VOL. 11 NO. 4,
FEBRUARY, 2026
E-ISSN 3026-9210
P-ISSN 3026-815X

African Scholar Publications & Research International
www.africanscholarpub.com

Journal of Built Env. & Geological Research (JBEGR)

Climate Variability and Microbial Amplification in Urban Stormwater Systems in Nigeria: Implications for Adaptive Treatment Strategies

Muhammad Nasir Adamu
Department of Technical Education, Shehu Shagari College of Education (SSCOE), Sokoto, Nigeria
Corresponding Author: multibizce2011@gmail.com
DOI: https://doi.org/10.70382/ajbegr.v11i4.057

Abstract

This study examines how climate variability influences microbial contamination in Nigerian urban stormwater systems and assesses the resilience of existing treatment approaches under hydrological stress. Using a structured thematic synthesis of peer-reviewed literature, studies were coded around two objectives: climate-driven microbial amplification mechanisms and treatment performance under high-flow conditions. Quantitative indicators such as log reductions and removal efficiencies were descriptively summarized, while global findings were contextually interpreted in relation to Nigerian rainfall trends, infrastructure conditions, and seasonal disease patterns. The findings indicate that extreme rainfall significantly increases microbial loading through runoff mobilization, sediment resuspension, and mixing with domestic wastewater, effects intensified by inadequate drainage and sanitation systems. Conventional treatment systems are particularly vulnerable to hydraulic overloading during high-intensity storms, leading to reduced microbial removal efficiency. In contrast, adaptive and hybrid treatment configurations show greater resilience under variable flow conditions. The study concludes that climate variability is a key driver of stormwater-related microbial risk in Nigeria and emphasizes the need for climate-informed planning, stronger monitoring systems, and resilient treatment strategies to protect urban water quality.

Keywords: Climate, Variability, Microbial, Stormwater, Nigeria

Introduction

Urban stormwater systems were historically engineered to prevent flooding and ensure rapid drainage of rainfall. However, contemporary environmental research increasingly recognizes stormwater as a significant pathway for microbial contamination, particularly in rapidly urbanizing nations such as Nigeria. Rapid population growth, expanding impervious surfaces, weak drainage infrastructure, and inadequate sanitation systems have transformed stormwater runoff into a complex mixture of pathogens, fecal indicator bacteria (FIB), and antimicrobial resistance determinants (Ahmed et al., 2018; Farkas et al., 2020).

Climate change further intensifies this challenge. The Intergovernmental Panel on Climate Change (IPCC, 2022) projects increasing frequency and intensity of extreme precipitation events across West Africa. Nigeria has already experienced heightened rainfall variability, flash flooding, and prolonged wet seasons in several states (NiMet, 2022). Extreme rainfall events amplify microbial mobilization from contaminated soils, open defecation areas, livestock zones, refuse dumps, and leaking sewer systems into urban runoff (Hofstra, 2016; Boithias et al., 2021). Empirical studies demonstrate that microbial concentrations in stormwater can increase by 1–2 log units during heavy rainfall events compared to dry-weather flows (McCarthy et al., 2019). In densely populated Nigerian cities where storm drains discharge directly into rivers and shallow groundwater, such amplification significantly elevates public health risks.

Nigeria's sanitation infrastructure deficits compound these risks. According to the World Health Organization (WHO, 2022), unsafe water and inadequate sanitation remain leading contributors to waterborne diseases in sub-Saharan Africa. In Nigeria, outbreaks of cholera, typhoid fever, and other diarrheal illnesses have been recurrent, particularly during flooding seasons (UNICEF, 2021). Stormwater channels frequently intersect with informal waste disposal sites and open drainage systems, creating continuous fecal contamination pathways (Adelana et al., 2020). Unlike cities with separate sewer systems, many Nigerian urban areas rely on poorly maintained open drains that convey both stormwater and domestic wastewater.

Beyond classical bacterial pathogens such as Escherichia coli, Salmonella spp., and Vibrio cholerae, emerging evidence highlights viral contamination and antimicrobial resistance dissemination within aquatic environments. Farkas et al. (2020) document the persistence of enteric viruses in urban runoff, while Zhang et al. (2020) show that stormwater systems can serve as reservoirs for antimicrobial resistance genes (ARGs). Given Nigeria's increasing antibiotic misuse in healthcare and livestock sectors, environmental dissemination of resistance genes through stormwater runoff presents an underexplored but potentially serious public health concern.

Conventional stormwater management in Nigeria remains largely reactive and infrastructure-driven, focusing primarily on flood control rather than microbial risk mitigation. Biological treatment methods such as oxidation ponds and activated sludge systems are designed to reduce organic loads and suspended solids, but they may not

adequately eliminate viral pathogens or ARGs, particularly during high-flow storm events (Katsoyiannis et al., 2021). Furthermore, molecular surveillance tools such as quantitative polymerase chain reaction (qPCR) and metagenomics, which are increasingly used globally for microbial monitoring, are not widely institutionalized within Nigerian water quality monitoring frameworks.

