiry challenges the equitable distribution of water resources, questioning whether efforts prioritize wealthier districts or ensure universal access, including for downstream or rural communities reliant on the same catchments. While urban water security is a pressing concern, the underlying equity issues, often unaddressed, underscore the complexity of achieving water security that benefits all stakeholders equally (Hoekstra et al., 2018).

2.1.4 Integration perspectives

While integrated water management has traditionally emphasized the need for coherence across all aspects of water use and conservation, there is a growing recognition that water security must be embedded within broader development and environmental policies. Increasingly, water security is examined in relation to food and energy security, with urban studies highlighting the interdependencies between these systems (de Amorim et al., 2018). Urban food supplies, for example, are heavily reliant on external water resources for agricultural production, while urban energy systems are similarly influenced by water availability (Rasul & Sharma, 2016).

Conversely, urban water management itself is a significant consumer of energy. Water management measures, such as conservation and reuse, can further influence energy use and carbon emissions, as shown in a study on Las Vegas (Shrestha et al., 2012). With the increasing integration of renewable energy sources like biofuels, urban transport systems are also adding to external dependencies on land and water resources (Hoekstra et al., 2018). These interconnected challenges underscore the importance of aligning urban water management with broader urban planning, energy, and food supply policies to ensure sustainability and resilience in resource-constrained environments (Kenway et al., 2011).

2.2. Current State of Art and Knowledge Gaps

Over the past twenty years, the concept of water security has been increasingly addressed in different studies and through different lenses. Some studies have examined water security at the national level. For example, Su et al. (2019) analyzed and presented an integrated assessment and scenario simulation of the water security system (WSS) of Japan. They employed a system dynamics (SD) model to simulate the subsystems and future changes from 1995 to 2025 (system: water resources, water environment, and water disasters). They used a set pair analysis (SPA) method to evaluate the present state of the WSS across Japan's administrative divisions from a spatial perspective. These studies are valuable for understanding water security at the macro level but often overlook sub-national disparities.

Other studies consider water security from a regional or basin scale. Babel & Shinde (2018) proposed a framework for assessing water security at the basin scale using an indicator-based methodology rooted in the DPSIR (Driving Force-Pressure-State-Impact-Response) approach. Their framework considers five key dimensions – water availability, water productivity, watershed health, water-induced disasters, and water governance – measured through eight indicators. Li et al. (2017) created a freshwater ecosystem service flow model to assess water security in the Beijing-Tianjian-Hebei region, demonstrating that freshwater upstream flows impacted most of the region. Using a simplified Service Path Attribution Network (SPAN) model, Qin et al. (2019) incorporated integrated ecosystem service flows in water security simulations, identifying provincial variations in China's water security. Notably, these studies primarily focus on the natural resources dimensions and often lack a robust integration of socio-economic and governance factors critical for addressing urban water security.

Urban water security has gained significant attention due to increasing pressure on cities from population growth and climate change, leading to the consideration of the urban water security scale. Hoekstra et al. (2018) provided a comprehensive review of the concept of urban water security, which has evolved from integrated and sustainable water management to focus on broader water security concerns. Marçal et al. (2024) presented a novel approach to assessing inequalities in urban water security using a combination of indicator-based evaluation and geospatial analysis. Applying this framework to the city of Campinas, Brazil, revealed that significant spatial heterogeneity within the urban area exists despite the city´s overall good water security condition. Babel et al. (2020) implemented and utilized an indicator-based methodology in Bangkok, Thailand, which closely corresponds to the research conducted by Khan et al. (2020). They proposed a framework for assessing urban water security that incorporates a comprehensive water security index featuring five broad dimensions – water supply and sanitation, water productivity, water-related disasters, water environment, and water governance – measured through 12 indicators. While these studies offer valuable insights into urban water security challenges, they often emphasize existing conditions without considering the projections of future environmental changes.

In the need to bridge this gap, Karimi et al. (2021) collected data on urban water security from a cohort of cities in Iran, adopting a multi-city approach and incorporating both retrospective and prospective analyses. They evaluated urban water security trends from 2013 to 2019 and projected water resource availability in Iran up to 2100 using ensemble-based hydro-climatic regional climate model projections under different RCP scenarios. Their findings noted increasing pressure of climate change on water resources, highlighting vulnerabilities in the environmental dimension. However, governance dimensions were notably absent, and their framework did not account for the socio-economic dynamics that interact with climate factors to shape urban water security outcomes. Governance is a recognized prerequisite to achieving water security, as highlighted by UN-Water (2013). Weak governance structures, expressed through poor institutional management, inadequate adaptation to changes, and corruption, undermine efforts to achieve water security.

While the existing literature provides valuable insights into water security at national, regional, and urban scales, there are notable gaps. First, most of the studies consider equal weighting of indicators and dimensions in their urban water security framework, which fails to account for the contextual differences between cities, regions, and countries. This generalized approach may not accurately capture the unique challenges and priorities of specific contexts. Second, despite the growing concern about urban water security, to the best of my knowledge, no previous studies have explored this topic for the city of Kinshasa or even the Democratic Republic of Congo (DRC). Thus, this study is the first to address urban water security in Kinshasa, filling a critical gap in both the regional, and global discourse. By integrating the socio-economic dynamics, governance, and future urban water security, this research provides a tailored framework for understanding and addressing urban water security in a complex, understudied context.

2.3. Conceptual Framework of Urban Water Security

This study is grounded in the multi-dimensional nature of urban water security, which is influenced by three interrelated factors: the environment, socio-economic dynamics, and future environmental changes (Grey & Sadoff, 2007). Urban water security encompasses key dimensions such as availability, accessibility, health and sanitation, water affordability, environment, water-related disasters and governance inspired by Karimi et al. (2021) and Babel et al. (2020). These dimensions collectively reflect the dual challenges of managing water supply and demand while ensuring institutional and environmental sustainability. This framework situates urban water security within a broader context, highlighting how natural, socio-economic, and governance systems interact to shape outcomes.

Socio-economic factors, including economic structures, and policy decisions, influence how water resources are distributed and utilized (Santos et al., 2023). Governance plays a central role, mediating the relationship between water users and resources through institutional arrangements, investments, and regulatory mechanisms (Boran, 2023). The integration of these factors underscores the complex interdependencies inherent in urban water management.

3. MATERIALS AND METHODS

3.1. Study area

Kinshasa, the largest and fastest-growing city of DRC is located within latitude 4° 19' 39 S and longitude 15° 18' 48 E, with an area of 9,965 km^2. Kinshasa is in the western part of the country as shown in Figure 1, and borders to its west the city of Brazzaville, the capital city of the Congo Republic. Kinshasa experiences a tropical climate with an annual average precipitation of 1598.6 mm and an average mean surface air temperature of 24.7°C (World Bank, 2024). Kinshasa has a huge amount of natural water resources with Congo River and its tributaries serving as the main source of water supply in the city. However, the city experiences a water resources management crisis due to population growth and increasing demand (World Bank, 2020).

The population in Kinshasa was approximately 17 million in 2023, with a population growth rate of 4.4% making it one of the largest cities in Africa. The population growth driven by natural growth and province-to-province migration has led to uncontrolled settlement patterns making access to water and sanitation services very limited. Furthermore, Kinshasa has an inadequate water supply infrastructure with most of it between 30 and 70 years old leading to low efficiency of the system. Additionally, the impacts of water-related disasters are a growing concern in the city. In 2022, IFRC (2023) reported approximately 84,000 people affected by floods presenting a concern for city planners.

Two main reasons led to the selection of Kinshasa as an area of interest for this study. First, challenges in the water sector in the city are multifaceted encompassing water supply, socio-economic, and hydroclimatic factors. This presents an ideal area for understanding water security in its multidimensional form. Second, due to the severity of the present challenges, there is a need for evidence-based policy that captures the holistic context of water security in the city.

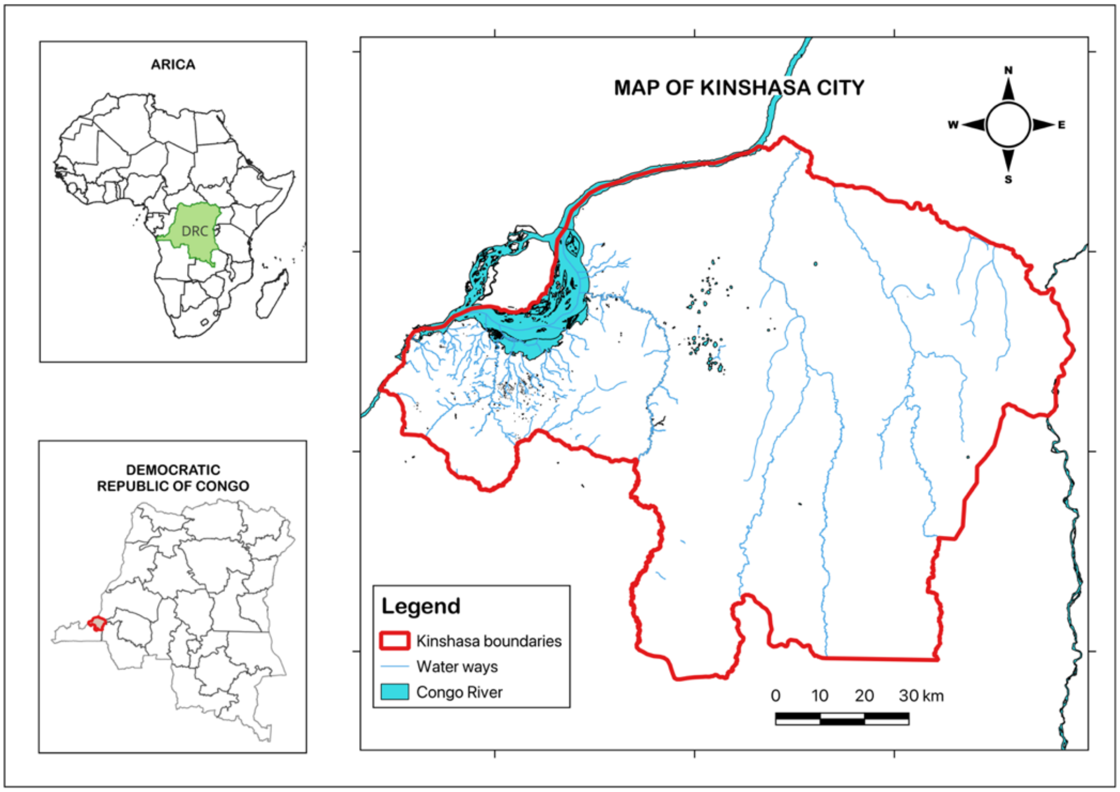

Figure 1: Map of Kinshasa City with waterways and location of the Congo River.

3.2. Date collection

This study used both quantitative and qualitative data collected from different sources. Statistical data ranging from 2015 to 2024 on indicators for availability, accessibility, economic value of water, water health and sanitation, and governance dimensions were obtained from REGIDESO (the national utility company). REGIDESO oversees urban water supply in DRC making it a reliable source. Indicators on water-related disasters were obtained from Public EM-DAT, an international disaster database of the Centre for Research on the Epidemiology of Disasters (CRED) (https://public.emdat.be/data, accessed on 4th March 2025). CRED inventories hazards and disasters worldwide from 1900 to the present. The database compiles data from various sources such as UN Agencies, non-governmental organizations, research institutions, reinsurance companies, etc. Annual average air temperature data from 2015 to 2024 were obtained from the Climate Change Knowledge Portal (CCKP) (https://climateknowledgeportal.worldbank.org/country/congo-dem-rep, accessed on 5th March 2025). Due to the long process of obtaining relevant demographic data from relevant authorities and time constraints, the population growth rate from 2015 to 2024 in Kinshasa was obtained from historical demographic trends in the Macrotrend online database. The per capita GDP was obtained from the Congo Central Bank (BCC). The raw collected data underwent checking to identify missing data and formatted it in tabular format using Excel. At this stage, the judgement on indicators impact – positive (P) or negative (N) – was done. Indicators which are inversely related to urban water security were judged negative while the ones positively related to urban water security were judged positive

3.3. Dimension and Indicators of Urban Water Security

This research used the Urban Water Security Index (UWSI) inspired by Karimi et al. (2021) and Babel et al. (2020) to assess urban water security in Kinshasa. The UWSI is a valuable framework for assessing the effectiveness of urban water systems. It allows policymakers and water managers to assess the outcomes of their strategies while identifying areas that require improvement (Khan et al., 2020). Specific measurable indicators shown in Figure 2 were selected for each dimension according to the available data to evaluate urban water security. These indicators were normalized to a scale of 1-5 where 1 indicates poor security, 2- fair, 3- satisfactory, 4- good, and 5- excellent security (Khan et al., 2020).

