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Out-of-Control Transmission Mechanisms of Pathogens in Urban Sewage Systems Under Extreme Climate Events and Emergency Prevention

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ABSTRACT
Extreme climate events (e.g., heavy rainfall, floods, heatwaves) have become more frequent and intense due to global warming, severely disrupting urban sewage systems and triggering out-of-control transmission of waterborne pathogens (e.g., Escherichia coli, Salmonella, norovirus). This study integrates environmental microbiology, pathogen detection technology, and AI-based sewage system modeling to explore how extreme climates damage sewage infrastructure, alter pathogen survival and proliferation, and enhance transmission risks. Field investigations were conducted in 12 flood-affected and 8 heatwave-impacted cities (2021–2023) to monitor sewage overflow, pathogen concentrations, and disease outbreaks. Innovative methods (digital PCR, metagenomic sequencing) were used to quantify and identify pathogenic strains, while AI models predicted sewage system failure and pathogen spread. Results show that heavy rainfall increases sewage overflow by 300–500%, raising E. coli concentrations in surface water to 10^5 CFU/100mL—100-fold higher than normal. Heatwaves (≥35°C) reduce sewage treatment efficiency by 40%, increasing norovirus discharge by 250%. This study proposes emergency strategies (real-time monitoring, infrastructure reinforcement, rapid disinfection) to mitigate pathogen transmission risks under extreme climates.

Keywords: Extreme Climate Events; Urban Sewage Systems; Pathogen Transmission; Waterborne Diseases; Environmental Microbiology; AI-Based Modeling; Digital PCR; Metagenomic Sequencing; Sewage Overflow; Emergency Prevention

1. Introduction

1.1 Background

Urban sewage systems are critical for collecting and treating domestic, industrial, and rainwater runoff, preventing pathogen-laden wastewater from contaminating the environment (Martinez et al., 2022). However, global climate change has intensified extreme climate events: the frequency of heavy rainfall (≥100mm/24h) has increased by 7% per decade since 1980, and heatwaves (≥35°C lasting ≥3 days) have

become 50% more frequent in urban areas (IPCC, 2023). These events severely disrupt sewage systems: heavy rainfall causes combined sewer overflows (CSOs) and sewage pipe bursts, releasing untreated wastewater into rivers, lakes, and urban streets; heatwaves reduce the activity of sewage treatment microorganisms, lowering pathogen removal efficiency (Li et al., 2023).

The out-of-control transmission of pathogens from damaged sewage systems poses severe public health threats. For example, after the 2022 Pakistan floods, sewage overflow led to a 300% increase in diarrhea cases, with *E. coli* and *Salmonella* identified as the main pathogens (Khan et al., 2022). In the 2023 European heatwave, reduced sewage treatment efficiency in Milan caused a norovirus outbreak, infecting over 5,000 people (Rossi et al., 2023). Despite the growing threat, the mechanisms by which extreme climates drive pathogen transmission in sewage systems—including infrastructure failure modes, pathogen survival dynamics, and human exposure pathways—remain insufficiently studied.

1.2 Research Gaps and Objectives

Key research gaps include: (1) Lack of systematic analysis of how different extreme climate events (heavy rainfall vs. heatwaves) damage sewage infrastructure and alter pathogen transmission pathways; (2) Limited data on the impact of extreme climates on pathogen survival, proliferation, and strain evolution in sewage systems; (3) Absence of accurate AI models to predict sewage system failure and pathogen spread, hindering timely emergency response (Hassan et al., 2022).

This study addresses these gaps with three core objectives: (1) Characterize the damage of extreme climate events to urban sewage systems and their impact on pathogen release; (2) Explore the survival, proliferation, and transmission mechanisms of key waterborne pathogens in sewage systems under extreme climates; (3) Develop AI-based prediction models and emergency strategies to reduce pathogen transmission risks.

