WATER INFRASTRUCTURE TYPES FOR CLIMATE CHANGE MITIGATION

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ABSTRACT

The current water infrastructure in Adamawa, which includes dams, boreholes, wells, overhead tanks, treatment plants, reservoirs, and levees, is outdated and lacks adequate capacity to manage the extremes of climate change effectively. Consequently, this study aims to identify and evaluate the most sustainable water infrastructure types for climate change mitigation along the River Benue floodplain of Yola. The research employed a mixed-methods approach, conducting field surveys for physical observation to document existing infrastructure, utilizing GIS mapping for spatial location and classification, analyzing aerial imagery (satellite images) to capture inaccessible areas, and holding interviews with stakeholders. These infrastructures were then assessed using Multi-Criteria Decision tools to determine their sustainability. The results show that dams ranked highest in sustainability (0.2590) due to their effectiveness in flood control and water storage, followed by boreholes (0.2298) for groundwater access, irrigation canals (0.2246) for improving agricultural productivity, and treatment plants (0.2182) for water supply management. The findings emphasize the need for an integrated water infrastructure strategy that includes energy-efficient irrigation systems, water pricing policies, afforestation, and community engagement to strengthen climate resilience and water security in the River Benue Valley. Furthermore, incorporating meteorological and hydrological data into adaptive water management practices is essential for long-term sustainability.

Keywords: Water Infrastructure, Benue Floodplain, Mitigation, Climate Change

1 INTRODUCTION

Water infrastructure plays a critical role in managing the impacts of climate change, particularly in riverine areas like the River Benue Valley in Yola, Nigeria [1]. The Benue Valley is integral to the livelihoods of local communities, supporting agriculture, drinking water, fishing, and transportation [2]. With the escalating effects of climate change, including erratic rainfall, severe flooding, and droughts, there is an urgent need to assess water infrastructures for greater resilience [3]. The River Benue, one of the major rivers in West Africa, stretches over 1,400 kilometers from Cameroon through Nigeria, converging with the Niger River at Lokoja [4]. As it passes through Yola, Adamawa State, it sustains many of rural and urban households, supporting agricultural activities and domestic water needs [5]. This river valley has rich alluvial soils, making it fertile for farming; however, this also leaves it vulnerable to flooding, especially during heavy rains. The wet season, spanning from June to October, is characterized by increased precipitation, which significantly influences agricultural productivity, water resource availability, and ecological balance in the region [6]. Often brings unpredictable rainfall and, at times, severe floods that threaten farmlands, infrastructure, and livelihoods, disrupting socio-economic activities and posing significant challenges to disaster management efforts [7]. Water Infrastructure Facilities and structures such as dams, levees, reservoirs, and drainage systems are designed to manage water resources, control flooding, and ensure water availability, playing a crucial role in supporting agricultural activities, industrial processes, and domestic water supply while mitigating the impacts of climate change [8]. Water infrastructural Projects Construction of systems and structures that are necessary for the impoundment, treatment, storage, and distribution of water for various uses. It includes Dams and Reservoirs, Irrigation Systems, Water Supply Systems, Water Treatment Facilities, Wastewater Facilities and Stormwater Management Systems. Water projects are infrastructures/facilities that make some areas of land or water more profitable, productive or useful. It is synonyms to water development, water program.