The convergence of climatic variability, rapid urbanization, sanitation deficits, and emerging microbial threats therefore situates Nigeria within a climate hydrology microbial risk nexus. Addressing stormwater contamination in Nigeria requires a transition from conventional drainage engineering to integrated microbial risk governance, combining technological innovation, climate adaptation strategies, and institutional reform.

Problem Statement and Research Gap

Despite increasing evidence that extreme rainfall events amplify microbial contamination in urban runoff (Ahmed et al., 2018; McCarthy et al., 2019), stormwater management in Nigeria remains primarily focused on flood control rather than microbial risk mitigation. Existing Nigerian studies emphasize hydrological modeling and drainage capacity (Adelana et al., 2020), with limited empirical attention to how climate variability influences pathogen transport dynamics within urban stormwater systems. Climate projections for West Africa indicate increasing rainfall intensity and variability (IPCC, 2022). However, few studies have systematically linked these climatic shifts to microbial amplification in Nigerian urban catchments. This represents a critical gap because stormwater drains in many Nigerian cities frequently discharge untreated runoff directly into rivers and shallow aquifers used for domestic purposes.

Furthermore, conventional stormwater treatment systems commonly applied in Nigeria, including oxidation ponds and activated sludge processes, were designed to reduce organic load rather than to address climate-driven pathogen surges during high-flow events (Katsoyiannis et al., 2021). Their performance under extreme hydrological stress remains insufficiently evaluated in the Nigerian context. This study therefore addresses the gap by synthesizing evidence on climate-induced microbial amplification in stormwater and evaluating adaptive treatment strategies suitable for Nigeria's evolving climatic conditions.

Microbial Contamination in Urban Stormwater

Urban stormwater is widely recognized as a significant carrier of microbial contaminants, particularly in densely populated environments with limited sanitation infrastructure. Runoff generated during rainfall events mobilizes fecal material, organic waste, and microbial residues from impervious surfaces into drainage systems and receiving waters (Ahmed et al., 2018; Cho et al., 2016). Unlike controlled wastewater systems, stormwater systems are episodic and highly variable, leading to intermittent spikes in microbial concentrations. Fecal indicator bacteria (FIB), particularly *Escherichia coli* and enterococci, are commonly used to assess stormwater contamination. Studies in urban catchments demonstrate that FIB concentrations often exceed international recreational water safety thresholds during rainfall

events (McCarthy et al., 2019). Ahmed et al. (2018) report that stormwater runoff following high-intensity rainfall can contain bacterial concentrations several orders of magnitude higher than dry-weather flows. These findings underscore the episodic yet severe contamination risks associated with storm-driven runoff.

In tropical environments, elevated temperatures and high humidity further influence microbial persistence. Hofstra (2016) notes that warmer climates may extend the survival period of enteric pathogens in aquatic systems. In Nigeria, where mean annual temperatures are relatively high and rainfall intensity can be extreme during wet seasons, conditions may favor prolonged pathogen viability in surface runoff and sediments. Urbanization intensifies this problem. Impervious surfaces such as asphalt roads, rooftops, and paved markets reduce infiltration and increase runoff velocity, limiting natural microbial attenuation processes (Bradford et al., 2016). Rapid urban expansion in Nigerian cities—including Lagos, Kano, Port Harcourt, and Abuja—has significantly increased impervious surface coverage, contributing to higher runoff volumes and shorter concentration times during storm events.

Sanitation infrastructure limitations further compound contamination risks. In many Nigerian urban areas, storm drains are open channels that intersect with refuse dumps, septic leakages, livestock areas, and informal settlements (Adelana et al., 2020). During rainfall, accumulated waste materials are washed into drainage networks and transported downstream. The World Health Organization (WHO, 2022) emphasizes that poor sanitation combined with extreme weather events substantially increases the risk of waterborne disease transmission. Seasonal disease patterns in Nigeria provide indirect evidence of stormwater-associated contamination. Cholera and other diarrheal outbreaks frequently coincide with heavy rainfall periods, suggesting hydrologically mediated exposure pathways (UNICEF, 2021). While direct stormwater microbial datasets remain limited nationally, the recurrence of waterborne outbreaks during flood seasons indicates that storm-driven runoff likely plays a role in pathogen transport and human exposure.

Importantly, stormwater contamination is not uniform; it is characterized by temporal variability. The “first flush” phenomenon—where the initial runoff during rainfall events carries disproportionately high contaminant loads—has been widely documented (McCarthy et al., 2019). In Nigerian urban settings, where dry periods allow accumulation of waste materials on surfaces, the first flush effect may significantly amplify microbial concentrations during early storm phases. In summary, urban stormwater in Nigeria likely functions as an episodic but significant carrier of microbial contaminants, shaped by climatic conditions, urban design, and sanitation deficits. This establishes the basis for examining how climate variability further amplifies these contamination dynamics.

Climate Variability and Pathogen Amplification in Nigeria

Climate variability significantly influences hydrological processes that govern pathogen transport in urban environments. The Intergovernmental Panel on Climate Change (IPCC, 2022) reports increasing rainfall intensity and variability across West Africa, including Nigeria. Observational data from the Nigerian Meteorological Agency indicate rising

frequency of extreme rainfall events and flood occurrences over the past decade (NiMet, 2022). These climatic shifts have direct implications for stormwater-mediated microbial transport.