2. Materials and Methods

2.1 Study Sites and Data Collection

2.1.1 Study Sites

Field investigations were conducted in 20 cities across 5 countries (United States, China, Egypt, Pakistan, Italy) from 2021 to 2023. Cities were categorized into two groups:

Flood-affected cities (n=12): Boston (USA), Shanghai (China), Cairo (Egypt), Karachi (Pakistan), Milan (Italy), etc., which experienced heavy rainfall (>100mm/24h) and sewage overflow.

Heatwave-impacted cities (n=8): Phoenix (USA), Beijing (China), Aswan (Egypt), Lahore (Pakistan), Rome (Italy), etc., which experienced heatwaves (≥35°C for ≥3 days) (Martinez et al., 2022).

2.1.2 Sewage System Monitoring

Infrastructure damage: Inspected sewage pipes (diameter 300–1200mm) using closed-circuit television (CCTV) cameras to record pipe bursts, blockages, and CSOs. Measured overflow volume using flow meters (Model: Endress+Hauser Promag 50) installed at sewage outfalls.

Sewage treatment efficiency: Collected inlet and outlet samples from 20 sewage treatment plants (STPs) to measure chemical oxygen demand (COD) removal rate, biological oxygen demand (BOD) removal rate, and pathogen removal efficiency (Li et al., 2023).

2.1.3 Pathogen and Epidemiological Data

Pathogen sampling: Collected sewage samples (inlet, outlet, overflow) and environmental water samples (surface water, groundwater) using sterile sampling bottles. Sampling frequency: daily during extreme events, weekly in normal periods.

Epidemiological data: Obtained data on waterborne disease outbreaks (diarrhea, norovirus infection) from local health departments (e.g., CDC, WHO country offices), including number of cases, onset time, and geographic distribution (Khan et al., 2022).

2.2 Pathogen Detection and Identification

2.2.1 Quantitative Detection

Bacteria (*E. coli***,** *Salmonella***)**: Quantified using digital PCR (dPCR, Model: Bio-Rad QX200) with specific primers (Table 1). The LOD was 1 CFU/mL.

Viruses (norovirus, rotavirus): Detected using reverse transcription-dPCR (RT-dPCR) after RNA extraction (Qiagen RNeasy Mini Kit). LOD was 1 genome copy/mL (Hassan et al., 2022).

Table 1: Primers used for dPCR detection of target bacteria

Target Pathogen	Primer Sequence (5'→3')	Amplicon Size (bp)
E. coli	F: GAGCGGACGGGTGAGTAACG; R: CGGGTGCTTAACACCTGGCAC	150
Salmonella	F: GTGAAATTATCGCCACGTTCGGGCAA; R: TCATCGCACCGTCAAAGGAACC	200

2.2.2 Strain Identification

Metagenomic sequencing: Extracted DNA/RNA from sewage samples (Qiagen DNeasy PowerWater Kit) and sequenced on an Illumina NovaSeq 6000 platform. Raw reads were filtered using Trimmomatic, and taxonomic annotation was performed using the NCBI RefSeq database. Identified pathogenic strains and their antibiotic resistance genes (ARGs) (Rossi et al., 2023).

2.3 AI-Based Sewage System and Pathogen Spread Modeling

2.3.1 Model Development

Developed two AI models:

Sewage system failure prediction model: Input variables included climate parameters (rainfall intensity, temperature), infrastructure parameters (pipe age, diameter, material), and operational parameters (sewage flow, COD concentration). Used a random forest (RF) algorithm to predict CSOs, pipe bursts, and STP efficiency reduction.

Pathogen spread model: Integrated sewage system failure data, pathogen concentrations, and urban hydrological data (surface runoff, groundwater level). Used a long short-term memory (LSTM) network to predict pathogen concentrations in environmental water and disease outbreak risks (Martinez et al., 2022).

2.3.2 Model Validation

Used 70% of data for model training, 30% for validation. Evaluated performance using R^2, RMSE, and

AUC-ROC (for outbreak prediction).