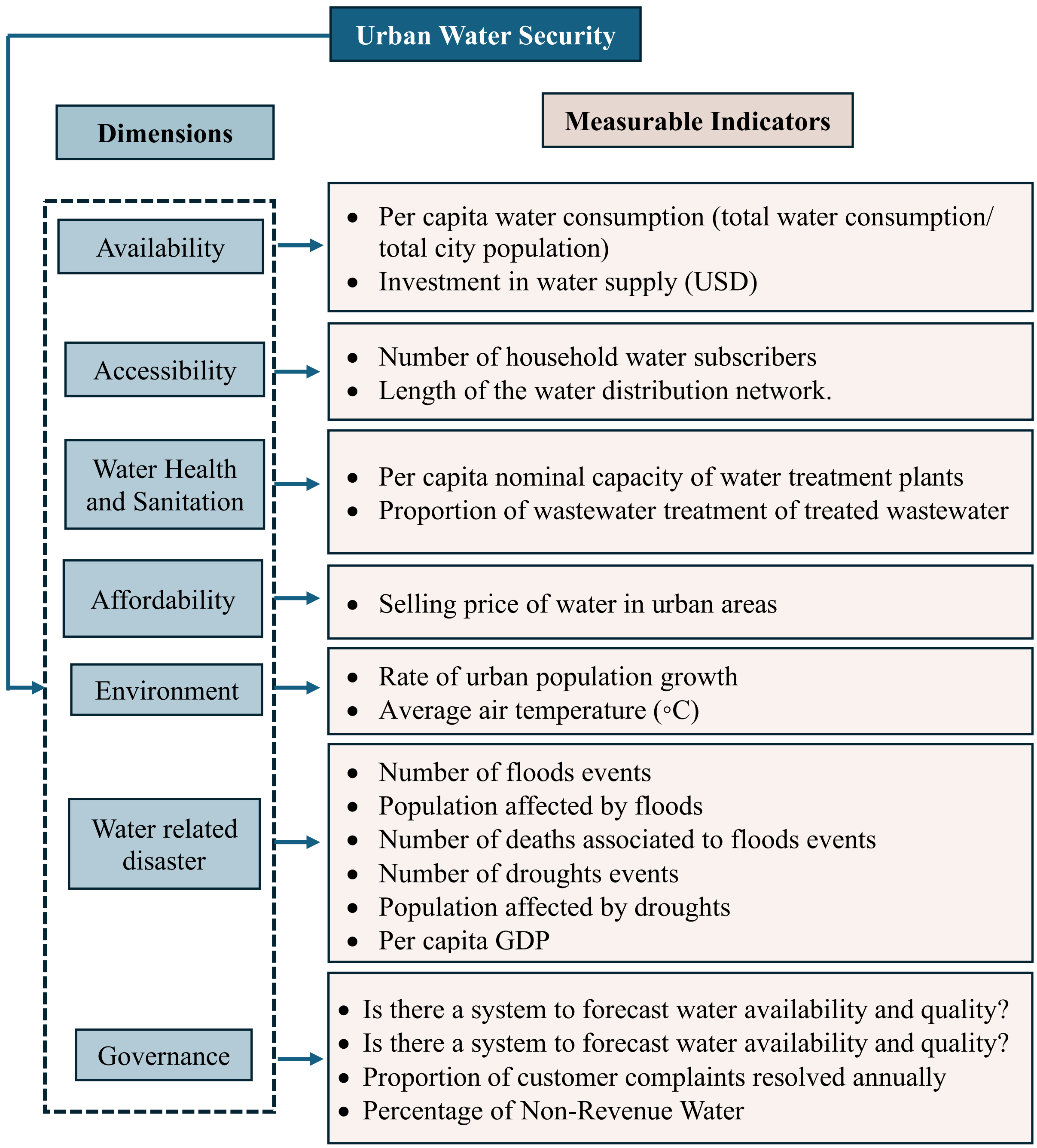

Figure 2: Utilized Kinshasa urban water security dimensions and their respective indicators.

3.3.1. Availability dimension

The availability aspect pertains to the accessibility of water resources for daily functions measured by the per capita water use per day (total domestic consumption/city population) and the investment budget in water supply (Babel et al., 2020). In 2021 the Work Bank committed to fund water supply in Kinshasa to ensure an acceptable level of water availability for the population by 2026. The total amount of the project was USD 255 million given in instalments throughout the life span of the project (World Bank, 2020). This study used this amount as the maximum benchmark of investment in the water supply indicator as it represents what is needed in Kinshasa to reach an acceptable level of water supply in the city. According to USAID (2021), from 2015 the contribution of the government to the national water budget dropped to 10% hindering the sustainability of the water sector. Moreover, the government contribution to the budget in water supply from the same years has considerably dropped from zero in the same year to 10% in other years, leaving the water supply of the city in the hands of external funders. This study uses the maximum contribution of the government from 2015 to 2024 as the minimum threshold considering that the government should contribute more to the sector. The highest contribution that the government made was USD 9.36 million, realized in 2019 as shown in Table 1.

Table 1: Threshold for availability indicators.

Indicators	Unit	Standardization					Reference
		(S_{min})1	**2**	**3**	**4**	**(S_{max})5**	
Per capita water user	L/C/D	<20	21-50	51-90	91-100	>100	Babel et al. (2020)
Investment in water supply	Million USD	<9	-	-	-	>255	

3.3.2. Accessibility dimension

Accessibility represents the second dimension of water access and refers to both users' general access to water and the water infrastructure (Khan et al., 2020). In this study, the number of subscribers to the water supply network and the length of the water supply network were used to measure the accessibility dimension according to Karimi et al. (2021). To standardize the number of subscribers and the length of the target, data from the Agence Francais du

Developpement (AFD)'s project on combating Cholera and Diarrheal by renovating water supply infrastructure in the city of Uvira, Eastern part of DRC, were used. To ensure that the 280,000 Uvira inhabitants have access to sufficient water, the project targeted 5,360 subscribers and a 108,396 m long water supply network (Gallandat et al., 2021).

Built on Uvira's case, this study determined the maximum threshold for the length of the network and the number of subscribers following the assumption that the number of subscribers depends on the population density of the city while the length of the distribution network depends on the area of the city. Uvira is a small city with a higher population density than Kinshasa meaning that there are more shared connexions than in Kinshasa. However, the network must cover the area of the city regardless of how many inhabitants live in the city. Based on these assumptions, this study determined the maximum threshold for the number of subscribers and length of the network by:

$$\mathrm{S_k}\left({}^{1}/_{1{,}000\ \text{inhab.}}\right) = \left(\frac{\mathrm{S_u}}{\mathrm{P_u}} \times 1{,}000\right)\sqrt{\frac{\mathrm{PD_u}}{\mathrm{PD_K}}} \qquad \text{Eq. (1)}$$

$$\mathrm{L_K}\ (\text{in meter}) = \frac{\mathrm{L_u}}{\mathrm{A_u}} \times \mathrm{A_k} \qquad \text{Eq. (2)}$$

where, S_k is the number of subscribers in Kinshasa, S_u is the number of subscribers in Uvira, P_k and P_u are the population in Kinshasa and Uvira, respectively. The population density in Uvira (PD_u) and in Kinshasa (PD_k) were obtained from the proportion of the population to the area of the respective city. L_k is the the length of the network in Kinshasa, L_u is the length of the network in Uvira, A_u is the area of Uvira and A_k is the area of Kinshasa. The area of Kinshasa is 9,965 km^2 (from the National Institute of Statistics), and the area of Uvira is 16.96 km^2 (from Gallandat et al., (2021).

Before the AFD's in Uvira, only 31% of the population had access to water presenting a low level of water supply (Gallandat et al., 2021). This study used 30% of the maximum threshold as the minimum threshold to assess the security level of the accessibility dimension in Kinshasa.

3.3.3. Water Health and Sanitation Dimension

This dimension signifies that users have access to water of good quality according to national and international standards. To measure this dimension, Babel et al. (2020) suggested using the quality of the water supply as a parameter including pH, turbidity, and coliform count in the water. However, these variables were not available and REGIDESO reports testify to the accordance of water supply to WHO standards, the nominal capacity of available water treatment plant was used to measure this dimension. As the quality standard is assumed to be met by the water treatment plant, this study uses the per capita quantity that the water treatment can cover.

Furthermore, Babel et al. (2020) used the percentage of treated wastewater to measure the environmental dimension considering the quality of wastewater that is discharged into natural water resources. This study used the same indicator to measure sanitation as the level of wastewater management ensuring the health of humans. Table 2 shows the maximum and minimum thresholds used for the nominal capacity of the treatment plants.

Table 2: Threshold for water quality indicators.

Indicators	Unit	Standardization					Reference
		1	2	3	4	5	
Nominal capacity of treatment plant overpopulation	L/C/D	<20	21-50	51-90	91-100	>100	Babel et al. (2020)
The proportion of treated wastewater	%	<60	61-70	71-80	81-90	91-100	Babel et al. (2020)

3.3.4. Water Affordability

This dimension reflects the fact that water must be affordable to the population. To measure this dimension, this study used the average selling price for 1 cubic meter of water as the indicator. The benchmark is inspired by Khan et al. (2020) as shown in Table 3.

Table 3: Threshold for affordability indicators.

Indicators	Unit	Standardization					Reference
		1	2	3	4	5	

Selling price of water	USD/m^3	>1	1	0.75	0.5	>0.4	Khan et al. (2020)

3.3.5. Environment

This dimension pertains to external elements that do not form a part of the urban water system but have an impact on it (Babel et al., 2020). The annual average air temperature and the population growth rate are considered to measure this dimension according to Karimi et al. (2021) and normalized as shown in Table 4.

Table 4: Threshold for environment indicators.

Indicators	Unit	Standardization					Reference
		1	2	3	4	5	
Average annual air temperature	^{0}C	>40	35-40	30-35	25-30	<25	Aboelnga et al. (2020)
Population growth rate	‰	>8.88	8.88-8	7.11-7.99	6.2-7.1	<6.20	Su et al. (2019)

3.3.6. Water-related disaster

This dimension encompasses the level of city vulnerability to water-related disasters (Babel et al., 2020). To measure the vulnerability of Kinshasa, this study used the number of floods per year (flood frequency), number of deaths associated with flood events, number of people affected by floods, number of droughts per year (droughts frequency), and population affected by flood per year. Furthermore, the per capita GDP was used as an indicator of this dimension to measure the capacity of the population to recover from disaster. The threshold used to scale the number of floods, and the number of deaths associated with floods and per capita GDP were found in existing works (Aboelnga et al., 2020; Shao et al., 2012; Su et al., 2019). Aboelnga et al. (2020) proposed a threshold for a three-year frequency of occurrence. However, as this study evaluated the security per year, an annual distribution of the three-year frequency as a threshold was used.

For people affected by flooding, the total number of populations that were affected by the May 2024 flood in Bangladesh was considered as a poor security level. Bangladesh, being known as one of the top countries at high risk of flood, experienced a devastating flood which affected approximately 18 million people in May 2024, leaving the country with alarming crisis and critical losses (FAO, 2024). For the high level of security that can be expected from the city, this study used the flood event which occurred in Kinshasa in 2007. This flood lasted one week and recorded a number of 1600 people affected. Even though the lowest one in history has a record of 21 people affected, the one in 2007 provides flexibility for policymakers to target as the lowest one occurred in 2001, and the population density of the city was very low. Therefore, the flood that occurred in 2007 is more realistic as the target of the highest security of the city. Furthermore, as no drought event was recorded in Kinshasa for this study's timeframe, there is no need to standardize the number of droughts and population affected by drought, thus the security is considered excellent for the number of droughts and people affected by droughts. Table 5 shows the threshold of indicators of the water-related disaster dimension.

Table 5: Threshold for indicators in water-related disasters dimension.