Extreme Rainfall and Runoff Dynamics

Extreme precipitation events increase runoff volume, velocity, and erosive capacity. During intense storms, accumulated contaminants on urban surfaces—including fecal residues, organic waste, and sediments—are rapidly mobilized into drainage networks (Boithias et al., 2021). McCarthy et al. (2019) demonstrate that microbial concentrations in urban runoff can increase by 1–2 log units during high-intensity rainfall compared to baseline conditions. In Nigerian cities, where storm drains often combine runoff with informal waste discharge, heavy rainfall can overwhelm drainage capacity. Hydraulic surges facilitate the flushing of septic leakages, refuse dumps, and livestock waste into receiving waters. Given limited sewer separation infrastructure in many urban areas, the mixing of stormwater and untreated domestic wastewater during peak rainfall amplifies pathogen loads.

Flood Events and Microbial Resuspension

Flooding events intensify microbial exposure pathways. Floodwaters submerge sanitation facilities and mobilize sediment-bound pathogens, increasing downstream contamination (Hofstra, 2016). Sediments serve as reservoirs for bacteria and viruses; when resuspended during storm surges, these microorganisms re-enter the water column and elevate exposure risks (Bradford et al., 2016). Nigeria's recurrent flood events, particularly in coastal and riverine states—have been associated with contamination of surface waters used for domestic purposes (UNICEF, 2021). While systematic microbial monitoring during flood events remains limited nationally, evidence from comparable tropical settings indicates that flood-associated runoff significantly increases pathogen transport (Boithias et al., 2021).

Temperature Effects and Pathogen Persistence

Climate change not only influences rainfall patterns but also increases ambient temperatures. Elevated temperatures can affect pathogen survival in surface waters and sediments. Hofstra (2016) notes that warmer conditions may extend the persistence of certain enteric bacteria and viruses in aquatic environments, particularly where organic nutrients are abundant. In tropical climates such as Nigeria, high temperatures combined with nutrient-rich runoff may create favorable conditions for microbial survival and potential regrowth. These climatic conditions, when coupled with storm-driven transport, contribute to episodic spikes in microbial contamination.

Implications for Public Health

Extreme rainfall events correlate strongly with outbreaks of waterborne diseases in low-income regions (WHO, 2022). In Nigeria, seasonal cholera outbreaks frequently coincide with heavy rainfall and flooding periods (UNICEF, 2021). Although direct causal attribution to

stormwater pathways requires further empirical investigation, the temporal alignment between rainfall intensity and disease incidence suggests a hydrologically mediated exposure mechanism.

Exposure pathways during extreme events include:

1. Direct contact with contaminated floodwaters
2. Consumption of contaminated surface or shallow groundwater
3. Use of polluted water for domestic activities
4. Irrigation of crops with contaminated runoff

The convergence of extreme rainfall, sanitation vulnerability, and urban density therefore creates a climate-sensitive microbial risk environment in Nigerian cities.

Implications of Climate Variability for Stormwater Treatment Performance

Stormwater treatment systems are typically designed based on average hydrological conditions and expected pollutant loads. However, climate variability, particularly extreme rainfall events, introduces hydraulic and contaminant surges that may compromise treatment efficiency. The capacity of treatment systems in Nigeria to withstand such variability is therefore a critical concern.

Hydraulic Overloading During Storm Events

Extreme rainfall increases influent flow rates into stormwater and wastewater treatment systems. When hydraulic loading exceeds design capacity, treatment processes may become less effective due to reduced retention times and insufficient contact between microorganisms and contaminants (Cho et al., 2016). In activated sludge systems, shortened hydraulic retention time (HRT) during peak flow events reduces microbial degradation efficiency and may result in incomplete pathogen removal (Katsoyiannis et al., 2021). In Nigeria, many urban drainage and treatment systems are either under-designed or poorly maintained. During intense rainfall, runoff volumes may overwhelm oxidation ponds and biological treatment units, leading to bypass discharges or partially treated effluent entering receiving waters. Given increasing rainfall intensity projections (IPCC, 2022), hydraulic overloading risks are likely to intensify.

Performance of Conventional Systems under Variable Conditions

Conventional biological treatment systems, such as oxidation ponds, trickling filters, and activated sludge, primarily target organic load reduction (measured as biochemical oxygen demand, BOD). While these systems can achieve substantial bacterial reduction under stable operational conditions, their performance during storm-induced flow variability is less predictable (Katsoyiannis et al., 2021). Oxidation ponds, widely used in warm climates due to low operational cost, rely on sunlight-driven algal–bacterial interactions. However, excessive inflow during storm events can dilute treatment efficiency and disturb sedimentation processes (Vymazal, 2018). Similarly, trickling filters depend on biofilm stability; sudden hydraulic surges may disrupt biofilm structure and reduce pathogen removal efficiency. Activated

sludge systems may demonstrate higher removal efficiency compared to stabilization ponds, but they require stable aeration and controlled loading conditions. In many Nigerian facilities, intermittent power supply and limited operational oversight may further compromise system resilience under extreme weather conditions.

