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The Global Sanitation Crisis

Case Studies on Climate-Resilient Urban Sanitation Approaches

BACKGROUND PAPER

A Product of The World Bank's
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The World Bank
1818 H Street NW, Washington, DC 20433
Telephone: 202-473-1000; Internet: www.worldbank.org

Cover Photos
Large: Iguaçu Wastewater Treatment Plant (Credit: Sanepar). Lower right: Biogas storage from anaerobic domestic sewage treatment at Atuba Sul WWTP, Curitiba, Brazil (Credit: Sanepar). Lower left: Nature-Based Solution (constructed wetlands) for sewage sludge treatment at the Santa Helena wastewater treatment plant in Santa Helena, Brazil (Credit: Sanepar).

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Abbreviations

ASA	Advisory Services and Analytics
AURA	Autoridade Reguladora de Águas
BORDA	Bremen Overseas Research and Development Association
CBS	Container-based sanitation
CEPT	Centre for Environmental Planning and Technology
CMWSSB	Chennai Metropolitan Water Supply and Sewerage Board
COP	Conference of Parties
CRI	City Resilience Index
CRS	Climate-Resilient Sanitation
CSO	Combined Sewer Overflow
CWIS	Citywide Inclusive Sanitation
ESAWAS	Eastern and Southern Africa Water and Sanitation Regulators Association
ESG	Environmental, Social and Governance
EU	European Union
EWS	eThekwini Water and Sanitation
FM	Failure mode
FSM	Faecal Sludge Management
FSTP	Faecal Sludge Treatment Plant
GCF	Green Climate Fund
GHG	Greenhouse Gas
GWP	Global Water Partnership
HIC	High income Country
IFI	International Financial Institution
KIWASCO	Kisumu Water and Sanitation Company Limited
LMICs	Low- and Middle-Income Countries
MEL	Monitoring, evaluation, and learning
MWSS RO	Metropolitan Waterworks and Sewerage System Regulatory Office
NACOSTEC	Nakuru Countywide Sanitation Technical Steering Committee
NAP	National Action Plan
NBS	Nature Based Solution
NDC	Nationally Determined Contribution
NGO	Non-governmental Organisation
NRW	Non-Revenue Water
OSS	Onsite Sanitation
PIRF	Policy, Institutional, Regulatory, and Financing
PUB	Public Utilities Board
SFPUC	San Francisco Public Utilities Commission
SuDS	Sustainable Drainage Systems
ToR	Terms of Reference
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations Children's Fund
WASH	Water, Sanitation and Hygiene
WSUP	Water and Sanitation for Urban Populations
WWTP	Wastewater Treatment Plant

Photo: A treatment plant in Philipsburg, Sint Maarten (Credit: Martin Gambrill).

Executive Summary

This background paper presents an analysis of nine global case studies illustrating climate adaptation and mitigation strategies within the urban sanitation sector. Spanning diverse contexts—from high-income to low-income settings across four continents—the case studies examine both sewered and non-sewered sanitation systems at various stages of the sanitation service chain. They highlight responses across different levels of government, including city, state, and national, and showcase a range of policy, regulatory, and institutional approaches.

Each case study explores the unique climate challenges facing urban sanitation, the strategies implemented, and their outcomes. The paper identifies key resilience-building qualities demonstrated through these interventions and distils lessons learned, offering actionable insights for policymakers, utilities, and development partners aiming to enhance climate resilience in urban sanitation systems globally.

Key Technical Messages

1. Leverage urban water scarcity as a catalyst for promoting climate-resilient sanitation technologies and service models.

Water scarcity is a strong driver for adopting climate-resilient urban sanitation. Greater awareness of this risk among policymakers can create a more receptive enabling environment to pilot new approaches to water supply and sanitation (WSS) services and to develop markets for resource reuse. Water scarcity should therefore be seen as an opportunity to innovate in urban sanitation. For example:

San Francisco, USA

To reduce pressure on scarce freshwater resources, the San Francisco Public Utilities Commission (SFPUC) invested in a sewer upgrade program that transformed wastewater treatment plants (WWPTs) into resource recovery facilities. The city also introduced graywater and blackwater[1] reuse systems within buildings and at district scale.

Singapore

To improve water security in the face of drought and population growth, Singapore developed an integrated water management system. This includes high-grade water reclaimed from wastewater (NEWater) and desalinated water, both used for industrial and indirect potable purposes.

Chennai, India

Water scarcity prompted the development of wastewater recovery and reuse markets, supported by national, state and city-level policies. The service provider developed a 'carrot and stick' approach—offering competitive tariffs for treated wastewater and mandating reuse requirements. To cover WWTP operating costs, the service provider also developed energy recovery markets through biogas generation, alongside growing markets for resource recovery products, including wastewater sludge.

1 Graywater is household wastewater from sinks, showers, bathtubs, and laundry which can be safely reused for sub-surface irrigation; blackwater is the wastewater from bathrooms and toilets that contains fecal matter and urine.

Kenya

In response to water scarcity and the urgent need for improved sanitation services in low-income urban areas, the private sector developed a business model for container-based sanitation. These sealed, portable units require no water to operate and can be relocated during flooding events. Typically deployed where onsite sewered sanitation systems are not feasible and/or where sewers have not yet been introduced, they also generate reuse products for the agriculture and energy sectors, supporting a circular economy.

Building on the success of these interventions, policy reform is needed in some countries to enable the adoption of wastewater and sludge reuse and to scale circularity in urban sanitation.

2. Test the effectiveness of new sanitation technologies and service models to demonstrate proof of concept and enable scale-up.

Evidence of the effectiveness and impact of new sanitation technologies and service models can give decision-makers the confidence to develop appropriate policy and regulatory frameworks for wider adoption and scale. Engaging users during the testing and demonstration phase is essential to ensure that technologies and services are responsive to local needs and adapted to the specific context. For instance:

Nairobi, Kenya

A pilot of container-based sanitation demonstrated proof of concept and catalyzed broader uptake across the city, as well as in other cities and countries. For example, Lusaka, Zambia is currently piloting a similar project.

San Francisco, USA

San Francisco is influencing national wastewater reuse efforts by sharing lessons learned with other cities. New York, for instance, is in the early stages of adopting insights from the San Francisco experience.

Lusaka, Zambia

The Lusaka Sanitation Program has enabled the Lusaka Water and Sanitation Company (LWSC) to develop and test new service delivery models for toilet upgrading and fecal sludge management (FSM) in peri-urban areas. These efforts have strengthened the resilience of sanitation services and reduced the vulnerability of vital groundwater resources to environmental contamination.