Indicators	**Unit**	**Standardization**					**Reference**
		1	**2**	**3**	**4**	**5**	
Number of floods	Nbr	>8	7-8	5-7	4-5	<4	Su et al. (2019)
Flood deaths	Nbr/Y/100000 habitants	>350	150-250	30-150	10-30	<10	
Population affected by floods	Nbr/year/10000	>1800	-	-		<0.0016	
Number of droughts	-	-	-	-	-	-	
Population affected by droughts	-	-	-	-	-	-	
Per capita GDP	USD	3000	-	-	-	77000	Shao et al. (2012)

3.3.7. Governance

For the governance dimension, Babel et al. (2020) proposed three indicators, the overall management of the water sector (institutional factor), the potential to adapt to future change (adaptability factor), and citizen support for water security (public support factor). These indicators are measured through qualitative data collected with questionnaires. However, as this research evaluated urban water security trends from 2015 to 2024, collecting data through questionnaires or interviews did not work as relevant stakeholders were not able to remember information about the past and some of them, were in their position only from the early 2020s. To be able to measure the governance dimension this study instead used available measurable indicators inspired by the questionnaires proposed by Babel et al. (2020) as shown in Table 6.

Table 6: Indicators for measuring the governance dimension of urban water security.

Questionnaire from Babel et al. (2020)	**Used measurable indicators in this study**
The overall management of the water sector (Institutional factor)	
Is public opinion sought when developing water-related plans for the city?	No information was found
Is there a provision for the public to register their grievances?	The proportion of customer complaints resolved annually
Is there an official mechanism to monitor Non-Revenue Water (NRW)?	Percentage of non-revenue water
Is there a provision to incentivize water conservation?	No information was found
Does the organization consult other water organizations during the development of annual or long-term plans?	No information was found
The potential to adapt to future change (adaptability factor)	
Does recycling and/or reuse of water take place in the city?	No information was found
Is there a centralized database for water-related information?	Is there a centralized database for water-related information? Information was available from the relevant authority.
Is there a system to forecast water availability and quality?	Is there a system to forecast water availability and quality? Information was available from the relevant authority.
Are future driver future drivers of change (e.g., climate change) taken into	No information was found

consideration when developing long-term master plans?	
Is there a mechanism for the organizational staff to upgrade water-related knowledge?	No information was found
Citizen support for water security (public support factor) was not considered in the indicators as no measurable indicators were found to capture the evolution of public support for water security in the city.	

The purpose of the question about no revenue water and the public grievance is to know the level of institutional management of the water governance dimension (Babel et al., 2020). This study used the threshold for measuring the number of customer complaints and the percentage of non-revenue water proposed by Aboelnga et al. (2020) and Khan et al. (2020) respectively, as shown in Table 7.

Table 7: Normalization of measurable indicators in the governance dimension.

Indicators	Unit	Standardization					Reference
		1	2	3	4	5	
Customer complaints annually	Nº/y/10000 subscribers	>300	200-300	100-200	50-100	<50	Aboelnga et al. (2020)
Percentage of non-revenue water	%	>25	20-25	15-20	10-15	<10	Khan et al. (2020)

The threshold for qualitative indicators proposed by Babel et al. (2020) is shown in Table 8.

Table 8: Normalization of qualitative indicators.

Answer	Scale
Not yet considered	1
Under consideration/ under development	2
In place but not yet implemented	3
Partially implemented	4
Mostly implemented	5

3.4. Normalization

Data on indicators were collected in different scales and units, requiring a benchmark for analysis. This study used a scale of 1-5 where the thresholds for scaling were selected according to existing work on water security. However, for certain indicators, thresholds are proposed by this study and normalized using (Khan et al., 2020):

$$X_i = X_{mi} + \frac{V_i - V_{min}}{V_{max} - V_{min}} \times (X_{max} - X_{min}) \qquad \text{Eq. (3)}$$

where, X_i is a normalized indicator, V_i is the observed value of the indicator, V_{min} and V_{max} are the minimum and maximum proposed threshold respectively, X_{min} and X_{max} are the minimum (1) and maximum (5) scale respectively. Some indicators such as the urban population growth rate are inversely related to urban water security, meaning that the lower the better. In this form, Eq. (3) will take the form:

$$X_i = X_{min} + \left(1 - \frac{V_i - V_{min}}{V_{max} - V_{min}}\right)(X_{max} - X_{min}) \qquad \text{Eq. (4)}$$

3.5. Weighting of indicators

In seek of simplicity some studies like Karimi et al. (2021) and Khan et al. (2020) assume all indicators to have the same weights in the water security framework, suggesting that all indicators contribute to or impact equally the overall water security and have the same priority. However, this is not realistic as the impacts of indicators are different depending on their priority in the framework. To weigh indicators across their respective dimensions and dimensions across the overall urban water security, this study employed the analytical hierarchy process (AHP) for multi-criteria decision-making. The AHP is a widely used method for multi-criteria decision-making developed by Saaty (1987) that considers the difference in unit of measurement of indicator to prioritize. This method is based on a set of pairwise comparisons done between indicators. The pairwise comparison is done on a scale of 1 to 9 as shown in Table 9.

Table 9: Scale of relative importance.

Scale	Scale meaning	Explanation
1	Equal importance	Two indicators have equal importance for a goal
3	Moderate importance	A slight preference is for one indicator over another
5	Strong importance	Strong preference is on one indicator over another
7	Very strong or demonstrated importance	An indicator is preferred very strongly over another. its dominance is demonstrated in practice
9	Extreme importance	The evidence preferring one indicator over another is of the highest possible order of importance
2,4,6,8	Intermediate value	

The pairwise decisions are collected from tailored selected 12 to 20 experts in the field of interest. This study used opinions from 16 experts carefully selected from academia and city planners. The AHP Excel sheet developed by Goepel was used as both the survey questionnaire and a tool for the relative weight calculation. In the AHP method, indicators are represented through a matrix of a set of n indicators:

$$\begin{pmatrix} I_{11} & I_{12} & \cdots & I_{1n} \\ I_{21} & I_{22} & \cdots & I_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ I_{n1} & I_{n2} & \cdots & I_{nn} \end{pmatrix} \qquad \text{Eq. (5)}$$

The weight of the indicator is represented by $(w_1, w_2, \dots w_n)$, and the relative priority of an indicator over the other is represented as $\left(w_i/w_j\right)$. The AHP decision tool compares the weight of each indicator over the others with respect to the goal presented in matrix form:

$$\begin{pmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{pmatrix} \qquad \text{Eq. (6)}$$

After transforming the pairwise into the matrix, it becomes a mathematical computation of the eigenvector.

3.5. Urban Water Security calculation

3.5.1. Coding of indicators

For a clear data representation, indicators were coded by the combination of the first character of each word in the dimension and indicator. "I" was added at the end of dimension to mean index and the number of the indicator in the dimension was added for indicators in their respective dimension as shown in Table 10.

Table 10: Coding of indicators.

Dimension	Code (dimension)	Indicator	Codes (indi.)
Water availability	WAI	Per capita water consumption	WAI1
		Investment in water supply	WAI2
Water accessibility	WACI	Number of water subscribers	WACI1
		Length of the water distribution network	WACI2
Water health and sanitation	WHSI	Per capita nominal capacity of water treatment plants	WHSI1
		The proportion of wastewater treatment of treated wastewater	WHSI2
Affordability	AI	Selling price of water in urban areas	AI1
Environment	EI	Rate of urban population growth	EI1
		Average air temperature	EI2
Water-related disaster	WRDI	Number of flood events	WRDI1
		Population affected by floods	WRDI2
		Deaths related to flood events	WRDI3
		Number of drought events	WRDI4
		Population affected by droughts	WRDI5
		Per capita GDP	WRDI6
Governance	GI	Is there a system to forecast water availability and quality? (Information was available from the relevant authority)	GI1
		Is there a centralized database for water-related information (information was available from the relevant authority)?	GI2
		Customer complaints annually	GI3
		Percentage of Non-Revenue Water	GI4

3.5.2. Urban Security across dimensions and the overall Urban Water Security Index

The urban water security index across dimensions (D_i) based on the normalized indicators and the UWSI are calculated according to Khan et al. (2020):

$$D_i = \frac{\sum_{i=1}^{n} X_i W_i}{\sum_{i=1}^{n} W_i} \quad \text{Eq. (7)}$$

$$UWSI = \frac{\sum_{i=1}^{n} D_i W_j}{\sum_{i=1}^{n} W_j} \quad \text{Eq. (8)}$$

where W_i and W_j are the weights assigned to normalized indicator X_i and urban water security across dimensions D_i, while $UWSI$ is the overall urban water security index.

3.6. Future Water Security

Future water security was projected for 2030 and 2040 considering two different scenarios. First, based on the business-as-usual scenario considering that no improvement will be done, the observed Urban Water Security Index will keep its behaviour. Second, based on anticipated improvement in indicators with low performances.

3.6.1. Business-as-usual Scenario

For this scenario, no improvement in water security is considered to happen. The observed trends will continue till 2040. The Urban Water Security Index was projected by extrapolating the observed Urban Water Security Index. Four regression models – linear, quadratic, exponential and Segmented (Piecewise) regression models – were tested based on how well they match the variation in the observed Urban Water Security Index.

The linear model is the best fit when the trend behaviours show a steady increase or decrease over time. The quadratic regression is used when the trend behaviours show a parabolic shape. The exponential regression model is used when the change increases or decreases at an accelerating rate over time. Piecewise linear or segmented regression model is used when the trend behaviour shows two or more different trend behaviour in the observed period (Douglass et al., 2012). These models were computed following these equations:

Linear regression model: $UWSI_t = \beta_0 + \beta_1 t$ Eq. (9)

Quadratic regression model: $UWSI_t = at^2 + bt + c$ Eq. (10)

Exponential regression model: $UWSI_t = \alpha e^{\gamma t}$ Eq. (11)

Piecewise with two segments for a single breaking point $t = d$,

$$UWSI_t = \begin{cases} \beta_i + \beta_j t, & t < d \\ \beta_i + \beta_j d + \beta_k (t - d), & t \geq d \end{cases} \quad \text{Eq. (12)}$$

where $UWSI_t$ is the projected urban water security index for year t, β_0 is linear intercept, β_t is the slope or the change rate of urban water security over time, a is the quadratic intercept, b is the linear coefficient presenting the initial trend, c is the quadratic coefficient determining the curvature of the trend, α is the intercept (it is similar to β_0, but in a transformed scale), γ is the growth rate, β_i is the intercept for the segment model, β_j is the slope before the breaking point, β_k is the change in slope after the breaking point, d is the estimated breaking point. and t is the predictor variable (year).

To decide on what modal to adopt, the coefficient of determination (R^2) and the root mean squared error (RMSE) for each model were computed and compared. The higher coefficient means that the model explains better the variations in the urban water security trend while the lower RMSE means that the model prediction has less prediction error (Douglass et al., 2012). The purpose is to find the model which captures better the trend behaviour and has a higher level of accuracy. The coefficient determinant and the RMSE were computed using the equation:

$$R^2 = 1 - \frac{SS_{Residual}}{SS_{Total}} \quad \text{Eq. (13)}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i + y_i')^2} \quad \text{Eq. (14)}$$

where, R^2 is the coefficient of determination, $SS_{Residual}$ is the difference between actual and predicted value (sum of squared errors), SS_{Total} is the variation in urban water security, $RMSE$

is the Root Mean Squared Error, n is the number of observations, y_i is the actual observed value of urban water security, and y_i' is the predicted value from the model,

3.6.1. Improvement scenario

In this scenario indicators with low level of water security are expected to experience improvement over the years as follow:

i. Availability dimension, the water consumption is expected to reach 60 L/p/d in 2030 (satisfactory security) and 100 L/p/d in 2040 (Excellent security), while the investment budget is expected to reach USD 255 million by 2023 as per the multisectoral project and urban resilience project of the World Bank (World Bank, 2020). The water consumption is based on the acceptable level of water accepted by the World Health Organization assuming that the city planners are committed to reaching these standards.
ii. For the accessibility dimension, all the two indicators are assumed to reach a security level of 4 in 2030 and excellent security in 2040.
iii. For the Water Health and Sanitation dimension, the per capita nominal capacity of the water treatment plant is assumed to reach 4 in 2030 and 5 in 2040. This indicator is parallel to the per capita water consumption in the availability dimension, thus the assumption applied to the per capita consumption is applied. The proportion of treated water is assumed to reach 70% (fair security) in 2030 and 85% (good security) in 2040.
iv. In the environmental dimension, the population growth is anticipated to reduce reaching a fair level in 2030 and a satisfactory level in 2040, and the annual air temperature is assumed to maintain its security level
v. In the Governance dimension, the percentage of non-revenue and number of customers' complaints are supposed to reduce to and reach good security in 2030 and excellent in 2040, while the remaining dimensions are assumed to reach satisfactory security in 2030 and reach excellent in 2040.