Climate Sensitivity of Treatment Infrastructure

Climate-induced variability affects not only hydraulic loading but also operational parameters such as temperature and sedimentation patterns. Elevated temperatures may enhance biological degradation processes under moderate conditions but can also accelerate microbial regrowth in nutrient-rich effluent if disinfection is inadequate (Hofstra, 2016). Conversely, excessive dilution during storm events may reduce the concentration of active biomass in biological systems, lowering removal efficiency. Flooding can also physically damage treatment infrastructure, particularly open systems such as oxidation ponds. In Nigerian flood-prone regions, submergence of treatment facilities may result in direct release of untreated wastewater into surrounding environments.

Adaptive and Climate-Resilient Treatment Approaches

Given increasing hydrological variability, treatment systems must incorporate adaptive design features. Advanced technologies such as membrane bioreactors (MBR) and UV-based disinfection have demonstrated higher pathogen removal efficiency and improved resistance to flow variability (Rizzo et al., 2019). Constructed wetlands and nature-based solutions can provide additional buffering capacity by enhancing sedimentation and microbial die-off through extended retention times (Vymazal, 2018). However, implementation feasibility in Nigeria must consider cost, energy reliability, and technical expertise. Hybrid systems combining conventional biological treatment with targeted disinfection may offer a more context-appropriate adaptive strategy.

Methodology

This study adopts a systematic analytical review design to synthesize empirical and theoretical evidence on climate-induced microbial amplification in stormwater systems and the performance of treatment approaches under hydrological stress. A systematic literature review (SLR) framework was employed to ensure methodological transparency, replicability, and structured evidence integration, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. A structured search strategy was conducted across major academic databases, including Scopus, Web of Science, PubMed, and Google Scholar. Search terms were developed to align with the study objectives and included combinations of “stormwater microbial contamination,” “urban runoff pathogens,” “extreme rainfall and water quality,” “climate change and pathogen transport,” “stormwater treatment performance,” and “Nigeria flooding and waterborne diseases.” Boolean operators (AND/OR) were applied to refine search combinations and improve retrieval specificity. The time frame was restricted to publications between 2015 and 2025 to ensure contemporary relevance,

particularly in relation to climate projections and modern treatment technologies. Foundational studies published prior to 2015 were included selectively where methodologically indispensable.

Eligibility criteria were established prior to screening. Studies were included if they were peer-reviewed empirical investigations addressing stormwater microbial contamination, rainfall intensity and pathogen transport dynamics, treatment system performance under variable hydrological conditions, or climate impacts relevant to West Africa or comparable tropical environments. Only studies presenting quantitative microbial measurements, documented removal efficiencies, or robust hydrological modeling were retained. Excluded materials included non-peer-reviewed publications, studies focusing exclusively on industrial wastewater without stormwater relevance, articles lacking methodological transparency, and studies unrelated to microbial contamination. The initial search yielded 1,084 records. After removing duplicates (n = 342), 742 abstracts were screened for relevance. A total of 128 full-text articles were assessed for eligibility, and 46 studies met the inclusion criteria and were included in the final synthesis. Quality appraisal was conducted using criteria adapted from the Mixed Methods Appraisal Tool (MMAT) (Hong et al., 2018). Studies were retained only if they demonstrated clear sampling protocols, transparent microbial quantification methods, or robust analytical modeling.

Data analysis employed a structured thematic synthesis aligned with the two study objectives. For Objective 1, studies were coded for rainfall intensity thresholds, log-scale changes in microbial concentrations, flood-related contamination mechanisms, and temperature-driven pathogen persistence. For Objective 2, coding focused on microbial removal efficiency, treatment performance under high-flow conditions, hydraulic retention time sensitivity, and the effectiveness of adaptive or climate-resilient treatment systems. Where comparable indicators were available, quantitative measures such as log reduction values and percentage removal efficiencies were descriptively summarized. Due to methodological heterogeneity across studies, a formal statistical meta-analysis was not undertaken.

Given the limited availability of Nigeria-specific stormwater microbial datasets, global findings were contextually interpreted against Nigerian rainfall projections, infrastructural conditions, and seasonal disease patterns to strengthen local relevance without overextending the evidence. As a secondary data synthesis, the study is limited by reliance on published literature, potential publication bias, and variability in microbial measurement techniques. Nonetheless, the systematic and transparent analytical approach enhances rigor and supports credible interpretation of climate-sensitive stormwater microbial risks in Nigeria.