Cape Town, South Africa

Community engagement in informal settlements revealed that toilets imported from Europe were not sufficiently robust to accommodate all body types or user groups, such as children, leading to reduced user confidence.

External actors and development partners can play a key role by providing catalytic finance to support demonstration projects, helping to establish proof of concept for climate-resilient sanitation approaches.

3. Integrate sanitation with other urban services to increase urban resilience and promote circularity.

Synergies across urban services—such as water supply, energy, sanitation (both sewered and onsite), drainage and solid waste management—can enhance urban resilience and create efficiencies that go beyond typical business-as-usual practices. Integrated service delivery also opens up opportunities for resource recovery and reuse, supporting the development of a circular business model for energy, water and waste. For example:

Paraná, Brazil

The state utility, Sanepar, has incorporated climate risk management into water, sanitation and solid waste services with plans to integrate further with other urban sectors, such as energy and agriculture.

San Francisco, USA

SFPUC has adopted a 'one-water' approach that integrates water supply, energy and wastewater, supporting a holistic and systems-based model for water management.

Singapore

Singapore has implemented an integrated approach to water delivery, wastewater recycling, and stormwater management to address climate change challenges, such as sea level rise, and to support both climate mitigation and adaptation.

Cape Town, South Africa

The city's water and sanitation department has expanded its mandate to include catchment, stormwater and river management enabling an integrated approach to water resilience.

Miami, USA

Miami-Dade county uses treated wastewater for industrial cooling to support water conservation, but concerns over aquifer contamination limit reuse for domestic or irrigation purposes—highlighting the need for context-specific reuse strategies.

In many contexts, realizing synergies across urban services will require policy, institutional and regulatory reforms to enable integration across multiple levels of government.

4. Mainstream climate resilience into Citywide Inclusive Sanitation (CWIS) approaches.

Citywide Inclusive Sanitation aims to ensure that everyone has access to safely managed sanitation services across the entire sanitation service chain—whether through sewered or onsite systems—including appropriate wastewater and fecal sludge management. To remain effective, CWIS must evolve to address the effects of climate change on environmental and public health risks linked to inadequate or absent sanitation. This requires mainstreaming climate considerations into CWIS planning, design and implementation processes. Some examples include:

Lusaka, Zambia

The Lusaka Sanitation Program has strengthened LWSC's capacity to deliver onsite sanitation services, including fecal sludge management. This has led to increased uptake of safely managed sanitation in peri-urban, low-income communities. LWSC has also developed new service models to encourage households connections in sewered areas.

Cape Town, South Africa

The Informal Settlement Basic Services Department is dedicated to providing and regulating both sewered and non-sewered sanitation systems in communities most vulnerable to climate change impacts, particularly flooding.

Key Policy, Institutional, and Regulatory (PIR) Messages

Chapter 3 of the main report entitled, *"The Global Sanitation Crisis: Pathways to Urgent Action,"* outlines core overarching recommendations for strengthening PIR and the enabling environment required to advance climate-resilient urban sanitation. Learnings specific to the city-level case studies are summarized below.

1. Build cross-sector partnerships to support capacity building, knowledge sharing and advocacy for climate-resilient urban sanitation.

Climate-resilient urban sanitation can be advanced through partnerships that span multiple sectors, institutions and levels of governance. Multilateral organizations, national and local governments, utilities, academia, the private sector, non-governmental organizations (NGOs) and civil society—particularly those working in climate change and sanitation—should collaborate to strengthen capacity, identify effective resilience strategies and innovations, facilitate cross-sector knowledge exchange, and advocate for the integration of climate resilience in urban sanitation systems. Examples from the case studies include:

Singapore

As the national water agency, the Public Utilities Board (PUB) collaborates with a range of partners to support the translation and commercialization of promising water technologies. Initiatives include the Singapore Water Exchange (SgWX), which incubates new startups, and the Global Innovation Challenge, which invites companies and researchers to propose solutions to PUB's operational challenges.

Chennai, India

The city's utility has established partnerships with universities and technical institutions to undertake research on wastewater and energy recovery. These collaborations have successfully attracted external funding to support ongoing work.

Cape Town, South Africa

The Water and Sanitation Department has joined the Leading Utilities of the World network, providing regular opportunities for knowledge exchange with leading utilities around the globe.

Paraná, Brazil

The utility Sanepar participates in knowledge-sharing forums with other Brazilian utilities to foster peer learning and exchange lessons learned. It also collaborates with applied research institutions internationally on water supply and sanitation topics and contributes to climate-related initiatives, including local climate action planning processes.

Bangladesh

The CWIS-FSM Support Cell, housed within the Department of Public Health Engineering, partners with development agencies, local governments, NGOs and academic institutions to advocate for the implementation of CWIS across the country.

External actors and development partners can play a key role by providing catalytic finance to support demonstration projects, helping to establish proof of concept for climate-resilient sanitation approaches.

2. Create time and space for innovation in climate resilience.

Advancing climate-resilient urban sanitation requires innovation and a shift away from business-as-usual approaches. Utilities should allocate dedicated staff time—separate from day-to-day service delivery—and provide institutional support to pilot new technologies and service models. For example:

Chennai, India

The success of the Chennai Metropolitan Water Supply and Sewerage Board in incorporating wastewater and energy recovery into treatment facilities has been attributed to leadership support that enabled engineers to pilot and scale innovative approaches.

Singapore

PUB has established an Integrated Validation Plant to test state-of-the-art design concepts for future wastewater reclamation facilities designed to produce high-grade reclaimed water, while optimizing both energy consumption and generation.

3. Mainstream climate resilience into guidelines, standards and codes of practice across the sanitation service chain.

Regulations, guidelines, standards and codes of practice play an essential role in enabling service providers to adopt climate resilient technologies and service models. Integrating climate considerations into these frameworks at every stage of the sanitation service chain helps institutionalize resilience and drive consistent implementation. Examples from the case studies:

Chennai, India

Changes to policy and building codes have made the use of treated wastewater mandatory for large users, and wastewater recycling compulsory in new housing and commercial developments.

Singapore

Large water users in water-intensive industries are required to recycle at least 50% of their water. Financial and technical support is available for companies implementing these projects, including design advisory services, operational efficiency support, and assistance to meet regulatory requirements.

Cape Town, South Africa

The city developed a standard operating procedure for the installation of decentralized sanitation systems (wastewater treatment package plants), which has encouraged developers to adopt this technology.

Miami, USA

State legislation requiring elimination of marine outfalls and 60% wastewater reuse by 2025 pushed Miami-Dade to adopt deep injection wells and invest in wastewater recycling.

Cape Town, South Africa

The city is also developing service standards for providers of non-sewered sanitation in informal settlements. At the national level, a Water and Sanitation Servicing Standards document has been released for public comment. These measures aim to improve service quality, support provider accountability, and build user confidence in new toilet models.