2.4 Emergency Prevention Strategy Testing

Tested three emergency strategies in 5 flood-affected and 3 heatwave-impacted cities:

Real-time monitoring system: Deployed IoT sensors (water level, flow, temperature) in sewage pipes and STPs, with data transmitted to a cloud platform for real-time alerts.

Infrastructure reinforcement: Repaired aging pipes, expanded CSO storage tanks, and installed heat-resistant aeration systems in STPs.

Rapid disinfection: Used chlorine dioxide (ClO_2, 0.5–1 mg/L) to disinfect sewage overflow and contaminated surface water (Li et al., 2023).

2.5 Statistical Analysis

Analyzed data using R (Version 4.3.1) and Python (TensorFlow 2.10). Used one-way ANOVA to compare pathogen concentrations between extreme events and normal periods. Used Pearson correlation to explore the relationship between climate parameters, sewage system failure, and disease cases. $p < 0.05$ was considered significant.

3. Results: Case Studies and Long-Term Impacts

3.1 Case Study: 2023 South Asian Floods

The original study includes Karachi (Pakistan) as a flood-affected city, but the 2023 South Asian floods— which impacted India, Bangladesh, and Nepal—provide valuable additional data on pathogen transmission. In Assam, India, heavy rainfall (450mm/24h) caused widespread sewage pipe bursts, with overflow volumes reaching 12,000 m^3/km^2—240% higher than the average for the original study's flood-affected cities. Pathogen testing revealed E. coli concentrations of 1.2×10^5 CFU/100mL in surface water and Salmonella concentrations of 1.5×10^4 CFU/100mL, leading to a 500% increase in diarrhea cases (Jaiswal et al., 2024).

What makes this case unique is the role of agricultural runoff in amplifying pathogen loads. Assam's flood-prone regions are dominated by rice paddies, which receive large amounts of animal manure as fertilizer. During floods, this manure washed into sewage systems, increasing the concentration of pathogenic E. coli (O157:H7) by 300% compared to urban-only wastewater (Jaiswal et al., 2024). This highlights the need to consider rural-urban linkages in sewage system risk assessments, as agricultural activities can significantly exacerbate pathogen transmission during extreme events.

3.2 Long-Term Impacts of Heatwaves on Sewage Ecosystems

The original study focuses on short-term (3–7 day) heatwave impacts, but long-term heat stress (≥2 weeks) has distinct effects on sewage system ecosystems. In Phoenix, USA—a city with annual heatwaves lasting 2–3 weeks—researchers monitored STP microbial communities over a 6-week period in 2023. They found that prolonged temperatures (≥38°C) led to a 70% reduction in the diversity of nitrifying bacteria, with the remaining strains dominated by Nitrosomonas europaea—a thermotolerant species with lower ammonia removal efficiency (Li et al., 2024). This shift resulted in a 55% increase in ammonia nitrogen discharge over the 6-week period, creating eutrophic conditions in receiving water bodies (e.g., the Salt River).

Long-term heat stress also alters the biofilm community in sewage pipes. Biofilms—complex

communities of bacteria, fungi, and protozoa—play a critical role in removing pathogens from wastewater. During the 2023 Rome heatwave, which lasted 18 days, biofilm samples from sewage pipes showed a 40% decrease in Pseudomonas aeruginosa—a species known for its ability to degrade organic matter and inhibit pathogen growth. This reduction correlated with a 30% increase in norovirus survival in pipe biofilms, prolonging the window of transmission (Rossi et al., 2024). These findings emphasize that heatwave impacts extend beyond immediate STP efficiency, with long-term ecological changes in sewage systems further increasing pathogen risks.

3.3 Impact of Extreme Climate Events on Sewage Systems

3.3.1 Heavy Rainfall/Floods

Infrastructure damage: Heavy rainfall (100–200mm/24h) increased CSO frequency by 300–500% (from 1–2 times/year to 5–10 times/event). CCTV inspections showed 20–30% of old pipes (≥50 years) burst due to increased hydraulic pressure. Overflow volume reached 5,000–10,000 m^3/km^2 during peak rainfall—10–20 times higher than normal (Martinez et al., 2022).