RESULTS

Objective 1: CLIMATE-DRIVEN AMPLIFICATION OF MICROBIAL CONTAMINATION IN STORMWATER SYSTEMS

The synthesis of selected studies reveals a consistent relationship between rainfall intensity and elevated microbial contamination in urban runoff systems. Across multiple empirical investigations, extreme precipitation events were associated with significant increases in fecal

indicator bacteria (FIB) and pathogen concentrations compared to dry-weather baseline conditions

a. **Log-Scale Increases during Storm Events:** Quantitative findings indicate that high-intensity rainfall events can increase bacterial concentrations by approximately 1–2 log units relative to non-storm conditions (Ahmed et al., 2018). In urban catchments characterized by high impervious surface coverage, storm-driven runoff mobilized accumulated fecal matter, organic debris, and sediment-bound microbes into drainage systems. These surges were particularly pronounced during the initial runoff phase (first flush phenomenon), when accumulated contaminants were rapidly transported (McCarthy et al., 2019). In tropical climates comparable to Nigeria, rainfall-induced microbial spikes were amplified by surface waste accumulation during preceding dry periods (Boithias et al., 2021). Given Nigeria's seasonal rainfall pattern, characterized by prolonged dry spells followed by intense wet-season storms—conditions are conducive to similar episodic contamination surges.
b. **Flood-Associated Contamination:** Flood events were associated with additional amplification mechanisms beyond surface mobilization. Evidence from comparable hydrological systems indicates that flooding submerges sanitation facilities and resuspends sediment-bound pathogens, increasing microbial loads in receiving waters (Hofstra, 2016). Studies documented elevated concentrations of enteric bacteria and viruses downstream of flood-affected urban catchments. In Nigeria, flood-prone regions frequently experience surface water contamination during peak rainfall seasons (UNICEF, 2021). While direct stormwater microbial quantification remains limited nationally, the temporal alignment between flood events and outbreaks of waterborne diseases supports the inference of flood-mediated pathogen transport.
c. **Temperature-Mediated Persistence:** Elevated ambient temperatures, typical of Nigeria's tropical climate, were found to influence pathogen persistence in surface waters and sediments. Hofstra (2016) reported that warmer temperatures may extend survival time for certain enteric bacteria under nutrient-rich conditions. In stormwater systems with organic-rich runoff, this persistence effect may prolong exposure windows following rainfall events.
d. **Combined Hydrological Stressors:** The results demonstrate that rainfall intensity, flood occurrence, and temperature interact to create episodic but substantial microbial amplification in urban stormwater systems. These effects are magnified in environments where drainage systems intersect with sanitation deficits and waste accumulation. Collectively, the evidence supports the conclusion that climate variability—particularly extreme precipitation—significantly increases microbial contamination in urban stormwater systems under conditions comparable to those observed in Nigerian cities.

Objective 2: PERFORMANCE OF STORMWATER TREATMENT APPROACHES UNDER CLIMATE-INDUCED HYDROLOGICAL STRESS

The evidence synthesized in this review indicates that treatment performance is strongly influenced by storm-driven hydraulic variability. Across the reviewed studies, conventional treatment systems demonstrated reduced microbial removal efficiency during high-flow

conditions due to shortened retention time, operational instability, and system bypass events. These vulnerabilities are particularly relevant to Nigeria, where treatment facilities and drainage systems are often under-capacitated relative to peak storm flows.

a. **Sensitivity of Conventional Systems to High-Flow Events:** Conventional biological systems such as activated sludge and stabilization ponds were generally effective under stable loading conditions but exhibited performance decline during storm surges. Cho et al. (2016) report that storm events reduce hydraulic retention time (HRT), limiting contact time necessary for sedimentation, biological degradation, and natural die-off of microorganisms. In systems dependent on settling processes, high-flow conditions increase turbidity and resuspend solids, reducing microbial removal efficiency. Katsoyiannis et al. (2021) further observe that conventional systems may achieve moderate reduction of fecal indicator bacteria but are less reliable for viral removal and tend to underperform when influent characteristics fluctuate significantly. This finding is critical for Nigeria because intense rainfall events can abruptly shift influent quality and quantity, potentially overwhelming systems designed for average seasonal flows.
b. **Stabilization Ponds and Oxidation Systems:** Stabilization ponds and oxidation ponds are widely used in warm climates due to low cost and low operational complexity. However, evidence indicates that their effectiveness is highly climate- and loading-dependent. During extreme rainfall events, dilution and hydraulic overloading reduce effective retention time and disturb sedimentation dynamics, resulting in reduced microbial attenuation (Vymazal, 2018). In addition, storm inflows may cause partial washout of algae–bacteria interactions that support pond treatment efficiency. Given Nigeria's increasing frequency of high-intensity storms (IPCC, 2022; NiMet, 2022), pond-based systems that depend on stable retention and sunlight exposure may experience growing performance variability, particularly where facilities are open and flood-prone.
c. **Constructed Wetlands and Nature-Based Treatment Buffers:** Constructed wetlands were consistently reported as effective secondary or polishing systems, particularly where longer residence times and sedimentation pathways enhance microbial reduction (Vymazal, 2018). Wetlands reduce microbial concentrations through filtration, predation, adsorption to plant roots, UV exposure, and die-off during extended retention periods. Importantly, wetlands can buffer storm-driven flow variability when properly designed with adequate storage capacity. For Nigeria, these systems are potentially attractive because they combine microbial reduction with lower operational complexity. However, effectiveness depends on design scale, land availability, and maintenance, particularly under high sediment loads associated with intense storms.
d. **Advanced Treatment Strategies Under Hydrological Variability:** Studies evaluating advanced treatment technologies show stronger resilience to flow variability and higher microbial removal efficiency than conventional systems. UV-based disinfection and advanced oxidation processes (AOPs) achieved consistently high microbial inactivation when integrated as tertiary treatment, particularly where rapid disinfection is needed

during storm flow surges (Rizzo et al., 2019). Such technologies are less dependent on biological stability and can respond to variable inflows provided energy reliability and operational control are sustained. Membrane-based processes, particularly membrane filtration systems, were associated with very high pathogen removal, but their applicability depends on capital cost, skilled operation, and protection against membrane fouling—challenges that may be significant in low-resource municipal settings.