The projected Urban Water Security Index in 2030 and 2040 was calculated using Eq. (7) and Eq. (8) (section 3.5.2).

4. RESULTS AND DISCUSSION

4.1. Standardization of Water Accessibility Indicators

The standardization of indicators was made to convert all indicators to a scale of 1 to 5 (section 3.3). The thresholds for both the number of subscribers and the length of network change as the population increases per year for the timeframe of this study (2015-2024) are shown in Table 11. The threshold of the number of subscribers decreases over time as they are inversely affected by the population density while the length of the network remains the same as it depends on the city area.

Table 11: Threshold for accessibility indicators.

	Standardization									
	2015	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
Population in Kinshasa (million)	11.59	12.1	12.62	13.17	13.74	14.34	14.97	15.62	16.31	17.03
Number of subscribers (Nbr/1000 inhab.)										
Vmax	72.10	70.59	69.11	67.66	66.23	64.83	63.46	62.11	60.79	59.49
Vmin	21.63	21.18	20.73	20.30	19.87	19.45	19.04	18.63	18.24	17.85
Length of network (million m)										
Vmax	63.6	63.6	63.6	63.6	63.6	63.6	63.6	63.6	63.6	63.6
Vmin	19.1	19.1	19.1	19.1	19.1	19.1	19.1	19.1	19.1	19.1

4.2. Weighting of dimensions and indicators

The purpose of weighting indicators and dimensions was to know how much each indicator weighs in its respective dimension, and how much each dimension weighs in the overall urban water security. This means that indicators contribute or influence their respective dimension differently according to their priorities, and dimensions contribute differently to the overall urban water security. The weight of each indicator in its respective dimension and each dimension in the overall urban water security are shown in Table 12.

Table 12: Weights of indicators and dimensions.

Code of dimension	Weight of dimension	Codes of indicator	Weight of indicator
WAI	0.162	WAI1	0.314
		WAI2	0.686
WACI	0.172	WACI1	0.525
		WACI2	0.475
WHSI	0.176	WHSI1	0.524
		WHSI2	0.476
AI	0.134	AI1	1
EI	0.108	EI1	0.65
		EI2	0.35
WRDI	0.069	WRDI1	0.131
		WRDI2	0.169
		WRDI3	0.364
		WRDI4	0.084
		WRDI5	0.108
		WRDI6	0.145
GI	0.179	GI1	0.234
		GI2	0.237
		GI3	0.309
		GI4	0.219

The weights are calculated in terms of percentage where 1 represents 100% weight. For example, the dimension GI weight is 0.179 in the overall urban water security meaning that GI while GI1 weight is 0.234 in the GI. This means that GI has a 17.9% influence on urban water security while GI1 has a 23.4 % influence on the GI dimension. It is possible to have a maximum weight for AI1 which weights 1 in AI meaning that it has 100% of the AI dimension. This happened because AI1 is the only indicator measuring AI, automatically representing the maximum influence on AI. However, AI is not the only dimension measuring the overall urban water security, thus from AHP computation, it has 0.134 weight meaning that it influences the overall urban water security by 13.4%.

4.3. Urban Water Security Index

4.3.1. Urban Water Security Index across dimensions

After weighting all indicators in the respective dimension, the Waster Security Index across dimensions was computed from 2015 to 2024. The level of security index is between 1 to 5 according to Khan et al. (2020).

a. Water Availability Dimension (WAI)

Figure 3 shows the water security trend across the availability dimension, influenced by WAI1 and WAI2.

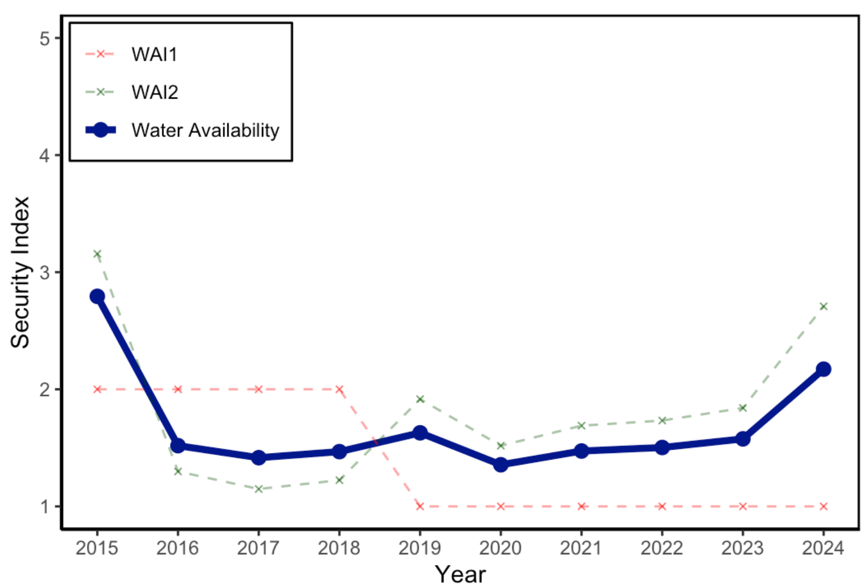

Figure 3: Security index for WAI.

The trend shows that the highest level of security index in the water availability dimension in Kinshasa was achieved in 2015 with WAI = 2.79, representing satisfactory security followed by a drastic decrease to 1.52 observed in 2016. From 2016 to 2024, the security level did not experience important changes varying between 1.52 and 2.17 observed in 2024 falling in the fair security level, except in 2017 where Kinshasa experienced the worst of 1.42 falling in the range of poor security (Khan et al., 2020). Notable, in Figure 3, the behaviour of WAI follows the pattern of the WAI2 indicator (the investment budget) explaining the 68.6% influence that this indicator has on the WAI versus the 31.4% of WAI1 (per capita water consumption).

b. Water Accessibility Dimension (WACI)

Figure 4 shows the variations of the security index in the water accessibility dimension influenced by two indicators, the number of subscribers to the water supply system (WACI1) and the length of the water distribution network (WACI2).

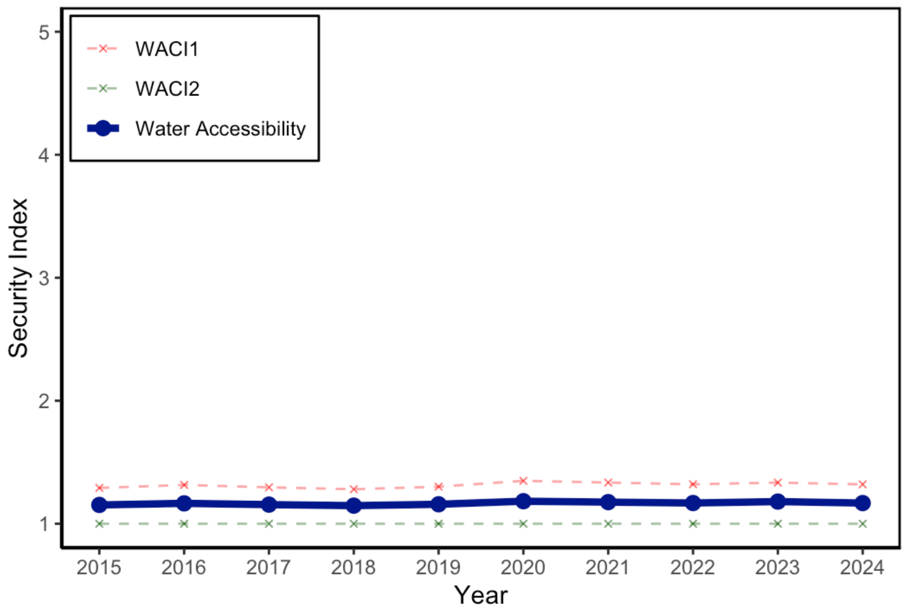

Figure 4: Security index for WACI.

Figure 4 reveals a stable trend varying from a security index of 1.15 to 1.18 through the entire period of 2015 to 2024 falling in the range of fair security levels. Despite the difference in the contribution of each indicator of water accessibility, they both are stable and do not experience important variation. However, WACI1 experiences small variation which seems to influence the behavior of the security index in the dimension while WACI2 remains constant at level 1. This is because WACI1 is the only indicator fluctuating thus influencing the behaviour of the security index of the dimension, but it does not reflect the difference in weight of both indicators.

c. Water Health and Sanitation Dimension (WHSI)

Figure 5 shows the trend of the security index in water health and sanitation dimension measured from two indicators, the per capita nominal capacity of the water treatment plant (WHSI1) and the percentage of the treated wastewater from the city (WHSI2). The water health and sanitation dimension does not experience any variation from the entire period with a constant security index of 1.52 falling in fair security.

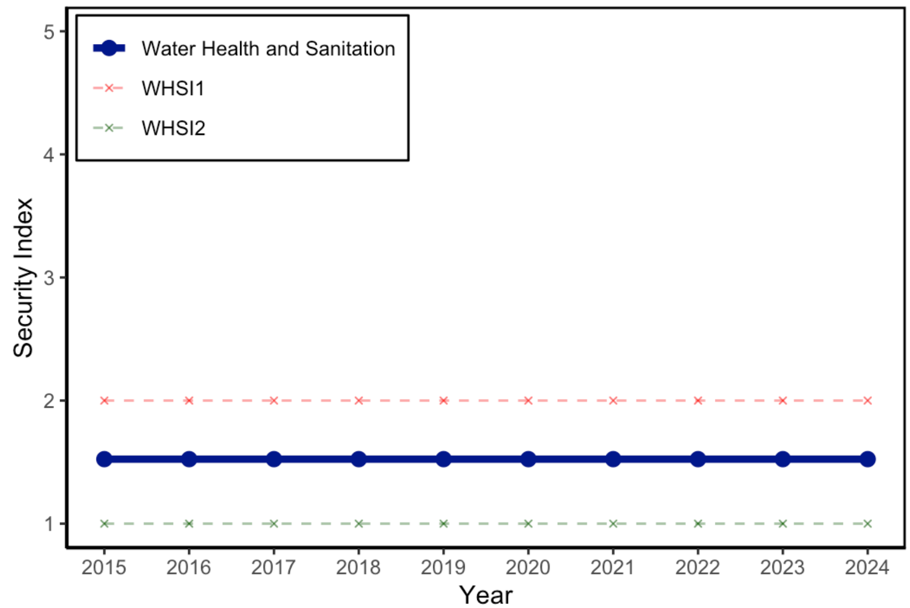

Figure 5: Security index for WHSI.

d. Affordability dimension (AI)

Figure 6 shows the trend of the security index in the affordability dimension measured from the price of one-unit cubic m of water in urban areas (AI1).

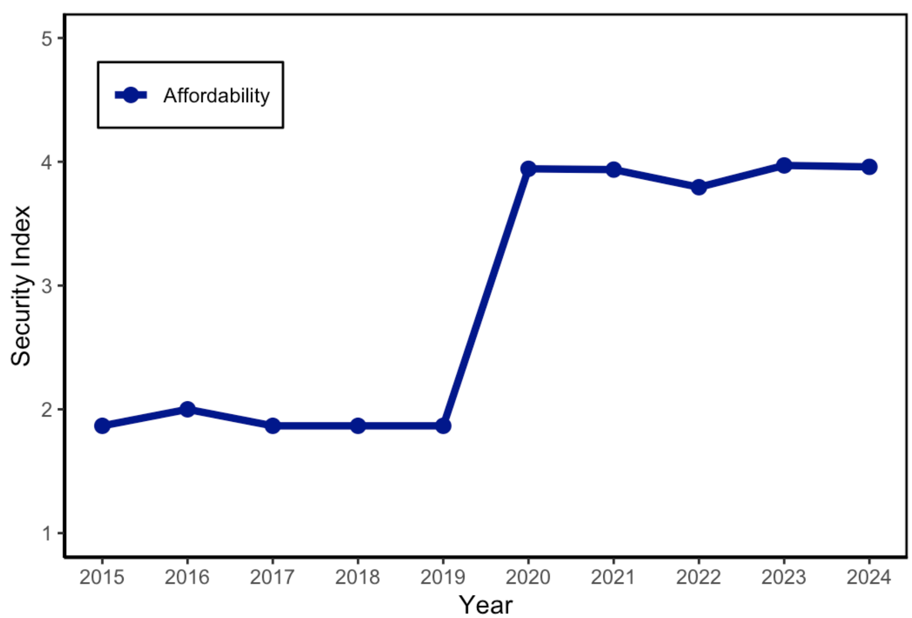

Figure 6: Security index for AI.