Nairobi, Kenya

FreshLife/Sanergy collaborated with the national government to ensure container-based sanitation was included in the Kenya Environmental Sanitation and Hygiene Policy, establishing a safe and cost-effective alternative to conventional sewers and other onsite sanitation systems.

4. Localize national climate policies and plans to the city level.

To maximize the impact of efforts to address climate change, sanitation must be integrated into climate action at all levels. This includes its inclusion in nationally determined contributions (NDCs) and national adaptation plans (NAPs), as well as the localization of these plans into city-level and service provider investment plans. Localizing national plans enables local actors to design context-specific activities and programs that align with national goals while addressing local challenges and opportunities. For example:

Bangladesh

Municipalities are in the process of developing local adaptation plans based on the 2022 National Adaptation Plan, which includes the development of climate-resilient WASH facilities to enhance wellbeing and livability in urban areas.

5. Ensure effective coordination across multiple governance levels and sectors (horizontal and vertical).

Climate change mitigation and adaptation impact all stages of the sanitation service chain and require coordinated action and shared decision-making across governance levels and sectors. Establishing cross-ministry and cross-departmental working groups or task forces—at both national and city levels—can facilitate this coordination and streamline the development and implementation of a shared climate resilience agenda. Effective coordination also depends on a common climate language and a shared understanding of climate risks among all stakeholders. Examples from the case studies include:

Cape Town, South Africa

> The Mayor established a team to coordinate the city's response to drought across departments. This team evolved into the Future Planning and Resilience Office, which now plays a central role in integrating, coordinating and monitoring resilience plans across city departments.

Singapore

> As the national Coastal Protection Agency, PUB leads and coordinates nationwide efforts to protect Singapore from rising sea levels. Due to varied land use across the country, site-specific studies are carried out to develop tailored coastal protection measures, alongside broad stakeholder engagement to gather feedback and ensure relevance.

At the city level, development partners can play an important technical and facilitation role in convening cross-ministry working groups and enabling cross-sectoral dialogue, particularly where institutional coordination is limited or emerging.

Key Finance Messages

1. Quantify and communicate the true cost—and public and environmental health risks—of climate change inaction.

Understanding the full costs of inaction, including the public and environmental health implications, is critical for driving long-term, proactive planning for climate-resilient urban sanitation. Although standard methodologies for calculating these costs are limited, generating and communicating such evidence can help build both the business case and ethical justification for early investment in adaptation. While cities and utilities can collect valuable local data, international and national actors also have a key role in building global evidence and advocating fit-for-purpose, cost-assessment methodologies. For instance:

San Francisco, USA

> In developing its business case for climate adaptation to address sea level rise, the city conducted a cost study of a 'do nothing' scenario, demonstrating that inaction would be more costly than proactive investment.

Paraná, Brazil

> Sanepar prioritizes the generation of knowledge and evidence on environmental matters, including climate change, to inform strategic planning and strengthen both internal and external engagement.

Lusaka, Zambia

> Repeated disease outbreaks in peri-urban areas—linked to groundwater contamination from unsafely managed sanitation systems—were worsened by rainfall and flooding. This public health risk became a key driver behind the Lusaka Sanitation Program financed by the World Bank, the AfDB, the EU and KfW.

Nairobi, Kenya

> In Mukuru, a low-income settlement, broader urban development upgrades—including improved sanitation services to respond to climate risks—have contributed to enhanced environmental quality within the community.

2. Focus on the financial viability of service providers as the foundation for accessing climate-related funding.

A range of climate-related funding mechanisms—including blue and green bonds—can support financing for climate adaptation and resilience in sanitation. However, access depends on the financial viability of service providers. Strengthening governance, creditworthiness and risk mitigation are key to a compelling investment case. Technical capacity within utilities must also be in place to manage funds effectively. Additionally, a strong focus on customer satisfaction can improve revenue collection, further enhancing financial sustainability and the ability to attract ongoing climate finance. Examples include:

San Francisco, USA

The SFPUC maintains financial stability by securing a high bond rating, enabling access to favorable rates on green bonds. It also implements a drought surcharge to build financial reserves and mitigate revenue losses during drought events.

Paraná, Brazil

Sanepar uses blue and green bond mechanisms to enhance its investment capacity for company growth and service improvement. The utility externally verifies these bonds to demonstrate compliance with ESG standards, reinforcing its reputation and maintaining trust with its customers and investors.

Cape Town, South Africa

The city restructured its services to include a commercial arm focused on customer service and trust-building. This shift led to a notable increase in customer satisfaction and revenue collection, which rose from 80% in 2018 to 93% in 2022.

Singapore

PUB has established a Green Financing Framework to fund sustainable projects in water monitoring, collection, storage and distribution, treatment, wastewater management and renewable energy projects. To qualify for green financing, projects must meet strict eligibility criteria, such as, reducing emissions, minimizing water loss, and decreasing waste.

3. Incentivize long-term use of climate-resilient services through targeted subsidies and tariff adjustments.

Section 7.6 of the background report explores how tariff structures can be adapted to support climate-resilient sanitation. City-level case studies show that regulators and service providers can use tariff mechanisms to encourage uptake and sustained public support for circular economy models—such as offering lower rates for recycled, non-potable water compared to potable water. In low-income settings, targeted subsidies may also be necessary to support household investment in climate-resilient containment systems and to incentivize private sector participation in fecal sludge management services. Examples from the case studies include:

Chennai, India

The utility developed a market for reused wastewater by introducing regulatory measures and ensuring cost parity with existing water suppliers, making reused water a viable alternative.

Lusaka, Zambia

The Lusaka Sanitation Program implemented a subsidy mechanism to promote the use of scheduled fecal sludge emptying services. Private operators are reimbursed by LWSC for the difference between the subsidized user fee and the full-service cost, including a reasonable profit margin.

Cape Town, South Africa

The city sells treated wastewater for irrigation and industrial use at a lower cost than conventional sources, such as groundwater and potable water, making it a more affordable and attractive option.

Key Messages for Households and Other Customers

1. Build household-level ownership of climate-resilient sanitation through improved access to data and customer communication.

Utilities can foster greater household ownership of climate-resilient sanitation by engaging customers and supporting their active participation in resilience-building efforts. Raising awareness of climate risks and adaptation measures is key. Transparency and regular provision of accessible, easy-to-understand data can empower households and strengthen their connection to service improvements. Examples from the case studies include:

Paraná, Brazil

Through environmental awareness initiatives, and by incorporating customer feedback into its operations, Sanepar aims to shift user mindsets—from viewing the utility as solely responsible to becoming active partners in reducing risk and building climate-resilient sanitation systems.