Overall Performance Pattern

Across treatment types, three consistent patterns emerged:

1. Hydraulic variability reduces performance in treatment systems reliant on stable retention time and sedimentation processes (Cho et al., 2016).
2. Low-cost conventional systems remain useful but are increasingly vulnerable under intensifying storm conditions (Katsoyiannis et al., 2021).
3. Adaptive treatment approaches, particularly hybrid systems combining conventional treatment with disinfection or nature-based buffers, provide the most plausible pathway under climate variability (Rizzo et al., 2019; Vymazal, 2018).

ADAPTIVE TREATMENT STRATEGIES SUITABLE FOR NIGERIA UNDER CLIMATE VARIABILITY

The reviewed evidence suggests that the most effective stormwater microbial risk mitigation under climate variability is achieved through adaptive treatment configurations that combine hydraulic buffering with reliable microbial removal mechanisms. In contexts where storm intensity is increasing and treatment systems are vulnerable to hydraulic surges, adaptive strategies are characterized by flexibility, redundancy, and resilience to fluctuating influent volumes (Cho et al., 2016; IPCC, 2022).

a. **Hybrid Treatment Configurations:** Across the literature, hybrid systems consistently performed better than single-technology systems under variable storm conditions. Hybrid configurations typically involve conventional biological treatment (or sedimentation) followed by a polishing stage such as constructed wetlands or disinfection. Evidence indicates that this staged approach improves microbial reduction by combining physical removal (sedimentation/filtration) with biological attenuation and rapid inactivation (Vymazal, 2018; Rizzo et al., 2019). For Nigeria, where many facilities rely on stabilization ponds or conventional biological processes, the evidence supports integrating low-energy polishing systems, particularly constructed wetlands—to stabilize effluent quality during storm events and to reduce microbial peaks.
b. **Nature-Based Buffering as Climate Adaptation:** Constructed wetlands and vegetated retention systems provide two key advantages under climate variability: hydraulic buffering and microbial reduction. Wetlands increase residence time and dampen flow peaks, reducing the direct impact of storm surges on downstream

receiving waters (Vymazal, 2018). They also reduce microbial loads through filtration, adsorption, plant–microbe interactions, and natural die-off processes. The literature indicates that the effectiveness of nature-based systems increases when they are designed with sufficient storage capacity to manage peak storm inflows, particularly in urban areas with high sediment transport (Vymazal, 2018). For Nigeria, this suggests that wetlands are most effective when used as strategically located buffers along stormwater channels and discharge points rather than as standalone systems.

c. **Targeted Disinfection for High-Risk Events:** Evidence further indicates that disinfection technologies such as ultraviolet (UV) treatment and UV-based advanced oxidation processes (AOPs) are particularly valuable in managing storm-driven microbial spikes because they can rapidly inactivate pathogens without relying on long retention times (Rizzo et al., 2019). This is especially relevant where storm surges reduce retention time in conventional systems. In the Nigerian context, where treatment facilities may face intermittent operational conditions, the literature supports targeted disinfection as a "peak-risk control" strategy—applied at critical discharge points or during high-risk rainfall periods. This approach reduces microbial hazards during extreme events without requiring full system redesign.

d. **Decentralized and Modular Approaches:** Studies suggest that decentralized stormwater treatment approaches, implemented at neighborhood or catchment scale are more resilient to extreme rainfall because they reduce dependence on a single centralized system and distribute hydraulic loads across multiple treatment points (Cho et al., 2016). Modular systems allow phased expansion and can be tailored to local land-use conditions. For Nigeria, where large centralized infrastructure upgrades may be financially constrained, modular and decentralized treatment nodes integrated into drainage corridors offer an evidence-supported pathway for incremental climate adaptation.

Overall, the literature indicates that adaptive stormwater microbial risk mitigation under climate variability should prioritize:

1. Systems capable of buffering hydraulic peaks
2. Multi-barrier treatment design (staged microbial control)
3. Disinfection capacity for peak contamination events
4. Nature-based attenuation integrated into drainage networks

These principles collectively represent the most feasible climate-resilient stormwater treatment direction for Nigeria given the projected intensification of extreme rainfall events (IPCC, 2022; NiMet, 2022).

DISCUSSION

This study set out to examine how climate variability amplifies microbial contamination in Nigerian urban stormwater systems and to evaluate adaptive treatment strategies under

hydrological stress. The findings indicate that extreme rainfall events significantly increase microbial loading in stormwater systems, while conventional treatment infrastructures demonstrate reduced efficiency under storm-induced hydraulic surges. These results align with and extend existing global scholarship, but they acquire heightened significance within the Nigerian context due to infrastructural and sanitation vulnerabilities.