2 LITERATURE

Flood mitigation involves strategies to reduce the impact of flooding on communities and ecosystems. Water infrastructure plays a crucial role in this process, with dams and levees controlling water flow and wetlands providing natural flood absorption. The integration of green and gray infrastructure enhances flood resilience by combining engineered solutions with ecological benefits [9]. [10] examined the challenges faced by urban water infrastructure in adapting to the impacts of climate change across various global contexts. The research highlights that urban areas are increasingly vulnerable to climate-induced stresses such as flooding, droughts, and water quality deterioration, which are exacerbated by rapid urbanization and aging infrastructure. The findings of the research emphasized that the integration of climate adaptation strategies into water management systems is crucial for enhancing the resilience of cities to these challenges. The study uses a global survey to explore the primary challenges that cities encounter when adapting urban water infrastructure to climate change. Key barriers identified included financial constraints, lack of political will, insufficient technical capacity, and institutional fragmentation. Additionally, the research highlighted the complexity of integrating new climate adaptation measures with existing infrastructure, as many cities are faced with outdated water systems that were not designed to cope with the current and future impacts of climate change. A central theme of the findings is the need for a holistic approach to water infrastructure adaptation, which includes not only upgrading physical infrastructure but also enhancing governance frameworks, public engagement, and policy coherence. The research emphasized that successful adaptation requires collaboration between various stakeholders, including local governments, utility providers, and communities. [10] also discussed innovative solutions being implemented in cities around the world, such as green infrastructure, smart water systems, and nature-based solutions, which can complement traditional engineering approaches. The findings concluded by stressing the importance of addressing the challenges of urban water infrastructure adaptation early to avoid costly and ineffective interventions in the future. It calls for more comprehensive, integrated strategies that consider both short-term needs and long-term sustainability.

2.1 GLOBAL INNOVATIONS AND PRACTICES

Globally, countries that are more vulnerable to climate change, particularly those in Southeast Asia and Europe, have made significant strides in building climate-resilient water infrastructure. One such example is the Netherlands, known for its sophisticated flood management system, including a network of dikes, sea barriers, and advanced forecasting tools [11]. The Dutch approach, which combines gray infrastructure (dams, levees) and green infrastructure (wetlands, floodplain restoration), is lauded for its adaptability and its focus on ecosystem-based solutions. By integrating natural water retention systems with traditional flood barriers, the Netherlands has successfully created a resilient infrastructure that not only protects urban areas from rising sea levels but also enhances biodiversity and ecosystem services [12]. In Singapore, the use of integrated water management systems demonstrates another example of climate-resilient infrastructure. The Marina Barrage, which controls the flow of water in the city-state, serves multiple purposes, including flood control, water supply, and recreational space. It is part of a broader strategy that emphasizes the importance of water conservation, treatment, and reuse in the context of climate change [13]. Singapore’s success lies in its ability to combine innovative engineering with sustainable practices, making it a global leader in climate-resilient water infrastructure. In the United States, especially in flood-prone regions such as New Orleans, a hybrid approach to water infrastructure that combines gray and green solutions has gained prominence. The New Orleans Master Plan for flood resilience emphasizes flood control through pumps and levees, while also restoring wetlands and natural buffers that absorb excess water during heavy rainfall [14]. This holistic strategy has become a model for cities worldwide, demonstrating that combining hard infrastructure with nature-based solutions is an effective way to mitigate flood risks and adapt to changing climate conditions. Water infrastructure innovations around the world are being leveraged to address the escalating challenges posed by climate change, particularly in regions vulnerable to flooding, water scarcity, and other climate-related disruptions. These innovations combine both technological advancements and nature-based solutions to create more resilient, sustainable water management systems. Countries like the Netherlands, Singapore, and Australia have pioneered solutions that can serve as models for climate resilience and adaptation in water infrastructure. In the Netherlands, a country renowned for its flood mitigation expertise, the development of room for the river projects is a groundbreaking innovation. These projects involve the strategic re-engineering of river channels and floodplains to allow more water to be safely stored during high-water events, thereby reducing flood risks in urban areas. The incorporation of green infrastructure, such as wetlands and floodplain reconnection, within these engineering solutions has not only improved flood safety but also restored valuable ecosystems and biodiversity [15]. Similarly, the Dutch "Delta Works" is an extensive network of dams, sluices, locks, dikes, and storm surge barriers that serves as a testament to how large-scale infrastructure can protect densely populated coastal areas from rising sea levels and storm surges driven by climate change [16]. Singapore's Marina Barrage is another exemplary innovation that combines flood control with water supply and recreational spaces. Located at the confluence of five rivers, the barrage functions as a tidal control mechanism that prevents flooding during high tides while capturing rainwater for potable use. It is a prime example of how water infrastructure can integrate multifunctionality—serving not only as a flood mitigation tool but also contributing to the city's sustainable water supply and enhancing urban green space. The success of this project has led Singapore to develop further smart water management systems, including the use of reclaimed water and desalination to secure its water resources [13].