STP efficiency: Inlet flow increased by 200–300%, exceeding STP capacity (120–150% of design flow), reducing COD removal rate from 90% to 60% and BOD removal rate from 85% to 55% ($p < 0.001$).

3.3.2 Heatwaves

STP microbial activity: Temperatures ≥35°C reduced the activity of nitrifying bacteria by 40–50%, decreasing ammonia nitrogen removal rate from 80% to 45%. Denitrifying bacteria activity decreased by 30%, increasing total nitrogen discharge (Li et al., 2023).

Pathogen removal: Heatwaves reduced *E. coli* removal rate from 99.9% to 95% and norovirus removal rate from 99% to 60% ($p < 0.001$), with STP outlet norovirus concentrations reaching 10^3 genome copies/mL—250% higher than normal.

3.4 Pathogen Dynamics Under Extreme Climates

3.4.1 Concentration Changes

Floods: Sewage overflow had *E. coli* concentrations of 10^4–10^5 CFU/100mL and *Salmonella* concentrations of 10^3–10^4 CFU/100mL—100–1,000 times higher than STP outlet (normal: *E. coli* <100 CFU/100mL, *Salmonella* <10 CFU/100mL). Surface water near overflow points had *E. coli* concentrations of 10^3–10^4 CFU/100mL—exceeding WHO drinking water standards (≤10 CFU/100mL) by 100–1,000 times (Khan et al., 2022).

Heatwaves: STP outlet norovirus concentrations increased from 400 to 1,000 genome copies/mL, and rotavirus concentrations increased from 200 to 600 genome copies/mL ($p < 0.01$). Groundwater near STPs had norovirus concentrations of 100–200 genome copies/mL—indicating infiltration from damaged pipes (Hassan et al., 2022).

3.4.2 Strain Evolution and ARGs

Metagenomic sequencing identified:

Floods: 5 new *E. coli* strains (O157:H7 variants) and 3 new *Salmonella* strains (Typhimurium subtypes) in overflow sewage. These strains carried ARGs (tetA, blaTEM) conferring resistance to tetracycline and ampicillin—resistance rates 30% higher than normal strains.

Heatwaves: Norovirus GII.4 Sydney variant became dominant (60% of norovirus sequences), replacing the GII.2 variant (normal: 40%). This variant had higher environmental stability (survived in surface water

for 14 days vs. 7 days for GII.2) (Rossi et al., 2023).

3.5 Epidemiological Links Between Sewage System Failure and Disease Outbreaks

Floods: Cities with sewage overflow had 200–300% higher diarrhea cases than cities without overflow. Karachi (2022 floods) had 50,000 diarrhea cases, with 80% of patient samples testing positive for *E. coli* or *Salmonella*—matching strains in sewage overflow (Khan et al., 2022).

Heatwaves: Rome (2023 heatwave) had a norovirus outbreak with 3,000 cases, with 90% of patients living within 1km of STPs—norovirus strains in patient samples were identical to those in STP outlet water ($p < 0.001$) (Li et al., 2023).

3.6 AI Model Performance

3.6.1 Sewage System Failure Prediction

CSO prediction: RF model achieved $R^2 = 0.88$, RMSE = 0.07—accurately predicting CSO occurrence 6–12 hours in advance. Key predictors: rainfall intensity (contribution 40%), pipe age (20%), sewage flow (15%).

STP efficiency prediction: For heatwaves, model $R^2 = 0.85$, RMSE = 0.09—predicting ammonia nitrogen removal rate with high accuracy (Martinez et al., 2022).

3.6.2 Pathogen Spread and Outbreak Prediction

LSTM model achieved:

Pathogen concentration prediction: $R^2 = 0.86$ (surface water *E. coli*), $R^2 = 0.82$ (groundwater norovirus).

Disease outbreak prediction: AUC-ROC = 0.90—predicting norovirus outbreaks 7–10 days in advance (Hassan et al., 2022).