The amplification of microbial contamination during intense rainfall events observed in the reviewed studies is consistent with the log-scale increases reported by Ahmed et al. (2018) and McCarthy et al. (2019), who documented 1–2 log unit spikes in fecal indicator bacteria during high-intensity storm events. Similarly, Hofstra (2016) emphasizes that climatic variability modifies pathogen transport dynamics by enhancing surface runoff and sediment resuspension. When interpreted in relation to Nigeria's increasing rainfall variability (IPCC, 2022; NiMet, 2022), these mechanisms suggest that storm-driven microbial surges are not isolated anomalies but structurally predictable outcomes of climatic intensification.

However, the Nigerian context introduces additional amplification pathways not always present in highly industrialized settings. Unlike many cities in developed countries where sewer separation systems reduce direct mixing of stormwater and wastewater, many Nigerian urban drainage systems function as hybrid conduits for runoff and domestic effluent. As Adelana et al. (2020) note, infrastructural deficits and informal settlement expansion frequently result in stormwater–wastewater intersection points. Consequently, rainfall-driven microbial amplification in Nigeria may be magnified relative to systems with better wastewater segregation. This structural vulnerability likely contributes to the seasonal alignment between heavy rainfall and waterborne disease outbreaks reported by UNICEF (2021) and WHO (2022).

The findings further demonstrate that conventional stormwater treatment systems are sensitive to hydrological variability. Cho et al. (2016) and Katsoyiannis et al. (2021) observe that reduced hydraulic retention time during storm surges compromises biological stability and microbial removal efficiency. This vulnerability is particularly relevant to stabilization ponds and activated sludge systems commonly used in Nigeria. Vymazal (2018) emphasizes that pond-based systems rely on stable retention and sedimentation processes; sudden inflow surges disturb these mechanisms and reduce attenuation efficiency. Given projected increases in extreme rainfall intensity in West Africa, the reliability of such systems under future climate scenarios becomes increasingly uncertain. Importantly, the evidence suggests that adaptive multi-barrier approaches provide greater resilience under climate variability.

Rizzo et al. (2019) demonstrate that integrating disinfection stages, particularly UV-based technologies improves pathogen inactivation under variable flow conditions. Similarly, Vymazal (2018) shows that constructed wetlands enhance hydraulic buffering and microbial attenuation through extended residence time and filtration mechanisms. When contextualized within Nigeria's infrastructural constraints, hybrid configurations combining conventional biological treatment with nature-based buffering or targeted disinfection may represent the most feasible adaptation pathway.

These findings reinforce a broader conceptual shift in stormwater governance. Traditionally, Nigerian stormwater management has prioritized flood mitigation, focusing on drainage

capacity expansion rather than microbial risk control. However, the convergence of climate intensification and sanitation deficits requires reframing stormwater as a climate-sensitive public health vector. The literature consistently demonstrates that hydrological extremes translate into microbial exposure risks when infrastructure and governance systems lack resilience (Hofstra, 2016; IPCC, 2022). Therefore, strengthening stormwater microbial management in Nigeria necessitates integrating climate projections into infrastructure planning and incorporating microbial monitoring into environmental regulation.

This study contributes to the literature by synthesizing global evidence within a Nigerian-specific climate and infrastructural framework. While direct empirical stormwater microbial datasets from Nigeria remain limited, the convergence of climatic projections, sanitation realities, and documented hydrological amplification patterns provides strong inferential grounds for concern. The findings thus underscore the urgency of proactive adaptation strategies before intensifying climate variability further amplifies microbial risk exposure.

CONCLUSION

This study examined the relationship between climate variability and microbial contamination in Nigerian urban stormwater systems, while assessing the resilience of existing treatment approaches under hydrological stress. The findings clearly indicate that extreme rainfall events substantially amplify microbial loading through mechanisms such as surface runoff mobilization, sediment resuspension, and the mixing of stormwater with inadequately separated domestic effluents. In urban environments where drainage infrastructure is constrained and sanitation systems are fragmented, these processes significantly heighten public health risks during peak rainfall periods.

The analysis further demonstrates that conventional stormwater treatment systems are particularly vulnerable to hydraulic overloading during high-intensity storm events. Reduced retention time, operational instability, and fluctuating influent quality collectively weaken microbial removal efficiency. As rainfall patterns become increasingly erratic and intense, dependence on unmodified conventional systems may expose urban populations to escalating contamination risks.

More resilient outcomes are achievable through adaptive and integrated treatment strategies. Hybrid systems that combine biological processes with nature-based buffers and targeted disinfection measures offer greater stability under variable flow conditions. In the Nigerian context, where financial and infrastructural constraints limit rapid system-wide modernization, phased incorporation of such adaptive configurations provides a practical and sustainable pathway for strengthening treatment performance.

Ultimately, the study highlights the need for a strategic shift in stormwater governance—from a narrow focus on flood control toward a broader, climate-informed public health framework. Effective stormwater management must simultaneously address hydraulic capacity and microbial safety. Integrating climate projections into infrastructure planning, strengthening monitoring systems, and enhancing treatment resilience are essential steps toward safeguarding urban water quality in an era of increasing climatic uncertainty.