3 METHODOLOGY

Data collection process involves field survey and direct observations to document the types, conditions, and functionality of water infrastructures. Next is administering questionnaires and conducting interviews with key stakeholders, including government officials, Engineers, and community members, to evaluate perceptions and strategies related to water infrastructure. Another aspect is analyzing secondary data from policy documents, reports, and climate impact studies to understand current mitigation and adaptation practices and funding mechanisms for sustainable mitigation. Another critical stage is synthesizing all data to determine how existing or modified water infrastructures can reduce climate change impacts, focusing on resilience to flooding and water scarcity. In addition, four primary water infrastructure types for climate change mitigation: dams, boreholes, irrigation canals and treatment plants were put up. Multi-Criteria decision tool technique is used to identify the most sustainable mitigative water infrastructure.

4 RESULTS AND DISCUSSION

The assessment utilized Saaty's Multi-Criteria Decision-Making Technique (MCDMT), applying weighting and computational principles to determine the most sustainable option. The results on figure 1 below indicate that dams ranked highest in sustainability with an assessment score of 0.2590, followed by boreholes at 0.2298, irrigation canals at 0.2246, and treatment plants at 0.2182. This finding underscores the critical role of dams in climate change mitigation. Global projections suggest that flood risks will escalate due to climate change and population growth. The regulation of river flow by dams is crucial in mitigating these risks. Without such regulation, the estimated number of people exposed to annual flooding could reach 9.1 to 15.3 million by the end of the 21st century (Representative Concentration Pathways (RCP) 2.6 and 6.0 scenarios, respectively). However, integrating dams into flood mitigation strategies can reduce this exposure by 20.6% according to RCP2.6 and 12.9% under RCP6.0. While dams offer significant benefits in mitigating flood risks, their environmental impacts warrant further investigation. Climate change is expected to intensify hydrological variability, increasing flood frequency and altering precipitation patterns. [17, 18, 19, 20, 21]. The construction of over 2.8 million dams worldwide, with a total impoundment capacity ranging from 7,000 to 10,000 km³, has played a pivotal role in managing water resources. However, aging infrastructure and evolving climatic conditions pose challenges to the continued effectiveness of these structures. Enhancing dam operations through improved hydro-meteorological forecasting and adaptive reservoir management is essential to maintaining their flood mitigation capacity. [17, 18, 19, 20, 21]. Additionally, the assessment highlights concern regarding the resilience of boreholes, which ranked second. Boreholes are vital for providing potable water, particularly in regions where surface water is unreliable. However, their vulnerability to climate-induced risks, including declining groundwater levels and contamination, necessitates robust governance frameworks and adaptive management strategies. Addressing these challenges requires strengthening infrastructure resilience, improving policy implementation, and integrating climate adaptation measures into groundwater management. The figure illustrates respondents' perceptions of water sources and access challenges using Saaty's MCDMT. The prioritization criteria applied to the assessment of water infrastructure facilities in the figure were repeated in a pairwise comparison to determine the most viable options.

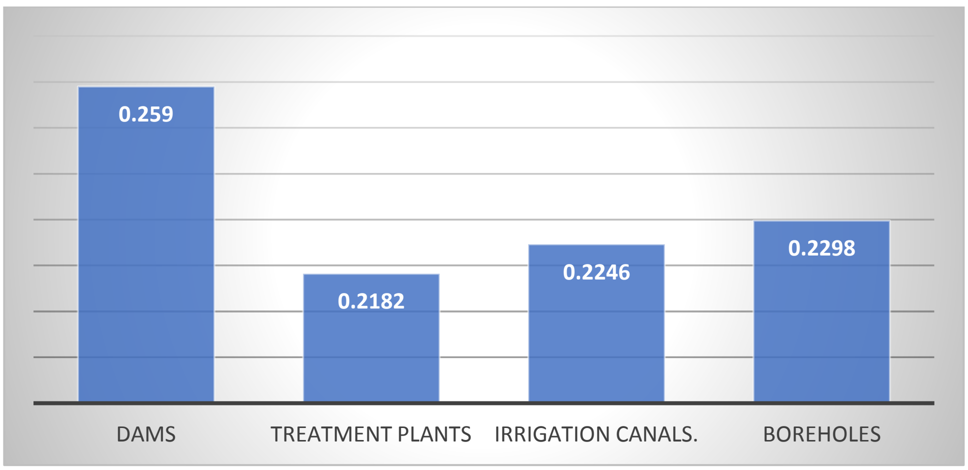

Figure 1. Sustainability of Water Infrastructural Facilities.