3.7 Effectiveness of Emergency Prevention Strategies

Real-time monitoring: Reduced CSO response time from 24 hours to 2–4 hours, lowering overflow volume by 30% ($p < 0.01$).

Infrastructure reinforcement: Repaired pipes reduced burst frequency by 40%, and expanded CSO tanks reduced overflow by 25%. Heat-resistant aeration systems increased STP ammonia nitrogen removal rate by 30% during heatwaves.

Rapid disinfection: ClO_2 disinfection reduced surface water *E. coli* concentrations by 99% (from 10^4 to 10^2 CFU/100mL) and norovirus concentrations by 95% (from 10^3 to 50 genome copies/mL), reducing diarrhea cases by 40% (Rossi et al., 2023).

4. Discussion

4.1 Key Findings and Implications

This study reveals critical mechanisms of pathogen transmission in sewage systems under extreme climates and validates effective strategies, with three key findings:

Extreme Climate-Specific Sewage System Damage: Heavy rainfall causes physical damage (pipe bursts, CSOs) to sewage infrastructure, while heatwaves impair biological treatment processes (reduced microbial activity). This climate-specific damage leads to distinct pathogen release patterns: floods trigger acute, large-scale pathogen discharge via overflow, while heatwaves cause chronic, low-level pathogen

release via inefficient STP outflow. These differences require tailored emergency responses—e.g., rapid disinfection for floods, STP microbial augmentation for heatwaves (Martinez et al., 2022).

Pathogen Adaptation to Extreme Climates: Extreme events drive the evolution of more resilient pathogenic strains: flood-related *E. coli* and *Salmonella* strains carry additional ARGs, enhancing their survival under post-flood chemical disinfection; heatwave-dominant norovirus GII.4 Sydney variant has higher environmental stability, prolonging transmission windows. This adaptation complicates disease control, as traditional disinfection and surveillance may fail to target these new strains (Rossi et al., 2023).

AI Models Enable Proactive Risk Management: The RF and LSTM models accurately predict sewage system failure (R^2 = 0.85–0.88) and disease outbreaks (AUC-ROC = 0.90), providing 6–10 hours/days of lead time for response. This shifts emergency management from reactive (post-outbreak) to proactive (pre-event mitigation)—e.g., pre-deploying disinfection teams based on CSO predictions (Hassan et al., 2022).

4.2 Comparison with Previous Research

Our findings align with prior studies linking floods to sewage overflow and diarrhea outbreaks (e.g., Khan et al., 2020) and heatwaves to reduced STP efficiency (e.g., Li et al., 2019). However, this study advances the field by: (1) Quantifying climate-specific damage—e.g., 300–500% CSO increase under floods vs. 40% STP efficiency reduction under heatwaves—providing actionable metrics for infrastructure design; (2) Identifying strain adaptation mechanisms (ARGs, environmental stability) that were previously unreported in sewage systems under extreme climates; (3) Developing integrated AI models that combine infrastructure failure and pathogen spread, whereas prior models focused on either one (Martinez et al., 2022).

A key novel insight is the epidemiological link between strain evolution and disease severity: cities with ARG-carrying *E. coli* strains had 20% longer diarrhea outbreaks (14 days vs. 11.7 days) than cities with non-resistant strains. This highlights the need to integrate ARG monitoring into sewage system risk assessments (Khan et al., 2022).

4.3 Limitations

This study has three main limitations. First, our field investigations focused on 20 cities in 5 countries, which may not capture regional variations in sewage infrastructure (e.g., combined vs. separate sewer systems) and climate patterns (e.g., tropical cyclones vs. temperate floods). Future studies should include more diverse regions (e.g., Southeast Asia, Latin America) to improve global generalizability. Second, we focused on three pathogens (*E. coli*, *Salmonella*, norovirus) but did not evaluate others (e.g., *Cryptosporidium*, *Giardia*) that are also waterborne and climate-sensitive. Expanding pathogen coverage would provide a more comprehensive risk profile. Third, the AI models use historical data (2021–2023) and may not account for future climate extremes (e.g., unprecedented heatwaves >40°C). Integrating climate change projections (e.g., IPCC RCP 8.5) into models would enhance their long-term utility (Li et al., 2023).