Chennai, India

The *City Connect* initiative supports coordination across water resilience efforts by maintaining an accessible online platform that updates residents on utility plans and connects users with related organizations and resources.

San Francisco, USA

Utility-customer communication focuses on water stress and encourages private and residential customers to invest in wastewater reuse and green infrastructure at the household level. This includes initiatives such as rainwater harvesting, permeable driveways, and onsite wastewater reuse systems.

2. Increase user acceptance of new technologies and service models through education campaigns.

User resistance to new, climate-resilient water supply and sanitation technologies—such as recycled wastewater for potable use—is common. However, targeted public education campaigns can play a critical role in increasing awareness, addressing misconceptions, and building public trust. Clear communication about safety, benefits, and environmental impacts is essential to foster acceptance and long-term adoption. For example:

Cape Town, South Africa

The Water and Sanitation Department uses multiple media platforms, including multi-language channels, to communicate with customers, and operates an improved Contact Centre to facilitate inquiries. However, engagement with users of non-sewered sanitation in informal settlements revealed the need for more accessible and user-friendly reporting channels for lodging complaints or reporting issues with private service providers.

Singapore

Initial public resistance NEWater, Singapore's reclaimed water initiative, was addressed through targeted communication efforts. Specially designed NEWater bottle labels were used at national events, and public education campaigns were rolled out in schools, community centers and workplaces. The launch of the NEWater Visitor Centre in 2003 provided a dedicated space for educating the public bridging the gap between scientific understanding and public perception.

3. Engage communities in climate-resilient sanitation initiatives to ensure needs are addressed.

Engaging community groups throughout the planning, design, and implementation of climate-resilient sanitation initiatives helps ensure that solutions are responsive to local needs, expectations, and contexts. Inclusive engagement also builds trust, fosters ownership, and supports the long-term success and sustainability of new service models and technologies. Examples from the case studies:

Singapore

PUB has initiated site-specific studies to explore possible coastal protection options and is conducting a series of community dialogue sessions ('Our Coastal Conversations') to gather ideas and feedback from the public and stakeholders.

Lusaka, Zambia

As part of the Lusaka Sanitation Program, residents were consulted on the design of climate-resilient sanitation facilities. Their preferences were incorporated into both the design and costing of the solutions, helping ensure community relevance and acceptance.

Nairobi, Kenya

The Special Planning Area process in Mukuru (one of Nairobi's largest low-income settlements) involved co-planning with residents to help identify priorities for upgrading informal settlements. This included improvements across multiple sectors such as, sanitation, housing, drainage and solid waste management.

Miami

Comprising professionals and community members, the Biscayne Bay Task Force reviews data and reports to identify emerging challenges facing residents and property owners. The Task Force serves as a central platform for stakeholder engagement on issues such as water quality, governance, infrastructure, marine debris, watershed restoration, education, outreach and funding.

Photo: Nature-Based Solution (constructed wetlands) for sewage sludge treatment at the Santa Helena wastewater treatment plant in Santa Helena, Brazil (Credit: Sanepar).

1

Introduction

Global Case Studies We Can Learn From

This background paper presents nine global case studies, developed to showcase good practices in climate change adaptation and mitigation within the urban sanitation sector.

These case studies span diverse contexts—from high-income to low-income settings, across four continents, and encompassing both sewered and non-sewered sanitation systems—while addressing various stages of the sanitation service chain. They also reflect responses at different regional scales, including city, state, and national levels, illustrating a range of governance approaches and strategies. Each case study highlights the context and challenges from the perspective of climate-resilient urban sanitation, the responses implemented, their outcomes, the resilience qualities demonstrated, and the lessons learned.

The Case Study Selection Process

Seventeen case studies were initially selected, ensuring a wide geographic spread and diverse sanitation interventions addressing different climatic drivers. The selection process involved a two-stage evaluation. The first stage assessed whether the case studies demonstrated positive climate adaptation impacts, either quantitatively or qualitatively, and whether sufficient data and quality sources were available for further investigation. Case studies that met these initial criteria proceeded to a more detailed evaluation based on climate considerations, response factors, and sanitation aspects.

Climate considerations prioritized case studies that addressed multiple hazards such as flooding, drought, extreme temperatures, or sea level rise, while also incorporating mitigation measures. The response factors emphasized integration with other sectors, the inclusion of diverse and relevant policy, institutional, regulatory and financing (PIRF) mechanisms, consideration of user engagement and behavior, and scalability for implementation in different contexts. Additionally, the selection process accounted for whether the response involved new solutions or retrofits and ensured representation across different regions and income levels. The diversity of stakeholders involved, including governments, utilities, NGOs, communities, and academia, was also considered.

Sanitation-specific factors included the extent to which different stages of the sanitation chain were covered, the type of sanitation system (sewered or non-sewered), and whether the system was centralized or decentralized. Following this evaluation, case studies were categorized as preferred, possible, or not possible based on the availability of information. Nine case studies were ultimately selected to ensure a broad geographic representation across low-, middle- and high-income countries while showcasing diverse sanitation initiatives.

An Updated Conceptual Framework

Since these case studies were developed, the climate-resilient sanitation analytical framework presented in the associated main report has evolved, informed by the feedback of sector professionals and emerging research. While the research framework of the original case studies focused on four key dimensions—infrastructure and service provision; user engagement; policies, institutions, and regulations; and financing—an updated conceptual framework now links climate-resilient urban sanitation to desired human, social, economic and environmental outcomes (Figure 1), aligning with the impacts on people, shared prosperity and the planet.

The updated conceptual framework for the analytical work emphasizes the transformative potential of climate-resilient sanitation systems. Building these systems requires capacities to respond to disruptions and adapt to climate impacts. Absorptive, adaptive, and transformative capacities form the foundation of climate-resilient sanitation.

Figure 1

Conceptual framework illustrating the links between safely managed, climate-resilient sanitation services and people, prosperity, and the planet

Source: Original figure for this publication, World Bank 2025.

Note: CRS = Climate-Resilient Sanitation

Respectively, these capacities are about the following:

A. Being able to cope in a reactive way to climate impacts on sanitation services,

B. Being able to incrementally adapt services so that they are less likely to fail and suffer disruption

C. Being able to significantly rethink and reconfigure sanitation services to be more resilient to climate shocks and also contribute to wider resilience in urban water cycles and communities (Box 1).

These capacities enable preparedness, risk mitigation, and longer-term system transformations to ensure sustainable service delivery. Interventions to address climate impacts on sanitation systems can focus on any of these capacities, based on specific contextual risks and available resources to support adaptation. In some contexts, prioritizing support for users to cope with disrupted services and reduce health and environmental risks may be preferred; in other contexts, building adaptive capacity to modify technologies or practices or transformative capacity to engage in wider systems change may be more desirable (GCF 2024).