The results align with previous research findings, which highlight observed hydrological changes associated with global climate change. Documented impacts include rising global surface temperatures, increased frequency and intensity of extreme weather events such as heatwaves and droughts, changes in precipitation patterns, reduced snow cover, and altered runoff dynamics [17, 18, 19, 20, 21]. These changes significantly affect water infrastructure operations, necessitating adaptive measures to ensure sustainability. Flood risks associated with climate change could exceed the design capacity of many existing dams, increasing the likelihood of catastrophic failure [22, 23, 24]. Traditional water management practices, which rely on stationarity and historical hydrological data, may no longer be sufficient [25]. The increasing occurrence of extreme flood and drought events underscores the need for resilient water infrastructure that can withstand climate variability [26, 27]. Dams have historically played a crucial role in mitigating water resource variability by regulating river flows and securing reliable water supplies for human consumption and environmental sustainability. However, the environmental and social consequences of dam construction remain a topic of debate [28, 29, 30, 31, 32]. Despite these concerns, dams remain essential for achieving water security, particularly in developing nations where demand continues to rise [33, 34, 35, 36]. Boreholes, which ranked second in sustainability, are crucial for ensuring potable water supply. However, they are increasingly vulnerable to climate risks such as groundwater depletion and contamination. The resilience of borehole infrastructure depends on governance arrangements that enhance sustainable water access, particularly in the face of climate variability. Ensuring long-term water security requires policies that integrate climate adaptation strategies into infrastructure planning. Research suggests that resilient water infrastructure should be designed, built, and operated with future climate conditions in mind [37]. Adaptation measures should address increasing flood and drought risks, shifting consumer water demand, and the financial implications of infrastructure modifications [38, 39]. A resilient water utility should be capable of withstanding extreme weather events, minimizing damage, and recovering quickly from service disruptions [38]. Additionally, water institutions must develop technical capacity to manage climate-induced challenges effectively. Water security is achieved when all individuals have access to sufficient, safe, and affordable water for daily needs [40]. Addressing water security challenges requires equitable distribution of potable water resources, particularly for vulnerable populations [41, 42, 43, 44]. Irrigation canals ranked third in this study on water infrastructure facilities for mitigating climate change. This assessment evaluates the impact of expanded irrigation and varying canal conveyance efficiencies on the production of key agricultural crops such as rice, wheat, and maize under changing climatic conditions across Adamawa State's diverse landscapes. Understanding irrigation efficiency and its effect on crop yields is critical for the effective management of water resources in agriculture. The study indicates that the benefits of improved irrigation efficiency vary by location, with significant effects on crop yields across regions such as Savanna plantation in Adamawa, Nigeria. Research suggests that global food production must double by 2050 to meet the demands of the growing population [45]. Currently, irrigated agriculture accounts for 40% of global food production while occupying only 22% of total cultivated land [46]. Projections indicate that the extent of global irrigated agriculture will need to double by 2050, significantly increasing the demand for irrigation water [47]. However, half of the water used for irrigation is currently unsustainable, exceeding local renewable water supplies and adversely affecting both local and downstream water flows [48]. This situation exacerbates water insecurity, particularly in the context of climate change, which directly influences precipitation patterns and temperature variability [49, 50, 51]. According to the findings of tis research, to ensure long-term sustainability in agriculture and environmental health, there is an urgent need to implement efficient and sustainable irrigation systems. Sustainable irrigation practices focus on reducing water losses, minimizing demand, and improving water productivity. Significant water conveyance losses in irrigation systems result from seepage through canal bunds, deep percolation in soil layers, runoff into drains, and evaporation from water surfaces [52]. These losses are also influenced by factors such as soil permeability, canal depth, wetted perimeter length, water table levels, and flow velocity [53,54]. Canal lining using materials such as concrete, geomembrane, bentonite, polyvinyl chloride, or plastic can significantly enhance conveyance efficiency by minimizing water loss before reaching fields [55]. This strategy not only increases water availability for irrigation but also improves water quality [56]. Efforts to address seepage and