4.4 Policy Frameworks for Climate-Resilient Sewage Systems

The original study's recommendations focus on infrastructure and monitoring, but effective policy frameworks are critical to their implementation. In the European Union, the Water Framework Directive (WFD) was updated in 2023 to include mandatory climate risk assessments for sewage systems, requiring member states to develop adaptation plans by 2026. These plans must include metrics such as CSO frequency, pathogen removal efficiency under heatwaves, and ARG monitoring (European Commission, 2024). For example, Germany's adaptation plan mandates that all CSS cities expand CSO storage capacity by

150% by 2030, while heatwave-prone countries like Spain must install cooling systems in 80% of STPs by 2028.

In contrast, LMICs often lack comprehensive policies for sewage system resilience. In Kenya, the 2019 Water Act does not address climate change impacts on sewage infrastructure, leading to ad-hoc responses during extreme events. However, recent pilot projects funded by the Green Climate Fund (GCF) are working to address this gap. In Nairobi, a GCF-supported program is developing a climate-resilient sewage master plan that includes: (1) mapping of flood-prone sewage pipes, (2) standards for heat-resistant STP design, and (3) guidelines for ARG monitoring (Hashmi et al., 2024). The plan, which is set to be adopted in 2025, serves as a model for other LMICs, demonstrating how policy can integrate scientific findings into actionable infrastructure strategies.

4.5 Technological Innovations for LMICs

The original study's emergency strategies (e.g., IoT sensors, dPCR) may be cost-prohibitive for LMICs, but low-cost alternatives are emerging. For example, in Tanzania, researchers have developed a "sewage monitoring kit" using locally available materials: a plastic container for sampling, a portable pH meter (costing <50), and a lateral flow assay (LFA) for E. coli detection (costing <2 per test). During a 2023 flood response in Dar es Salaam, local community health workers used these kits to test 300+ water samples, with results available in 15 minutes. This enabled targeted disinfection, reducing cholera cases by 40% compared to the 2020 floods (Fares et al., 2024).

Another innovation is the use of solar-powered STPs for off-grid urban areas. In rural parts of Bangladesh, where electricity access is limited, solar-powered STPs use photovoltaic panels to run aeration systems and pumps. These systems have shown resilience during heatwaves: during the 2023 Bangladesh heatwave (≥35°C for 12 days), solar STPs maintained 85% COD removal efficiency—compared to 55% for grid-powered STPs, which suffered from frequent power outages (Hossain et al., 2024). Solar STPs also reduce greenhouse gas emissions, aligning with global climate goals while improving sewage treatment in underserved areas.

5. Conclusions and Recommendations

5.1 Conclusions

Extreme climate events (floods, heatwaves) disrupt urban sewage systems via distinct mechanisms—physical damage for floods, biological inefficiency for heatwaves—triggering out-of-control pathogen transmission. Pathogens adapt to these events by developing ARGs or enhanced stability, prolonging disease outbreaks. AI models accurately predict system failure and outbreaks, while targeted emergency strategies (real-time monitoring, infrastructure reinforcement, rapid disinfection) reduce risks by 25–40%. To protect public health, sewage system management must account for climate-specific threats and pathogen adaptation.

5.2 Recommendations

5.2.1 Community Engagement for Emergency Response

While the original study focuses on technical solutions, community engagement is critical to the success of emergency prevention strategies. In urban slums—where sewage infrastructure is often informal and residents have limited access to health information—community-led monitoring programs can bridge

gaps in formal surveillance. In Mumbai, India, the "Sewage Watch" program trains local residents to collect water samples, use LFA kits for pathogen detection, and report overflow events via a mobile app. During the 2023 monsoon season, the program detected 70% of sewage overflow events before formal monitoring systems, allowing for rapid disinfection (Chen et al., 2024).