This paper recognizes the evolution of the conceptual framing of climate-resilient sanitation. While the case studies are presented using their original research framework, the paper incorporates additional analyses to highlight how these case studies exemplify the different resilience capacities—absorptive, adaptive, and transformative. By integrating the updated research framework with the original case studies, this paper serves as a comprehensive resource for stakeholders seeking practical examples to support cities in building sustainable, climate-resilient, urban sanitation systems.

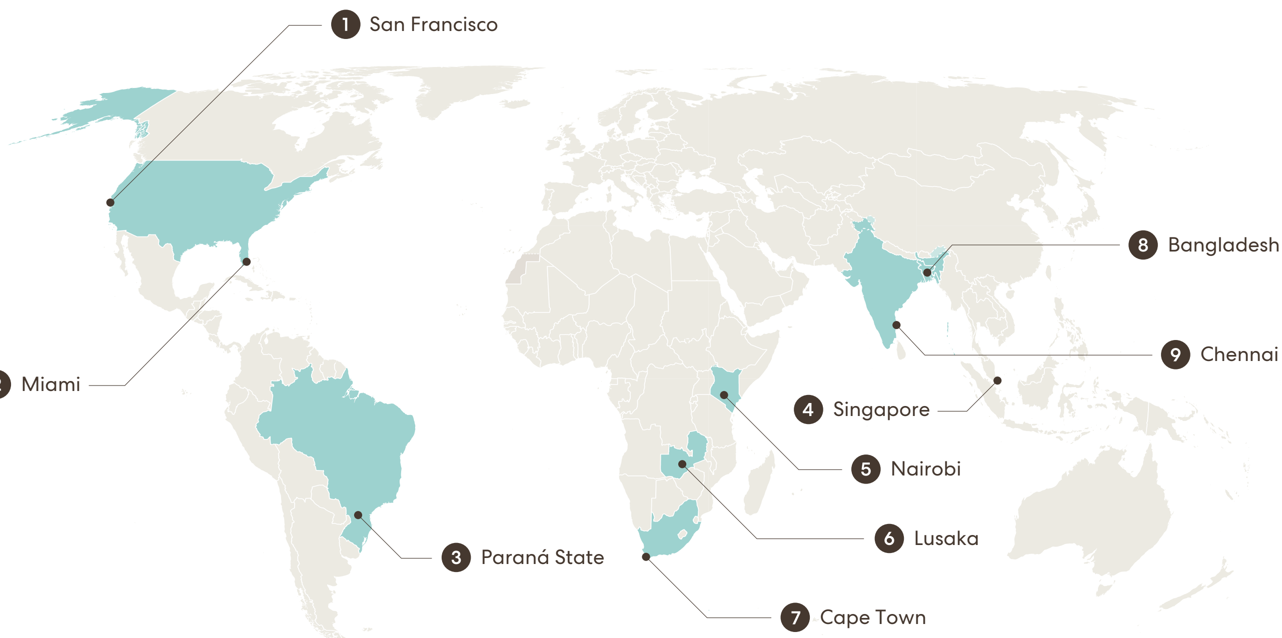
Box 1. Absorptive, adaptive and transformative capacity in the context of sanitation resilience[2]

1. Absorptive Capacity	2. Adaptive Capacity	3. Transformative Capacity
Focuses on maintaining stability by anticipating, planning, coping with, and recovering from short-term shocks and stresses. It aims to minimize negative impacts on individuals, households, communities, businesses, and authorities by implementing measures such as early warning systems, proactive system maintenance, and frequent fecal waste removal in coastal and flood-prone areas.	Involves being able to incrementally adapt services so they are less likely to fail and suffer disruptions. This process requires continuous learning, flexibility, and innovation. Examples include constructing raised toilets and adapting combined sewer networks in flood-prone areas to more consistently separate stormwater from wastewater, mobilizing communities for monitoring and data dissemination, diversifying water sources and sanitation systems—such as treated wastewater reuse and container-based sanitation (CBS) —and adapting sanitation policies to respond to evolving climate challenges.	Entails rethinking and reconfiguring sanitation services to enhance their resilience while contributing to broader urban resilience and water security. This approach addresses the root causes of risk and vulnerability to ensure more equitable risk-sharing. Actions include addressing financial and regulatory barriers, developing innovative financing mechanisms for the long-term viability of climate adaptation efforts, fostering cross-sectoral collaborations, integrating climate considerations into strategic planning and infrastructure development, implementing institutional reforms, and creating an enabling environment for wastewater reuse.

2 Adapted from Jeans et al. 2017

Table 1

Overview of the nine case studies



		Drought	Flooding	Sea Level Rise	Increased Temps
1 San Francisco	Use of green finance for investments promoting wastewater separation and reuse and reducing CSOs	×	×	×	
2 Miami	Septic tank-to-sewerconversions to protect the aquifer and the marine ecosystem from water pollution caused by sea-level rise and failing septic tanks		×	×	
3 Paraná State	Embedding climate-risk management into utility planning and operation to tackle urban water crises	×	×		
4 Singapore	An island city-state resourcefully approaching wastewater reuse	×	×	×	×
5 Nairobi	CRS embedded into integrated urban upgrading approaches to improve livelihoods of vulnerable low-income communities	×	×		
6 Lusaka	Reducing climate change vulnerability through improved sanitation services and their active management in peri-urban areas	×	×		
7 Cape Town	Promoting wastewater reuse and prioritizing access to sanitation in informal settlements to achieve a water-resilient city	×	×		
8 Bangladesh	Translating national policy into local action		×	×	×
9 Chennai	Reducing pressure on the city's water supply through large-scale wastewater reuse	×	×	×	

1 San Francisco Public Utilities Commission, USA

Climate hazard	Main issues	Prompt for action	Key enabling factors	Utility response	Main outcomes
· Drought · Flooding · Sea level rise	Caused by climate change: Water scarcity and frequent prolonged periods of drought. Sea level rise and storm surges. Existing urban issues: Aging sewer network leading to CSO over-flows during intense rainfall. Potable supply under threat from growing demand.	Need for additional sewer system capacity to sustain increased rainfall patterns and protect assets against sea level rise. Need to reduce/control potable water demand to manage water scarcity.	Innovative policy and regulatory landscape. Alternative capital in-vestment mechanisms in the wastewater sector. Innovative approach-es to stimulate the recycling of wastewa-ter, blackwater and greywater.	Upgrade of the sewer network to increase capacity. Centralized wastewa-ter reuse for irrigation. Green infrastructure to reduce stormwater runoff, enhanced by stormwater credit incentives. Mandatory onsite greywater and black-water reuse systems for non-potable use in large developments. Targeted vulnerable wastewater treatment assets to build ro-bustness against sea level rise.	Increased financial sustainability of the utility. Innovative culture within policy/regu-lation, infrastructure, service provision models, and ways of working. Utility created a regulatory framework to accelerate inno-vation and uptake of greywater reuse technology, creating a new service market for water reuse. Comprehensive sys-tem monitoring and data accessibility.