percolation losses in canals can facilitate the irrigation of additional agricultural land. Developing efficient irrigation infrastructure and ensuring the proper operation and maintenance of existing systems are critical for boosting agricultural production. Given the challenges associated with constructing new irrigation systems—including high capital costs, adverse topography, inadequate infrastructure, and political instability—enhancing the efficiency of existing infrastructure is a more viable strategy. Studies have evaluated surface irrigation system efficiency [57,58,59], calculated canal conveyance losses [60, 61, 62], and explored methods to minimize these losses [63, 64, 65, 66, 67, 68, 58, 69]. Further research has addressed failure mechanisms and treatment measures for canals [70] and the economic aspects of irrigation efficiency in relation to fuel consumption [71]. However, there is a research gap in assessing the impact of varied canal conveyance efficiencies on crop yields, particularly using biophysical crop models that incorporate climate change projections. Wastewater treatment plants ranked lowest in this study's assessment of water infrastructure facilities for climate change mitigation. These systems provide essential public health services, but their vulnerability to climate change poses significant risks to communities. Climate change impacts on wastewater infrastructure manifest over different timescales and across various socio-economic groups and geographic contexts. This study evaluated direct climate-related impacts on wastewater system elements including reticulated wastewater networks, on-site wastewater systems, and treatment plants in urban and peri-urban settings. The major impacts identified include nuisance flooding, spills, odor emissions, deterioration of water quality due to increased uncontrolled discharges, and infrastructure damage. These issues contribute to broader environmental, social, economic, and cultural challenges, such as asset loss, community disruptions, declining water quality, public health risks, and economic costs related to damage repairs and lost productivity. Similar challenges have been documented in developed nations, where urban wastewater systems have played a critical role in improving public health and reducing disease outbreaks [72]. However, these systems remain susceptible to malfunctions or failures when subjected to extreme weather events or conditions beyond their original design thresholds. For example, sewage contamination frequently results from combined sewer overflows during extreme rainfall events [73], while earthquake-induced infrastructure damage can lead to widespread pollution, as observed during the 2012 Christchurch Earthquake [74]. The increasing frequency of climate-related hazards—including sea-level rise, temperature increases, prolonged dry spells, extreme rainfall, and intense storms—poses a significant threat to wastewater infrastructure. These hazards compound and cascade across critical services and communities, impacting built environments, critical infrastructure, and socio-economic activities [75] (Stephenson, 2018). Compound hazards, such as concurrent coastal flooding and riverine flooding, exacerbate vulnerabilities in low-lying areas [76, 77]. To mitigate these impacts, climate change adaptation strategies for wastewater systems must be prioritized. Effective adaptation requires integrating scientific research with local knowledge and policy frameworks [78]. Impact assessments are essential for informing infrastructure planning and risk management strategies [79]. Sea-level rise and altered precipitation patterns are expected to have severe consequences for wastewater infrastructure, affecting treatment performance and the quality of receiving water bodies. These impacts will be most pronounced in low-lying and flood-prone areas but will also propagate system-wide through changes in temperature, groundwater levels, and user behavior. Addressing these challenges requires proactive governance, long-term planning, and investment in climate-resilient wastewater infrastructure. Local government authorities must incorporate climate risk assessments into infrastructure decision-making, balancing these considerations with factors such as land-use planning, population growth, and insurance retreat. Timely intervention is crucial to prevent the exacerbation of climate-related impacts on wastewater treatment systems and public health.

5 CONCLUSIONS

This study demonstrates that dams, boreholes, irrigation canals, and treatment plants play essential but varying roles in climate change mitigation within the River Benue Valley. Dams showed the highest sustainability due to their effectiveness in flood control and water storage, followed by boreholes, irrigation canals, and treatment plants. The findings emphasize the urgent need for integrated, climate-resilient water infrastructure planning supported by adaptive management practices. Strengthening governance, improving efficiency, and incorporating hydrological and meteorological data remain critical. Overall, a coordinated infrastructure strategy is vital for enhancing long-term water security and climate resilience in the region.

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