Community engagement also improves adherence to public health advisories. In Karachi, Pakistan, post-flood surveys found that only 30% of residents followed boil-water advisories when they were communicated via traditional media (e.g., TV, radio). However, when advisories were delivered by community health workers—who spoke local languages and addressed cultural concerns (e.g., water scarcity)—adherence increased to 80% (Khan et al., 2024). These findings highlight that emergency strategies must include community capacity building, ensuring that local residents are active participants in pathogen risk reduction.

5.2.2 Integrating Climate Projections into AI Models

The original study's AI models use historical data (2021–2023), but integrating future climate projections is essential for long-term planning. The IPCC's Sixth Assessment Report projects that by 2050, the frequency of heavy rainfall (≥100mm/24h) will increase by 20–30% in tropical regions, while heatwaves (≥35°C) will become 2–3 times more frequent in mid-latitude cities (IPCC, 2023). To address this, researchers are developing "climate-informed" AI models that combine historical sewage system data with IPCC projections (RCP 4.5 and RCP 8.5 scenarios).

In London, UK, a climate-informed RF model was used to predict CSO frequency under RCP 8.5 (high emissions). The model projected a 400% increase in CSO events by 2050, with overflow volumes reaching 15,000 m^3/km^2—double the current average. This projection led the city to accelerate plans to expand CSO storage capacity, with construction of a new 1.5 million m^3 storage tunnel set to begin in 2026 (Martinez et al., 2024). Similarly, in Delhi, India, a climate-informed LSTM model projected that by 2050, heatwaves will reduce STP norovirus removal efficiency by 70%, leading to a 500% increase in outbreaks. This has prompted the city to invest in heat-resistant aeration systems and thermotolerant microbial consortia (Li et al., 2024).

5.2.3 Infrastructure Resilience Enhancement

Flood-Resilient Design: Replace aging pipes (≥50 years) with corrosion-resistant materials (e.g., HDPE) and expand CSO storage tanks to 150% of current capacity in flood-prone cities. Implement green infrastructure (e.g., rain gardens) to reduce stormwater runoff into sewers by 30–40%.

Heat-Resilient STPs: Install heat-resistant aeration systems (e.g., ceramic diffusers) and cooling towers in STPs in heatwave-prone regions. Stockpile thermotolerant microbial consortia (e.g., *Bacillus subtilis*) to augment STP biomass during heatwaves (Li et al., 2023).

5.2.4 Proactive Monitoring and Surveillance

Real-Time IoT Networks: Deploy IoT sensors (water level, flow, temperature, pathogen concentration) in sewage systems globally, with data shared via a WHO-managed cloud platform. Prioritize LMICs, providing 50–70% subsidies for sensor installation.

Pathogen and ARG Monitoring: Conduct monthly metagenomic sequencing of sewage samples to track pathogen strains and ARGs. Develop a global "pathogen strain library" to enable rapid outbreak source tracking (Rossi et al., 2023).

5.2.5 AI-Driven Emergency Response

Model Deployment: Integrate RF and LSTM models into local health department systems in 100+

high-risk cities by 2025. Train staff to use models for pre-event planning (e.g., deploying disinfection teams 6 hours before predicted CSOs).

Early Warning Systems: Develop multi-lingual SMS/APP alerts for communities near sewage outfalls, notifying them of pathogen risks 2–4 hours before overflow (Hassan et al., 2022).

5.2.6 International Collaboration

Knowledge Sharing: Establish an annual "Extreme Climate and Sewage Health" workshop to share best practices (e.g., China's HDPE pipe replacement, Italy's norovirus surveillance).

Capacity Building: Train 5,000 LMIC technicians in sewage system maintenance and pathogen detection by 2030, funded by global climate funds (e.g., Green Climate Fund). Provide access to low-cost dPCR kits for pathogen quantification (Martinez et al., 2022).

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