2 Miami-Dade County Water and Sewer Department, USA

Climate hazard	Main issues	Prompt for action	Key enabling factors	Utility response	Main outcomes
· Flooding · Sea level rise	Caused by climate change: Saltwater intrusion to low lying areas. Large proportion of septic tanks at risk of seepage. Existing urban issues: Aging sewer infra-structure prone to fail-ure and overloading, with increasing pres-sure from population growth. Only source of potable water supply is Biscayne aquifer, which is threatened by pollution from sep-tic tank seepage.	Need to protect 120,000 vulnerable septic tanks through substitutions and connections to the sewer network, to mitigate rising water tables and frequent flooding, in order to ensure public and environmental health.	Clear roles and responsibility between private/public ownership. Robust groundwater modelling system to target vulnerable areas. Grant funding. 'One-Water' approach is being applied and considers water reuse and energy reduction using wastewater.	Connecting existing septic tanks to public sewer networks. New ordinance has increased the distance between new devel-opments and the sew-er network, meaning that developers must pay to connect to public sewers rather than install septic tanks. Treated wastewater is piped directly from the treatment plant for reuse as a cooling agent in the nearby nuclear power plant. The utility is on target for total elimination of 100% of marine outfalls by 2025, instead discharging wastewater treatment plant effluent into deep injection wells to avoid pollution of the bay and the surround-ing water bodies.	Protection of groundwater sources (i.e. Miami's only drinking water supply) and of public and environmental (marine) health. 'OneWater' approach and circular water practices reusing water for the energy sector. On track to deliver full removal of all wastewater effluent outfalls into the bay.

3 Sanepar Water and Sanitation Utility of Parana State, Brazil

Climate hazard	Main issues	Prompt for action	Key enabling factors	Utility response	Main outcomes
· Drought · Flooding	Caused by climate change: Water scarcity threatening the continued provision of sanitation services. Flooding events affecting water quality and impacting sanitation assets. Existing urban issues: Poor water quality due to pollution of river basins. Covid-19 pandemic added pressure on water supply and sanitation services	Climate change considered as a major business risk for the water and sanitation utility	Focus on knowledge and evidence generation through research and innovation. Environmental, social, and governance (ESG) considerations within an entrepreneurial mindset. State/territorial action through public and private integrated actions.	Internal mechanisms developed: greenhouse gases inventory; climate mitigation and adaptation plan. Circular economy initiatives established: biogas and renewable hydrogen for energy generation; sludge being used to improve soil health for agriculture; solid waste management to support water resilience in terms of improving water quality.	Safe water quantity and quality levels for operation. Generation of climate and environmental data and knowledge that informs decision making. Benefits to other sectors (biogas/ hydrogen for energy; nutrients for agriculture; solid waste management improvements).

4 Singapore city-state

Climate hazard	Main issues	Prompt for action	Key enabling factors	Utility response	Main outcomes
· Drought · Flooding · Sea level rise · Increased temperature	Caused by climate change: Water scarcity with prolonged dry spells threatening water availability. Increased rainfall worsening flood risks. Rising sea levels endangering coastal areas. Existing urban issues: Limited availability of groundwater, natural freshwater bodies, and land area for rainwater capture and storage. Pollution of already scarce water bodies. Growing population and expanding economy placing additional stress on already-strained water resources.	Need for national water security improvement – particularly to address vulnerability to climate change and insufficient water sources which, among other challenges, also affect continued sanitation service provision (i.e. too little water puts sewered sanitation at risk).	Political will to seek national water security. Investment in innovative technology.	'Four National Taps' strategy—integrated water management system, in particular the 'NEWater' technology for reclaimed water, reused from treated wastewater.	Water sustainability with increased water storage levels. Reclaimed water from wastewater reuse for industry use (e.g. wafer fabrication) and indirect potable reuse (e.g. through water storage reservoirs).

5 Low-income areas of Nairobi, Kenya

Climate hazard	Main issues	Prompt for action	Key enabling factors	Utility response	Main outcomes
· Drought · Flooding	Caused by climate change: Water scarcity (rising temperatures and more erratic rainfall). Overflow of sanitation facilities particularly in low lying informal settlements during flooding events. Existing urban issues: Ongoing urbanization means demand for water outstrips current supply. Limited sewerage and treatment plant coverage and effectiveness, leading to environmental pollution. Inadequate sanitation, water supply, SWM and drainage in informal settlements.	Achieving universal access to improved water and sanitation in low-income communities. Adding flexibility to sanitation provision models.	Development of Special Planning Areas allowed for sectoral planning and new approaches to be trialed. Existence of sanitation service delivery models outside of the water and sanitation company's purview. Existence of trunk sewers adjacent to the LICs.	Provision of simplified sewerage and container-based sanitation (CBS) services. Regulation/market development for re-use products. Use of carbon credits for CBS.	Piloting of flexible sanitation approaches. Proof of concept achieved for simplified sewerage and container-based sanitation. Adoption of appropriate technologies including container-based sanitation and simplified sewerage. Regulation and acceptance of re-use products for energy and agriculture.

6 Peri-urban utility service provision in Lusaka, Zambia

Climate hazard	Main issues	Prompt for action	Key enabling factors	Utility response	Main outcomes
· Drought · Flooding	Caused by climate change: Inward migration of rural population from climate affected areas. Water scarcity (rising temperatures and more erratic rainfall). Overflow of sanitation facilities particularly in peri-urban areas (PUAs) during floods. Existing urban issues: Frequent power outages/rationing due to reliance on hydroelectric power generation. Over reliance on (contaminated) groundwater for water supply. Inadequate sanitation, SWM and drainage in PUAs.	Increase access to safely managed sanitation in PUAs through improved containment and active management of septage and fecal sludge (FS). Rehabilitation of, and increased connections to, sewers. Reduce vulnerability of vital groundwater resources to environmental contamination.	Clear utility mandate for onsite sanitation (OSS) and fecal sludge management (FSM). Specific strategies, plans and investment programmed. Funding mechanisms to facilitate upgrading of OSS structures and promote their emptying.	Efforts to upgrade toilets to be climate resilient in PUAs. Generation of market demand for emptying services through new funding mechanisms. Upgrading and extension of sewerage network and improvement to wastewater and fecal sludge treatment plants.	Capacity of the utility to actively manage FSM enhanced. Climate-resilient designs for toilets and containment mainstreamed in target PUAs. Market for emptying and transportation services developed to reach lower income customers. Amount of FS and septage reaching the treatment plant increased. Amount of wastewater reaching wastewater treatment plant (WWTP) increased through upgrading/extension of sewerage network.