The trend reveals that from 2015 to 2019 the security index in AI experienced one security index of 1.87 expect in 2016 when it reached 2. Despite this trend behaviour, the security index remained in the range of fair security until 2020 when it experienced a drastic increase to 3.94, and experienced minor variation afterwards ranging between 3.94 and 3.97, all falling in the range of good security.

e. Environment Dimension (EI)

Figure 7 shows the trend of the security index in the environmental dimension measured by the average population growth rate (EI1) and annual air temperature (EI2).

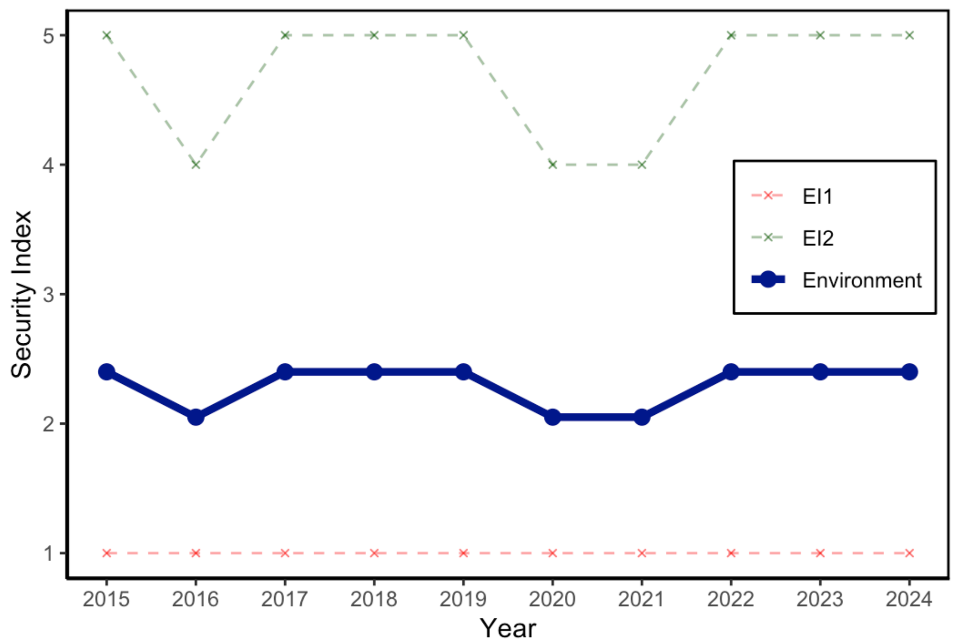

Figure 7: Security index for EI.

The trend reveals that the security index remained at 2.4 for the entire period except for 2016, 2020 and 2021 where it decreased to 2.05. Despite the few variations, the security index remained in the range of fair security for the entire period. EI2 varied between good (4) and very good (5) security while EI1 remained constant at a poor security level. This is due to the high population growth of the city which is because Kinshasa is among the cities with a high rate of population growth in Africa (World Bank, 2020).

f. Water Related-Disaster Dimension (WRDI)

Figure 8 shows the trend of the security index in water-related disasters measured by the number of flood events per year (WRDI1), population affected by flood events per year (WRDI2), deaths from flood events per year (WRDI3), number of drought events per year (WRDI4), population affected by droughts event per year (WRDI5), and per capita GDP (WRDI6).

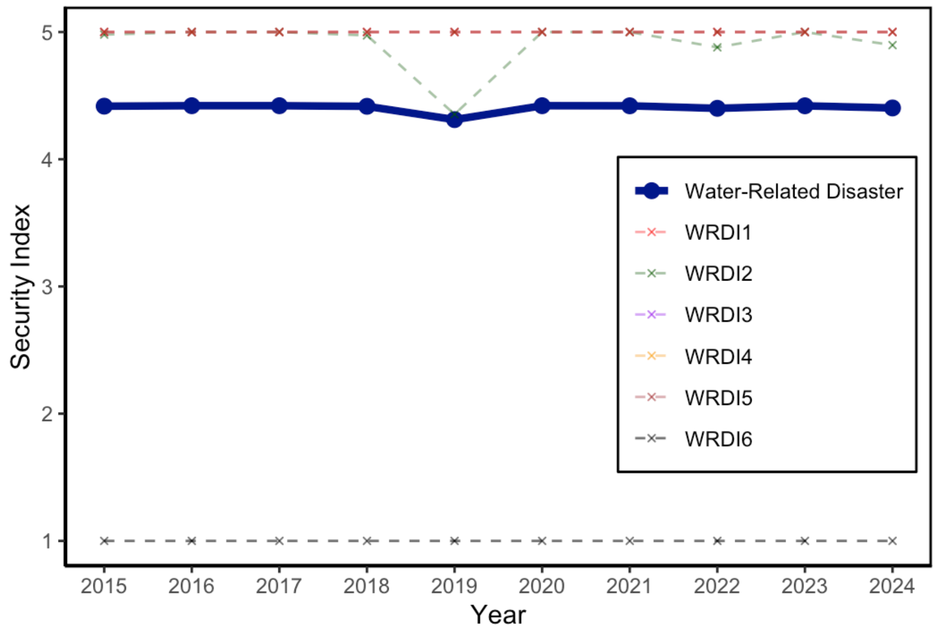

Figure 8: Security index for WRDI.

The trend reveals that the security index remained at 4.42 for the entire period except 2016, 2022 and 2024 where it decreased to 4.31 in 2019 and 4.40 in both 2022 and 2024. Despite the small variation, the security index remained in the range of good security for the entire period. Figure 8 shows that the behaviour of the security index is affected by WRDI 2 as it is the only indicator that experienced fluctuation throughout the period. WRDI1, WRDI3, WRDI4, and WRDI6 remained in the range of excellent (5) security, and WRDI 6 remained constant in the range of poor (1) security. However, this does not automatically mean that WRDI 2 contributed more than other indicators rather it influenced the behaviour shape as it fluctuated in the observation period.

Furthermore, it is very important to note that the fluctuation of the WRDI 2 (number of people affected by flood events per year) started from 2019 to 2024 while the security index of the number of flood events per year (WRDI 1) remained constant in the range of excellent security for the entire observation period. This means that the number of flood events that occurred from 2019 to 2024 in Kinshasa are in high level of security, but they hurt the city population, thus suggesting that the city had a low capacity to recover from floods even though their frequency of occurrence was low. This low-level capacity for recovery may be reflected in the security index of the per capita GDP which remained in a poor security range throughout the observation period (Babel et al., 2020).

g. Governance Dimension (GI)

Figure 9 shows the trend of the security index in the governance dimension measured by the adaptability factor (GI1 and GI2) and institutional factor (GI3 and GI4).

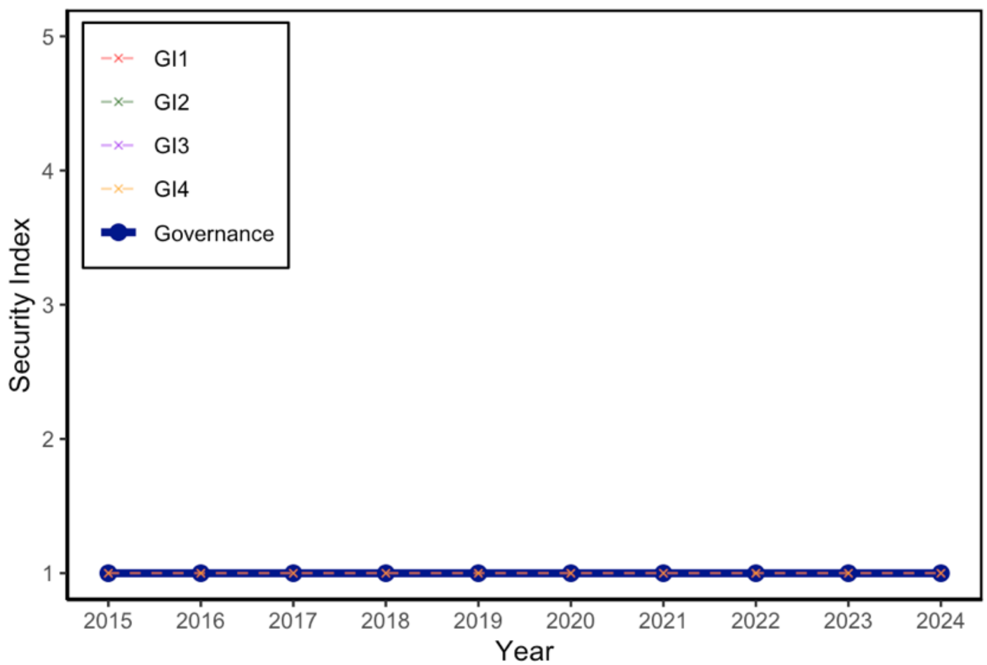

Figure 9: Security index for GI.

The security index of the Governance dimension did not experience any fluctuation throughout the entire observation period remaining in the range of poor security. This is explained by the fact that all indicators measuring within the dimension remained in the range of poor security.

4.3.2. Overall Urban Water Security Index (UWSI)

After computing the Security Index across all dimensions, the overall urban water security index (UWSI) was computed from the dimensions. Figure 10 shows the trend of the overall urban water security index throughout the observation period.

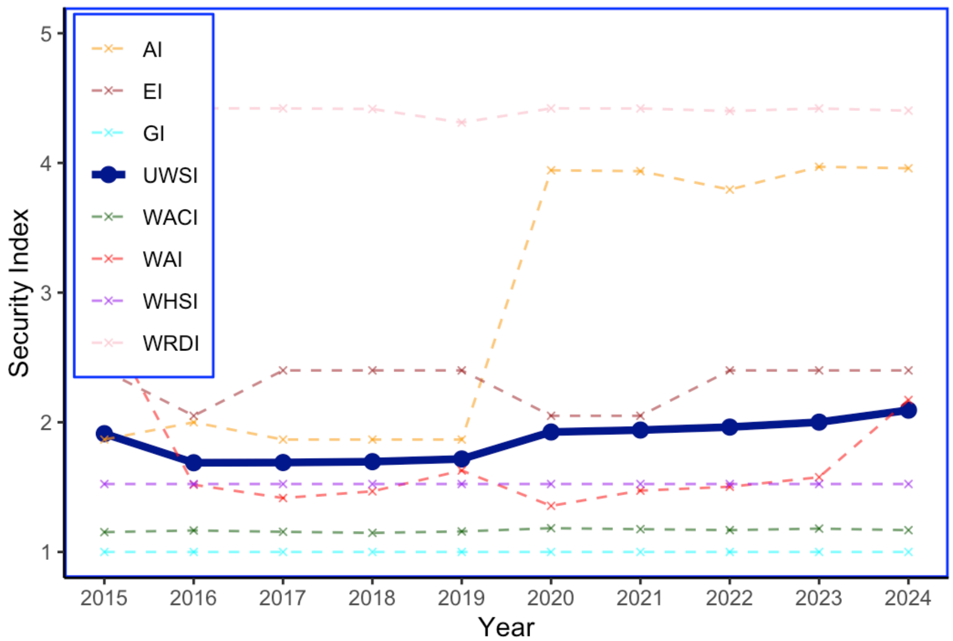

Figure 10: Overall Urban Water Security Index (UWSI).

The trend reveals that in 2016 the index of water security decreased from 1.91 observed in 2016 to 1.69. From 2016 to 2019 the trend shows minor fluctuation ranging from 1.69 to 1.72. In 2020, the security index increased slightly more than the previous year and reached 1.93 followed by minor fluctuation reaching 2.07 in 2024. Despite fluctuations, the UWSI remained in the range of fair security for the entire observation period. Although AI and WRDI reached good security almost for half of the observation period, this was not enough to enhance the state of water security beyond fair security due to differences in weights of dimensions in the UWSI.