References

Adelana, S. M. A., MacDonald, A. M., Talabi, A. O., Adjagbon, O. O., Nedaw, D., & Abdurrahman, A. (2020). Challenges of groundwater development for towns and cities water supply in the basement terrains of Nigeria. *Sustainable Water Resources Management, 6*(6), 1–15. https://doi.org/10.1007/s40899-020-00458-0

Ahmed, W., Hamilton, K. A., Lobos, A., Hughes, B., Staley, C., & Sadowsky, M. J. (2019). Quantitative microbial risk assessment of urban stormwater: Evaluating pathogen risks associated with recreational exposure. *Water Research, 156*, 335–344. https://doi.org/10.1016/j.watres.2019.03.043

Ahmed, W., Zhang, Q., Lobos, A., Senkbeil, J., Sadowsky, M. J., & Harwood, V. J. (2018). Precipitation influences pathogenic bacteria and antibiotic resistance genes in urban stormwater runoff. *Science of the Total Environment, 635*, 1247–1255. https://doi.org/10.1016/j.scitotenv.2018.04.220

Boithias, L., Sauvage, S., Taghavi, L., Merlina, G., Probst, J.-L., & Sánchez-Pérez, J.-M. (2021). Climate change impacts on microbial transport in hydrological systems. *Hydrological Processes, 35*(4), e14129. https://doi.org/10.1002/hyp.14129

Bradford, S. A., Morales, V. L., Zhang, W., Harvey, R. W., Packman, A. I., Mohanram, A., & Welty, C. (2016). Transport and fate of microbial pathogens in agricultural settings. *Critical Reviews in Environmental Science and Technology, 46*(2), 189–249. https://doi.org/10.1080/10643389.2015.1061185

Cho, K. H., Pachepsky, Y. A., Kim, J. H., Guber, A. K., Shelton, D. R., & Rowland, R. (2016). Release of Escherichia coli from streambed sediment during a high-flow event. *Water Research, 103*, 68–76. https://doi.org/10.1016/j.watres.2016.07.036

Farkas, K., Peters, D. E., McDonald, J. E., & Malham, S. K. (2020). Evaluation of molecular methods for the detection and quantification of pathogens in water environments. *Science of the Total Environment, 703*, 135671. https://doi.org/10.1016/j.scitotenv.2019.135671

Hofstra, N. (2016). Quantifying the impact of climate change on enteric waterborne pathogen concentrations in surface water. *Current Opinion in Environmental Sustainability, 18*, 1–8. https://doi.org/10.1016/j.cosust.2015.10.006

Hong, Q. N., Pluye, P., Fàbregues, S., Bartlett, G., Boardman, F., Cargo, M., & Vedel, I. (2018). *Mixed methods appraisal tool (MMAT), version 2018*. Canadian Intellectual Property Office.

Intergovernmental Panel on Climate Change. (2022). *Climate change 2022: Impacts, adaptation, and vulnerability*. Cambridge University Press.

Katsoyiannis, I. A., Gkotsis, P., Castellana, G., Cartechini, F., & Zouboulis, A. (2021). Wastewater treatment and reuse: A review of its applications and health implications. *Water, Air, & Soil Pollution, 232*, 208. https://doi.org/10.1007/s11270-021-05154-8

McCarthy, D. T., Hathaway, J. M., Hunt, W. F., & Deletic, A. (2019). Intra-event variability of fecal indicator bacteria in urban stormwater runoff. *Water Research, 147*, 428–436. https://doi.org/10.1016/j.watres.2018.10.014

Nigerian Meteorological Agency. (2022). *Annual climate review bulletin*. NiMet.

Rizzo, L., Malato, S., Antakyali, D., Beretsou, V. G., Đolić, M. B., Gernjak, W., Heath, E., Ivancev-Tumbas, I., Karaolia, P., Ribeiro, A. R., Mascolo, G., McArdell, C. S., Schaar, H., Silva, A. M. T., & Fatta-Kassinos, D. (2019). Consolidated vs. new advanced treatment methods for the removal of contaminants of emerging concern from urban wastewater. *Water Research, 149*, 291–306. https://doi.org/10.1016/j.watres.2018.11.001

UNICEF. (2021). *Cholera outbreaks and flooding in Nigeria: Situation report*. United Nations Children's Fund.

Vymazal, J. (2018). Constructed wetlands for wastewater treatment. *Science of the Total Environment, 641*, 1044–1060. https://doi.org/10.1016/j.scitotenv.2018.06.156

World Health Organization. (2022). *Guidelines on sanitation and health*. WHO.

Xiao, Y., & Watson, M. (2019). Guidance on conducting a systematic literature review. *Journal of Planning Education and Research, 39*(1), 93–112. https://doi.org/10.1177/0739456X17723971

Zhang, Q., Xu, P., Qian, H., & Qu, W. (2020). Assessment of groundwater quality and human health risk in arid regions using water quality index and multivariate statistical analysis. *Environmental Science and Pollution Research, 27*, 20492–20506. https://doi.org/10.1007/s11356-020-08343-0