7 City of Cape Town Water and Sanitation Department, South Africa

Climate hazard	Main issues	Prompt for action	Key enabling factors	Utility response	Main outcomes
· Drought · Flooding	Caused by climate change: Water scarcity. Failures in sanitation system due to the reduced wastewater flows. Overflow of sewers in times of flooding, particularly in informal settlements. Existing urban issues: WWTPs over capacity, limiting development of areas they serve. Aging sanitation infrastructure. Sewer blockages by illegal dumping of garbage.	Need for a water-resilient and water-sensitive city where everyone can have access to water and sanitation services.	Transformation of the utility to a customer oriented and financially stable department that has an integrated system approach, being responsible for water supply, sanitation, and catchment, stormwater and river management. Support from the authorities to coordinate stakeholders under established structures. Acceptance of treated wastewater reuse.	Treated wastewater reuse for potable and non-potable uses. Different sanitation options for flood-prone areas in informal settlements (chemical toilets, container toilets, portable flush toilets). Upgrading of the wastewater treatment system and improving the approach to monitoring and reporting failures. Preventive maintenance to avoid sewer blockages.	Financial stability of the utility. On track to deliver additional 300 million liters of water per day by 2030 by diversifying water sources including treated wastewater reuse for potable and non-potable uses. Reduction in sewer leaks and burst pipes, and increase in WWTPs capacity.

8 National Response in Bangladesh

Climate hazard	Main issues	Prompt for action	Key enabling factors	Utility response	Main outcomes
· Flooding · Sea level rise · Increased temperature	Caused by climate change: Inward migration of rural population from climate affected areas. Salt water intrusion into groundwater. Increased incidence of flooding causing damage to infra-structure including sanitation. Existing urban issues: Inadequate sewered and non-sewered sanitation and inad-equate wastewater and septage/FS treat-ment and disposal.	Climate impacts on coastal and rural communities leading to urban migration and increasing demand on urban sanitation services.	Government prior-itization of climate change. Development partner support for policy development. Water supply and sanitation prioritized in national adaptation planning. Creation of Citywide Inclusive Sanitation technical assistance hub for utilities/mu-nicipal governments.	Institutional strengthening. Policy strengthening. Utility research. Institutional behavior changes to focus on Citywide Inclusive Sanitation over infrastructure.	Inclusion of water, sanitation and climate change in city level planning. Research commis-sioned by utilities on cost-benefit analyses (CBA). Development partner support for new approaches. Translation of na-tional plans into local action plans.

9 Utility and City in Chennai, India

Climate hazard	Main issues	Prompt for action	Key enabling factors	Utility response	Main outcomes
· Drought · Flooding · Sea level rise	Caused by climate change: Water scarcity (rising temperatures and more erratic rainfall) including Day Zero event where reservoirs reached critical levels. Existing urban issues: Water supply does not meet demand of domestic, commer-cial and industrial customers. Inadequate septage management leading to environmental contamination.	Lack of available water for industry provided initial push for focus on wastewater reuse.	National Benchmark-ing and State Policies on Wastewater Reuse. Sanitation prioritized in City Resilience Plan. Tamil Nadu Urban Sanitation Support Programmed and Investment Plan. Technical Support Unit.	WWTPs adapted for onward sale of treated wastewater. Modular treatment facilities for riverside communities.	Market for treated wastewater developed. Increased volume of treated wastewater available for industrial use. Utility focus on climate-resilient wastewater treatment. Ecosystem restoration and improved water storage. Regulations to promote wastewater recycling implemented.

2

Photo: Sludge from a recycling program developed by Sanepar that serves small and medium-sized farmers is used as fertilizer. In the last 12 years, more than 300,000 tons of sludge have been recycled (Credit: Sanepar).

Detailed Case Studies

1. San Francisco
2. Miami
3. Paraná State
4. Nairobi
5. Lusaka
6. Cape Town
7. Chennai
8. Bangladesh
9. Singapore

1. San Francisco

KEY ASPECT

Green capital investments, targeted mandates and innovative services have enabled multi-scale programs to mitigate sewer overflows, promote wastewater recycling and counter water scarcity. San Francisco (SF) has introduced various water reuse and stormwater retention programs which avoid inflow or overload of the city's sewer system, promote recycling and reduce water use demand.

Key information

Location	• San Francisco, California, USA
Income Group	• High income country
Stakeholders	• Utility • Local government
Hazards	• Flooding • Water scarcity/drought • Sea level rise
Sanitation Characteristics	• Mixed (sewered, non-sewered; centralized, decentralized)
Sanitation failures covered by the climate-resilient solution	• Containment • Fecal Sludge (FS) delivery to treatment • FS treatment • Wastewater (WW) delivery to treatment • WW treatment
Other sectors that benefit from the response	• Energy • Stormwater • Water supply
Transformative capacities displayed by the case study	• Absorptive • Adaptive • Transformative

Context and Challenges

Climate change is impacting sanitation service provision in San Francisco in multiple ways, including through increased rainfall, prolonged drought and coastal flooding.

This is posing both a challenge and an opportunity for San Francisco Public Utilities Commission (SFPUC), which serves the 2.7 million people living in the San Francisco Bay Area with water, wastewater and energy. SFPUC serves a third of its customers directly (retail) and delivers wholesale to two thirds through various water agencies (SFPUC 2020).

A key sanitation challenge in San Francisco is the 1,900-mile, 100-year-old combined sewer system which is facing constraints due to growing population demand and the impact of more-frequent rainfall. The city's watershed contains a large amount of grey infrastructure, i.e. pavements and hard surfaces. This prevents infiltration and causes pressure on the combined sewer system, which regularly leads to polluted stormwater being discharged into the sea (SFPUC 2023).

Another important challenge is water scarcity caused by prolonged drought. SFPUC's wastewater service area provides an opportunity to diversify water supply through non-potable reuse applications, complementing the utility's efforts of water service planning. Water reuse has been considered a viable alternative since 1990, although centralized water reuse, which was first explored, was not found to be viable due to the hilly terrain and the high associated costs of pumping, thus driving the utility to explore decentralized water reuse options (SFRWQCB 2020).