This trend shows a snapshot of the current state of urban water security in Kinshasa. The city has a fair water security level (range: 1.5 to 2.5) with many indicators and dimensions experiencing a poor level of security. Attention is needed to all weak dimensions while maintaining the dimensions which are performing well such as water-related disasters. The summary of the security index across dimensions and the overall urban water security index is shown in Table 13.

Table 13: Urban Water Security Index from 2015-2024.

Urban Water Security Index										
Dimen.	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
WAI	2.79	1.52	1.42	1.47	1.63	1.36	1.47	1.50	1.58	2.17
WACI	1.15	1.17	1.16	1.15	1.16	1.18	1.18	1.17	1.18	1.17
WHSI	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52
AI	1.87	2.00	1.87	1.87	1.87	3.94	3.94	3.79	3.97	3.96
EI	2.40	2.05	2.40	2.40	2.40	2.05	2.05	2.40	2.40	2.40
WRDI	4.42	4.42	4.42	4.42	4.31	4.42	4.42	4.40	4.42	4.40
GI	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
UWSI	1.91	1.69	1.69	1.70	1.72	1.93	1.94	1.96	2.00	2.09

4.4. Future Urban Water Security Index

The projection of the Urban Water Security Index was computed from 2030 and 2040 based on two scenarios:

i. **Business-as-Usual Scenario:** In this scenario, no improvement in Urban Water Security is observed in Kinshasa, and the Urban Water Security Index maintain its trend behaviour.

ii. **Improvement Scenario:** In this scenario, improvement is expected to happen in indicators within each dimension falling in the range of poor, fair, and satisfactory security while the Affordability dimension and all indicators with security index in the range of good and excellent security are maintained to their last observation.

4.4.1. Extrapolation model for Business-as-Usual Scenario

As in Business-as-Usual Scenario the trend keeps its observed behaviour, an extrapolation model for projection was selected depending on the behaviour of the observed UWSI trend from 2015 to 2024. The observed trend as shown in Figure 10 has an unstable behaviour which makes it difficult to decide what extrapolating method to use. Four regression models were compared, mainly linear, quadratic, exponential, and piecewise or segmented regression models. Figure 11 shows the trend behaviour of each model compared to the observed UWSI from 2015 to 2019.

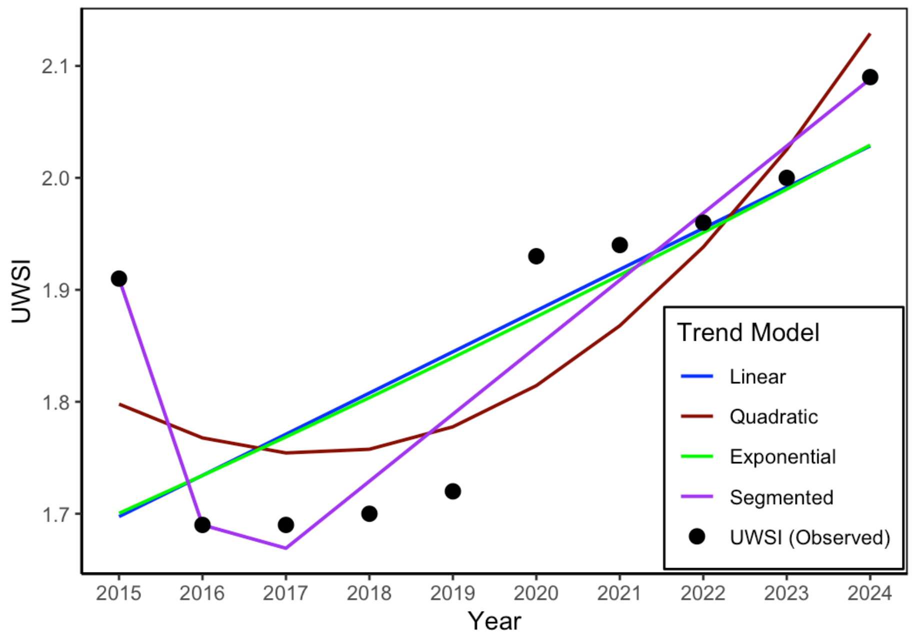

Figure 11: Trend models for UWSI.

The segmented model appears to follow the observed UWSI behaviour much better than all models, followed by the quadratic model. The linear and exponential regression models capture less of the observed UWSI trend. This is further validated by comparing the coefficient determent (R-squared) and the Root Mean Squared Error (RMSE) of each model as shown in Table 14.

Table 14: Models parameters comparison.

Model	R-squared	RMSE (Root Mean Squared Error)
Linear regression	0.5605	0.09357
Quadratic regression	0.7462	0.07110
Exponential regression	0.549	0.09196
Segmented (piecewise) regression	0.9273	0.03806

The segmented (piecewise) regression model had a coefficient of determinant of 0.9273 meaning that it matched the observed UWSI trend by 92.73 % making it the best choice for this extrapolation. The quadratic regression model followed with 74.62 % of the observed UWSI. The remaining models captured about 50% of the observed UWSI model. The Root Mean Squared Error of 0.038 strengthens the validation of the segmented regression model as the best fit for this extrapolation as it has the lowest RMSE.

4.4.2. Projected Urban Water Security Index

The Urban Water Security Index in Business-As-Usual Scenario was projected using the validated regression model (Segmented Model) and compared to the Urban Water Security Index for improvement Scenario. Figure 12 shows a comparison of the projected urban water security index for both 2030 and 2040.

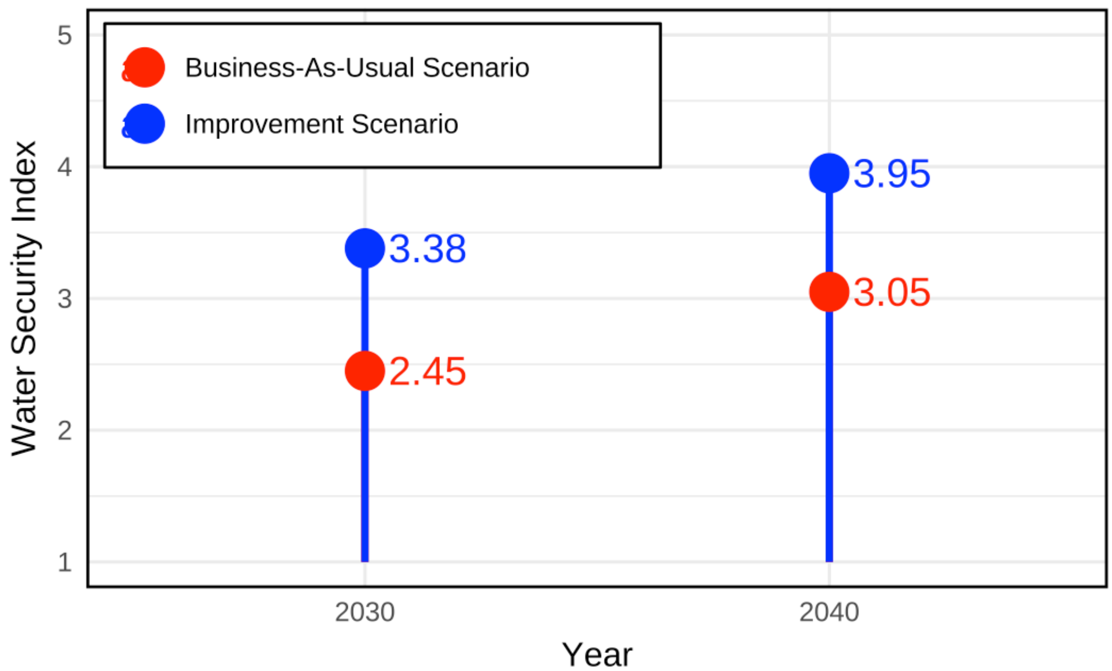

Figure 12: Projected Urban Water Security Index.

Figure 12 illustrates that the improvement scenario could enhance the urban water security index reaching 3.38 in 2030 and 3.95 in 2040 representing satisfactory and good security, respectively. However, if there is no improvement and the observed behaviour is maintained, in 2030 Kinshasa could experience an urban security of 2.45 while in 2040 it could reach 3.05. Despite the increase of water security in the business-as-usual scenario, the Urban Water Security Index could remain in the range of fair security in 2030 and reach a satisfactory level in 2040. Notably, by concretizing the improvement scenario Kinshasa can ensure acceptable urban water security for its population in 5 to 15 years, by ensuring that more attention and efforts are given to weak dimensions (WAI, WACI, WHSI, EI, and GI) of water security while preventing dimensions with acceptable level of security from deteriorating (AI and WRDI).

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

This study aimed to evaluate and present both the current and future state of urban water security in Kinshasa, DRC, across seven key dimensions: availability, accessibility, health, and sanitation, affordability, environment, water-related disaster and governance. To evaluate the current state of urban water security, the mini-max method was used to normalize indicators to a scale of 1 to 5, and the weighted sum method was used to calculate the urban water index across dimensions of water security and the overall water security. A scenario-based approach was applied to evaluate the future water state of Kinshasa considering the business-as-usual scenario and an improvement scenario.

Results revealed that in seven dimensions of urban water security, water-related disasters presented higher security varying from 4 to 4.4 followed by the affordability dimension which after drastically increasing from 1.87 in 2019 to 3.94 in 2020, reached 3.97 in 2024 falling in the range of good security. All remaining weaknesses revealed and fell in fair security in 2024 except the governance dimension which presented the poor security with a security index of 1 from 2025 to 2025. The overall urban water security from 2015 to 2024 varied between 1.69 to 2.09, presenting the current state of urban water security in the range of fair security.

For the future state of urban water security, estimations revealed a minor increase reaching 2.05 in 2030 and 3.38 in 2040, under the business-as-usual scenario and 3.38 and 3.95 in 2030 and 2040 respectively under the improvement scenario. This means that if nothing changes, in 2030 Kinshasa will have a fair level of water security and will reach a satisfactory level in 2040. However, if improvements are made in weak dimensions, Kinshasa could have a satisfactory level of water security in 2030 and reach a good level in 2040.

5.2. Limitations of this study

The methodology used in this study present some limitations which are important to note:

i. The selection of indicators was based on available data, and some data sources were based on estimates rather than direct measurement due to limited access to official statistics. This presents the limitation of this study in fully capturing the context of the city.

ii. The analytical hierarchy process (AHP) for weighting indicators was based on expert judgements, which despite being rigorous, remain subjective.

iii. The thresholds for water security for some indicators such as the length of the distribution network and the number of subscribers were determined based on assumptions which may not capture the reality of the city properly.

iv. The study primarily relied on citywide indicators measured annually, which may not capture inequality in water security at the household or community level, and seasonal distribution of water security. The informal settlement which constitutes a significant portion of Kinshasa was not analyzed due to limited desegrated data.

v. The business-as-usual scenario does not consider possible unexpected interventions, making its projection less flexible. The improvement scenario assumes steady progress without accounting for political instability, and economic, and social constraints.

vi. The hydrological system was not considered for present water security, while climate change impact and socioeconomic shifts beyond 2040 were not explicitly modelled. This may present the weakness of future scenarios considered in this study.

5.3. Recommendations

5.3.1. Recommendations for policymakers

Based on the findings, this study recommends policymakers in Kinshasa to:

i. Strengthen water governance institutions and adaptive measures to future changes considering:

- Developing a centralized database for real-time monitoring of water demand and consumption.
- Developing a research program on innovative water management and building more future scenarios to anticipate the future state of water security more accurately. This program would work on a future must plan which includes possible interventions according to different future scenarios.

- Establishing an independent body to oversee stakeholders’ participation with an emphasis on public participation and consideration. This would reduce customer complaints and build stockholders' trust in water governance institutions.
- Establishing a program to conduct regular assessments of the infrastructure, and track leaks and infrastructure deterioration. This would gradually reduce the non-revenue water.

ii. Set up a preliminary plan to improve water availability, accessibility and health and sanitation considering:

- Setting a clear target and conducting a preliminary study. This study could include construction of a wastewater treatment plant and an upgrading of the water treatment plant.
- Including public-private partnerships in the water framework to increase investment in water supply. This would ensure the availability of a sufficient budget for the water supply system.

iii. Set up a plan for climate resilience by considering:

- Budget allocation for water-related disaster mitigation and defense.
- Developing an early warning system.
- Developing an educational program to train the population on how to prepare for water-related disasters. This program could use both simple means of public communication such as TV, social media and a formal class.

iv. Strengthen the implementation of Integrated Water Resources Management (IWRM) and promote inter-sectoral coordination to align water security policies with urban planning, disaster management, and economic development.

5.3.2. Recommendations for future research

Based on the limitation of this study, future research should aim to:

i. Expand the range of indicators beyond currently available datasets, considering qualitative and community-based assessments. This means conducting a field data collection to ensure the availability of more data.

ii. Proper investigation of context-specific thresholds for water security indicators in Kinshasa.

iii. Disaggregate water security index at household and community levels to capture disparities and include seasonal and spatial analysis to assess the water security index fluctuations throughout the year.
iv. Consider incorporating dynamic modelling approaches that capture unexpected changes.
v. Develop a multi-scenario analysis that considers alternative pathways for water security in Kinshasa.
vi. Add more scenarios for future projection considering hydrological factors such as groundwater availability, precipitation patterns, river flow dynamics, and future climate change scenarios.
vii. Investigate more on the link between water security with broader environmental sustainability research.

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APPENDICES

Appendix 1: Observed values of used indicators (2015-2024).

Dimensions	Indicators	Unit	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Availability	Per capita water consumption (total domestic water consumption/total population)	l/c/d	25	23	22	21	19	19	19	19	20	20
	Investment in water supply	USD/year	141,652,258	27,344,187	18,128,494	22,769,826	65,313,092	40,869,255	51,387,578	54,078,173	60,693,003	114,060,934
Accessibility	Number of water subscribers	Nbr/1000 Inhabita	25	25	24	24	23	23	23	22	22	21
	Length of the water distribution network	m	3.247	3.250	3.741	3.787	3.778	3.830	3.828	3.883	3.890	3.883
Water Health and Sanitation	Per capita nominal capacity of water treatment plants	l/c/d	44	42	40	39	37	36	35	36	48	46
	The proportion of treated wastewater	%	0	0	0	0	0	0	0	0	0	0
Affordability	Selling price of water in urban areas	USD/m3	0.87	0.85	0.87	0.87	0.87	0.56	0.56	0.58	0.55	0.56
Environment	Rate of urban population growth	per thousand	43.40	43.30	43.30	43.30	43.40	43.60	43.80	44.00	44.00	43.90
	Average annual temperature	◦C	24.73	25.11	24.73	24.98	24.92	25.24	25.13	24.97	24.65	24.94
	Number of flood events	Nbr	1	0	0	1	1	0	0	1	0	1

Water-related Disaster	Population affected by floods	Nbr/year /10000	9.11	0.00	0.00	11.97	290.98	0.00	0.00	54.20	0.00	46.38
	Number of deaths associated with floods	Nbr/year /100000	0.27	0.00	0.00	0.39	0.31	0.00	0.00	1.12	0.00	1.76
	Number of drought events	Nbr	0	0	0	0	0	0	0	0	0	0
	Population affected by droughts	People	0	0	0	0	0	0	0	0	0	0
	Per capita GDP(National GDP/Population)	USD	1,964.13	1,927.27	1,916.98	1,943.66	1,942.81	1,896.53	1,930.53	2,009.21	2,096.10	2,113.67
Governance	Is there a system to forecast water availability and quality?		Not yet considered	Not yet considered	Not yet considered	Not yet considered	Not yet considered	Not yet considered	Not yet considered	Not yet considered	Not yet considered	Not yet considered
	Is there a centralized database for water-related information?		Not yet considered	Not yet considered	Not yet considered	Not yet considered	Not yet considered	Not yet considered	Not yet considered	Not yet considered	Not yet considered	Not yet considered
	Number of complaints	Nbr/year /10000 subscribers	1,248.19	73,458,189.97	48,938,593.68	65,846,108.74	89,367,467.87	29,297,915.61	51,748,533.33	59,510,950.86	122,707,888.49	80,799,672.03
	Per percentage of non-revenue water	%	45.28	49.85	48.79	45.14	42.30	41.24	42.38	43.10	44.87	39.35

Appendix 2: Normalized and coded indicators.

Dimensions	Indicators	Weights	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
WAI	WAI1	0.314	2	2	2	2	1	1	1	1	1	1
	WAI2	0.686	3.16	1.30	1.15	1.22	1.92	1.52	1.69	1.73	1.84	2.71
WACI	WACI1	0.525	1.29	1.32	1.30	1.28	1.30	1.35	1.33	1.32	1.33	1.32
	WACI2	0.475	1	1	1	1	1	1	1	1	1	1
WHSI	WHSI1	0.524	2	2	2	2	2	2	2	2	2	2
	WHSI2	0.476	1	1	1	1	1	1	1	1	1	1
AI	AI1	1	1.87	2.00	1.87	1.87	1.87	3.94	3.94	3.79	3.97	3.96
EI	EI1	0.65	1	1	1	1	1	1	1	1	1	1
	EI2	0.35	5	4	5	5	5	4	4	5	5	5
WRDI	WRDI1	0.131	5	5	5	5	5	5	5	5	5	5
	WRD2	0.169	4.98	5	5	4.97	4.35	5	5	4.88	5	4.90
	WRDI3	0.364	5	5	5	5	5	5	5	5	5	5
	WRDI4	0.084	5	5	5	5	5	5	5	5	5	5
	WRDI5	0.108	5	5	5	5	5	5	5	5	5	5
	WRDI5	0.145	1	1	1	1	1	1	1	1	1	1
GI	GI1	0.234	1	1	1	1	1	1	1	1	1	1
	GI2	0.237	1	1	1	1	1	1	1	1	1	1
	GI3	0.309	1	1	1	1	1	1	1	1	1	1
	GI4	0.219	1	1	1	1	1	1	1	1	1	1

Appendix 3: Pairwise comparisons AHP.

Appendix 3. 1: Availability dimension.

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 07.07.2022 | Free web based AHP software on: https://bpmsg.com

Only input data in the light green fields and worksheets!

n=	2	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	16	Number of Participants (1 to 20)	α:	0.1	Consensus: #######
p=	0	selected Participant (0=consol.)	2	7	Consolidated

Objective The goal of this comparison is to rank ttwo indicators that measure availability dimension: Per capita water consumption (WAI1) and Investment in water supply (WAI2).

Author Elie

Date 2-Mar-24 Thresh: 1E-08 Iterations: 14 EVM check: 7.7E-09

Table

	Criterion	Comment	Weights	+/-
1	WAI1	Per capita water consumption	31.4%	0.0%
2	WAI2	Investment in water supply	68.6%	0.0%
3			0.0%	0.0%
4			0.0%	0.0%
5			0.0%	0.0%
6			0.0%	0.0%
7			0.0%	0.0%
8			0.0%	0.0%
9		for 9&10 unprotect the input sheets and expand the	0.0%	0.0%
10		question section ("+" in row 66)	0.0%	0.0%

Result

Eigenvalue Lambda: 2.000 MRE: 0.0%

Consistency Ratio 0.37 GCI: n/a Psi: n/a CR: 0.0% 0.0%

AHP Analytic Hierarchy Process n= 2 Input 2

Objective: The goal of this comparison is to rank ttwo indicators that measure availability dimension: Per c

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

Participant 2 | 1 | α: 0.1 | CR: 0%

Name | Weight | Date | Consistency Ratio

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	WAI1	WAI2		
1	3				
1	4				
1	5				
1	6				
1	7				
1	8				

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

2,4,6,8 can be used to express intermediate values

Appendix 3. 2: Accessibility dimension.

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 07.07.2022 | Free web based AHP software on: https://bpmsg.com

Only input data in the light green fields and worksheets!

n=	2	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	16	Number of Participants (1 to 20)	α:	0.1	Consensus: #######
p=	0	selected Participant (0=consol.)	2	7	Consolidated

Objective The goal of this comparison is to rank ttwo indicators that measure accessibility dimension: Number of water subscribers (WACI1) and Length of the water distribution network (WACI2).

Author Elie

Date 4-Mar-24 Thresh: 1E-08 Iterations: 14 EVM check: 9.3E-09

Table

	Criterion	Comment	Weights	+/-
1	WACI1	Number of water subscribers	52.5%	0.0%
2	WACI2	Length of the water distribution network	47.5%	0.0%
3			0.0%	0.0%
4			0.0%	0.0%
5			0.0%	0.0%
6			0.0%	0.0%
7			0.0%	0.0%
8			0.0%	0.0%
9		for 9&10 unprotect the input sheets and expand the	0.0%	0.0%
10		question section ("+" in row 66)	0.0%	0.0%

Result

Eigenvalue				Lambda:	2.000		MRE:	0.0%
Consistency Ratio	0.37	GCI:	n/a	Psi:	n/a	CR:	0.0%	0.0%

AHP Analytic Hierarchy Process n= 2 Input 2

Objective: The goal of this comparison is to rank ttwo indicators that measure accessibility dimension: Nu

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

Participant 2	1		α: 0.1	CR: 0%
Name	Weight	Date		Consistency Ratio

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	WACI1	WACI2		
1	3				
1	4				
1	5				
1	6				
1	7				
1	8				

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

2,4,6,8 can be used to express intermediate values

Appendix 3. 3: Health and sanitation dimension.

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 07.07.2022 | Free web based AHP software on: https://bpmsg.com

Only input data in the light green fields and worksheets!

n=	2	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	16	Number of Participants (1 to 20)	α:	0.1	Consensus: #######
p=	0	selected Participant (0=consol.)	2	7	Consolidated

3 9

Objective The goal of this comparison is to rank ttwo indicators that measure health and sanitation dimension: Per capita nominal capacity of water treatment plants (WHSI1) and The proportion of wastewater treatment of

Author Elie

Date 4-Mar-24 Thresh: 1E-08 Iterations: 14 EVM check: 9.3E-09

Table

	Criterion	Comment	Weights	+/-
1	WHSI1	Per capita nominal capacity of water treatment plants	52.4%	0.0%
2	WHSI2	The proportion of wastewater treatment of treated wastewat	47.6%	0.0%
3			0.0%	0.0%
4			0.0%	0.0%
5			0.0%	0.0%
6			0.0%	0.0%
7			0.0%	0.0%
8			0.0%	0.0%
9		for 9&10 unprotect the input sheets and expand the	0.0%	0.0%
10		question section ("+" in row 66)	0.0%	0.0%

Result

Eigenvalue Lambda: 2.000 MRE: 0.0%

Consistency Ratio 0.37 GCI: n/a Psi: n/a CR: 0.0% 0.0%

AHP Analytic Hierarchy Process n= 2 Input

Objective: The goal of this comparison is to rank ttwo indicators that measure health and sanitation d

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

Participant 2 | 1 | α: 0.1 CR: 0%

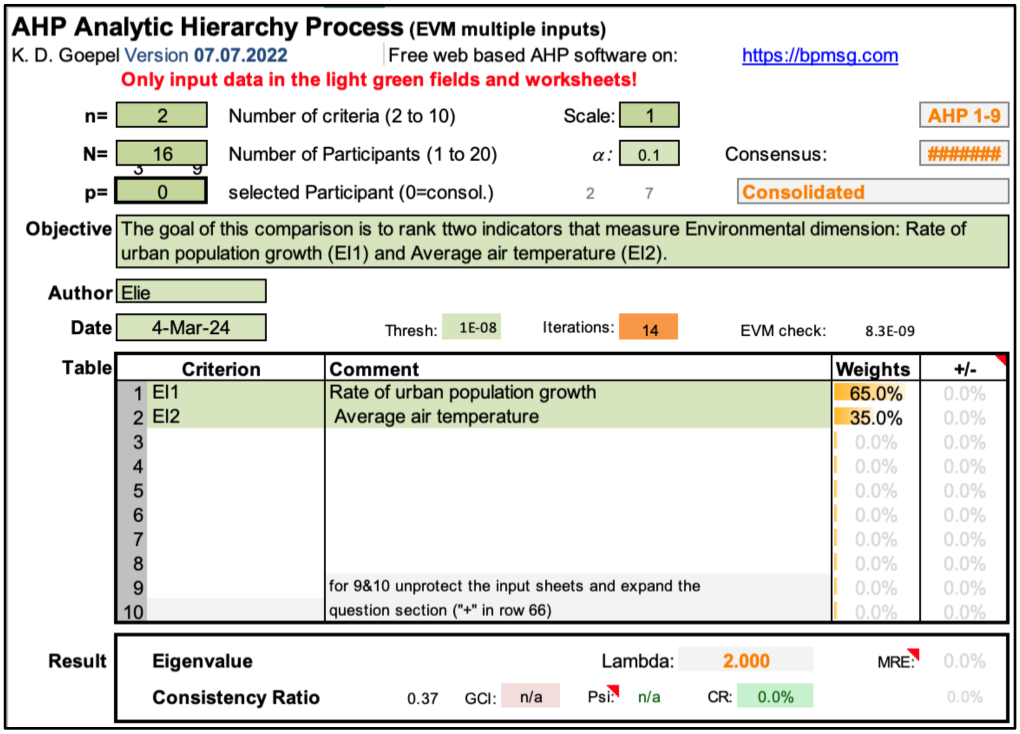
Name Weight Date Consistency Ratio

i	j	Criteria A	B	more important ? A or B	Scale (1-9)
1	2	WHSI1	WHSI2		
1	3				
1	4				
1	5				
1	6				
1	7				
1	8				

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

2,4,6,8 can be used to express intermediate values

Appendix 3. 4: Environmental dimension.



AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 07.07.2022 | Free web based AHP software on: https://bpmsg.com

Only input data in the light green fields and worksheets!

n=	2	Number of criteria (2 to 10)	Scale:	1		AHP 1-9
N=	16	Number of Participants (1 to 20)	α:	0.1	Consensus:	#######
p=	0	selected Participant (0=consol.)	2	7		Consolidated

Objective The goal of this comparison is to rank ttwo indicators that measure Environmental dimension: Rate of urban population growth (EI1) and Average air temperature (EI2).

Author Elie

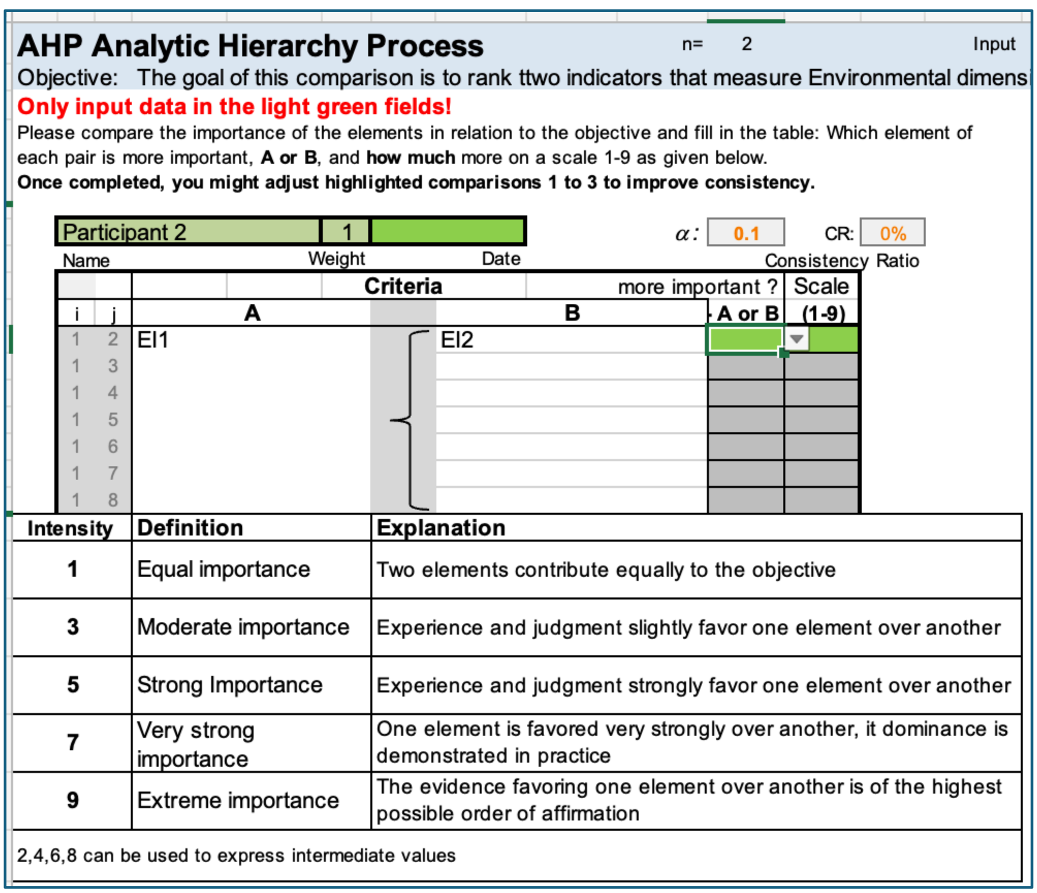
Date 4-Mar-24 | Thresh: 1E-08 | Iterations: 14 | EVM check: 8.3E-09

Table

	Criterion	Comment	Weights	+/-
1	EI1	Rate of urban population growth	65.0%	0.0%
2	EI2	Average air temperature	35.0%	0.0%
3			0.0%	0.0%
4			0.0%	0.0%
5			0.0%	0.0%
6			0.0%	0.0%
7			0.0%	0.0%
8			0.0%	0.0%
9		for 9&10 unprotect the input sheets and expand the	0.0%	0.0%
10		question section ("+" in row 66)	0.0%	0.0%

Result

Eigenvalue		Lambda: 2.000	MRE:	0.0%
Consistency Ratio	0.37 GCI: n/a	Psi: n/a	CR: 0.0%	0.0%



AHP Analytic Hierarchy Process n= 2 Input

Objective: The goal of this comparison is to rank ttwo indicators that measure Environmental dimensi

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

Participant 2 | 1 | α: 0.1 | CR: 0%

Name | Weight | Date | Consistency Ratio

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	EI1	EI2		
1	3				
1	4				
1	5				
1	6				
1	7				
1	8				

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

2,4,6,8 can be used to express intermediate values

Appendix 3. 5: Water-related disasters dimension.

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 07.07.2022 | Free web based AHP software on: https://bpmsg.com

Only input data in the light green fields and worksheets!

n=	6	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	16	Number of Participants (1 to 20)	α:	0.1	Consensus: #######
p=	0	selected Participant (0=consol.)	2	7	Consolidated

Objective The goal of this comparison is to rank indicators that measure water-related disasters dimension

Author Elie

Date 4-Mar-24 Thresh: 1E-08 Iterations: 5 EVM check: 1.6E-09

Table

	Criterion	Comment	Weights	+/-
1	WRDI1	Number of flood events	13.2%	1.7%
2	WRDI2	Population affected by floods	16.5%	2.0%
3	WRDI3	Deaths related to flood events	34.4%	4.2%
4	WRDI4	Number of drought events	9.1%	0.9%
5	WRDI5	Population affected by droughts	11.4%	1.1%
6	WRDI6	Per Capita GDP	15.4%	1.6%
7			0.0%	0.0%
8			0.0%	0.0%
9		for 9&10 unprotect the input sheets and expand the	0.0%	0.0%
10		question section ("+" in row 66)	0.0%	0.0%

Result

Eigenvalue Lambda: 6.031 MRE: 11.2%

Consistency Ratio 0.37 GCI: 0.02 Psi: 15.0% CR: 0.5%

AHP Analytic Hierarchy Process n= 6 Input

Objective: The goal of this comparison is to rank indicators that measure water-related disasters

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

Name	Weight	Date	α:	CR:
Participant 1	1	-	0.1	0%

Consistency Ratio

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	WRDI1	WRDI2		
1	3		WRDI3		
1	4		WRDI4		
1	5		WRDI5		
1	6		WRDI6		
1	7				
1	8				
2	3	WRDI2	WRDI3		
2	4		WRDI4		
2	5		WRDI5		
2	6		WRDI6		
2	7				
2	8				
3	4	WRDI3	WRDI4		
3	5		WRDI5		
3	6		WRDI6		
3	7				
3	8				
4	5	WRDI4	WRDI5		
4	6		WRDI6		
4	7				
4	8				
5	6	WRDI5	WRDI6		
5	7				
5	8				

Appendix 3. 6: Governance dimension.

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 07.07.2022 | Free web based AHP software on: https://bpmsg.com

Only input data in the light green fields and worksheets!

n=	4	Number of criteria (2 to 10)	Scale:	1		AHP 1-9
N=	16	Number of Participants (1 to 20)	α:	0.1	Consensus:	#######
p=	0	selected Participant (0=consol.)	2	7		Consolidated

Objective The goal of this comparison is to rank indicators that measure governance dimension: Is there a system to forecast water availability and quality? (GI1), Is there a centralized database for water-related

Author Elie

Date 4-Mar-24 Thresh: 1E-08 Iterations: 7 EVM check: 1.9E-09

Table

	Criterion	Comment	Weights	+/-
1	GI1	Is there a system to forecast water availability and quality?	23.4%	1.1%
2	GI2	Is there a centralized database for water-related information	23.7%	0.7%
3	GI3	Customer complaints annually	30.9%	1.4%
4	GI4	Percentage of Non-Revenue Water	21.9%	0.8%
5			0.0%	0.0%
6			0.0%	0.0%
7			0.0%	0.0%
8			0.0%	0.0%
9		for 9&10 unprotect the input sheets and expand the	0.0%	0.0%
10		question section ("+" in row 66)	0.0%	0.0%

Result

Eigenvalue Lambda: 4.002 MRE: 3.9%

Consistency Ratio 0.37 GCI: 0.00 Psi: 8.3% CR: 0.1%

AHP Analytic Hierarchy Process n= 4 Input

Objective: The goal of this comparison is to rank indicators that measure governance dimension

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

Participant 2 | 1 | α: 0.1 | CR: 0%

Name | Weight | Date | Consistency Ratio

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	GI1	GI2		
1	3		GI3		
1	4		GI4		
1	5				
1	6				
1	7				
1	8				
2	3	GI2	GI3		
2	4		GI4		
2	5				
2	6				
2	7				
2	8				
3	4	GI3	GI4		
3	5				
3	6				
3	7				
3	8				

Appendix 3. 7: Dimensions across the overall urban water security.

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 07.07.2022 | Free web based AHP software on: https://bpmsg.com

Only input data in the light green fields and worksheets!

n=	7	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	16	Number of Participants (1 to 20)	α:	0.1	Consensus: #######
p=	0	selected Participant (0=consol.)	2	7	Consolidated

Objective The goal of this comparison is to rank Dimensions that measur the overal water security index: Availability, Accessibility, Health and Sanitation, Affordability, Environment, Water-related disasters and

Author Elie

Date 4-Mar-24 Thresh: 1E-08 Iterations: 4 EVM check: 8.5E-09

Table

	Criterion	Comment	Weights	+/-
1	Availabiliyt		16.2%	2.4%
2	Accessibility		17.2%	3.0%
3	Health and sanitatior		17.6%	2.8%
4	Affordability		13.4%	1.7%
5	Environment		10.8%	2.1%
6	Water-related disast		6.9%	1.2%
7	Governance		17.9%	2.5%
8			0.0%	0.0%
9		for 9&10 unprotect the input sheets and expand the	0.0%	0.0%
10		question section ("+" in row 66)	0.0%	0.0%

Result

Eigenvalue Lambda: 7.077 MRE: 16.0%

Consistency Ratio 0.37 GCI: 0.04 Psi: 21.9% CR: 1.0%

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

Participant 2 | 1 | α: 0.1 | CR: 0%

Name | Weight | Date | Consistency Ratio

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Availabiliyt	Accessibility		
1	3		Health and sanitation		
1	4		Affordability		
1	5		Environment		
1	6		Water-related disast		
1	7		Governance		
1	8				
2	3	Accessibility	Health and sanitation		
2	4		Affordability		
2	5		Environment		
2	6		Water-related disast		
2	7		Governance		
2	8				
3	4	Health and sanitation	Affordability		
3	5		Environment		
3	6		Water-related disast		
3	7		Governance		
3	8				
4	5	Affordability	Environment		
4	6		Water-related disast		
4	7		Governance		
4	8				
5	6	Environment	Water-related disast		
5	7		Governance		
5	8				
6	7	Water-related disast	Governance		
6	8				