Coastal flooding is impacting sanitation service provision in San Francisco. The city is low-lying and experiences both high tides and severe weather (SF Planning 2022). This causes stormwater backflows into the sewer network, increasing fluvial floods and backwater flooding. Sea level rise has also been known to increase the hydrostatic pressure in the gravity fed wastewater system, leading to groundwater intrusion and contamination issues (California Water Boards 2023).

For ratepayers the climate challenges pose an increased economic burden. With growing needs for physical infrastructure upgrades, California's Proposition 218 outlines that one rate cannot subsidize another, which is causing challenges around affordability for customers of lower socio-economic backgrounds. As a result, SFPUC has to sustain a fine balance between infrastructure prioritization, maintaining the utility's reputable credit rating, and supporting consumers through affordable bills.

The USA's National Adaptation Plan identifies sewer overflows and damage to wastewater infrastructure as challenges resulting from climate change. The plan considers wastewater under its Priority Action 2, outlining the extent to which stakeholders and agencies share a responsibility for increasing resilience and adaptation to climate change (US EPA 2021). This national directive drives San Francisco's determination to adequately target their centralized sewer network in combating climate related challenges. It also enabled the regulatory environment for onsite water reuse systems that were pioneered by the SFPUC and the National Water Research Institute, who together developed a tailored regulatory water quality framework (EAWAG 2023). San Francisco's different city authorities continually rethink their approaches to mitigating climate effects on the city, with programmed such as ClimateSF, which aims to unite key city agencies whose services could be critically impacted (OneSF 2024a). This streamlines city responses through a coordinated effort.

The Responses

To address the effects of climate change through increased rainfall, drought and coastal flooding, SFPUC has adopted an integrated 'one-water' approach across water, energy and wastewater, which was introduced in 2016 (SFPUC 2019).

Embracing this holistic approach, SFPUC has increased the use of reused water networks, slowed the rate of combined wastewater entering the sewer networks, and protected assets from coastal flooding.

Increased the use of reused water networks

San Francisco has enabled the successful uptake of water reuse practices—contributing to more sustainable resource utilization. This measure reduces overall water consumption as well as water treatment needs.

At the neighborhood/district scale, Water Recycling Projects (e.g. 'Westside Enhanced') which include the construction of new recycled water treatment facilities located within existing wastewater treatment plants, have been implemented by SFPUC. The associated systems transmit treated wastewater to specific irrigation areas such as parks and golf courses, through which SFPCU is aiming to save up to 2 million gallons of water per day (7.6 MLD).

At the city scale, an overall upgrade to the aging sewer network under the Sewer System Improvement Programmed (SSIP) has enabled water reuse. As part of this program, aging wastewater treatment plants have been transformed into resource recovery facilities. These upgrades are concurrently ensuring adaptation to sea level rise by targeting vulnerable wastewater assets.

The SFPUC administers the Onsite Water Reuse Program, which allows for the collection, treatment and reuse of alternative water sources for non-potable applications in individual buildings and at the district scale. Legislation has also contributed to an increase in water reuse at a household level. The Onsite Water Reuse Programmed requires private property owners, within designated areas, to install onsite water reuse for any new or upgraded building over 100,000 ft^2 (9,290 m^2) and any new or existing irrigated areas of over 40,000 ft^2 (3,716 m^2) (SFPUC 2024). New developments of over 40,000 ft^2 are required to submit water budget calculations assessing the supply available from required alternative water sources and the projected demand from non-potable uses. These can be used for a variety of applications, including landscape irrigation and toilet flushing. These systems employ purple pipes to indicate that they contain treated wastewater effluent. Financial penalties exist for non-compliance. The associated change in legislation has led to market transformation, enabling the development, marketing and adoption of innovative technologies, while raising awareness among customers and real estate developers (EAWAG 2023).

Reduced inputs into the combined sewer networks

One of the ways in which SFPUC has minimized inflows into its combined sewer networks, to accommodate the more-frequent rainfall and associated flooding, is through a monitoring system. With close monitoring, SFPUC is aware of how wastewater is moving through the combined system. An early warning system facilitates preparation of the network in advance of predicted heavy rainfall.

The capacity of the system has also been increased through the Stormwater Management Ordinance, which mandates new and redevelopment projects to implement green infrastructure. Green infrastructure grant funding is available under the Green Infrastructure Grant Program for the design and construction of green stormwater infrastructure on large public and private properties, capturing runoff from at least 2000 m^2 of impervious surface. The interventions include rain gardens, permeable pavements, infiltration trenches, green roofs and rain-harvesting cisterns – which, since 2023, enhances the eligibility of stakeholders to apply for stormwater credits under the Stormwater Credit Program, which incentivizes a lower monthly sewerage bill of up to 90%.

Public educational programmed such as the Rain Ready Project have also ensured widespread public awareness of flooding, pushing community behavior change towards a more 'we're in it together' approach.

SFPUC has also adopted its Extreme Precipitation Project to help prepare for an uncertain future. The project looks to downscale global science data to understand how extreme precipitation will affect San Francisco, in support of analyses of the levels of service and size of systems that will be required in the future (SFPUC 2022; 2024)

Protecting against sea level rise and storm surges

SFPUC is tackling sea level rise and coastal flooding through its process of asset-by-asset protection, through which they are (i) identifying vulnerable wastewater infrastructure (e.g. pumping stations, separate and combined sewers, discharge outfalls) through Sea Level Rise Guidance that indicates zones vulnerable to inundation, and (ii) completing a sea level rise checklist for any vulnerable zones that are predicted to be affected by a 100-year storm before the year 2100 (OneSF 2024b). Adaptation measures implemented to date include the installation of backflow stops to prevent sewer backup and developing flood-proofing strategies for low level structures (SF Planning 2020).

SFPUC has also identified that long-term sea-level rise will require more thorough multi-agency planning and prioritization. This has been demonstrated through the Ocean Beach Project—the city's largest climate change adaptation project to date—which aims to create a new public space while simultaneously protecting key public assets, including a wastewater treatment plant. The plant is in an area subject to stormwater runoff, storm surges and continual erosion.

In addition, SFPUC is using innovative financing mechanisms to enable asset protection, including capital investment projects that advance climate change mitigation and adaptation through the issuance of green bonds. SFPUC is planning the sale of over USD 700 million in bonds to fund wastewater treatment and flood control management projects (SFPUC 2023). This approach to capital investment allows SFPUC to reduce its own costs and, consequently, reduce costs for its customers. This approach helps them reduce costs through lower interest rates, longer-term savings due to the nature of the projects being lower emissions and/or energy saving, and regulatory incentives for investing in green initiatives.

Table 2

San Francisco's climate-resilient sanitation responses and enabling environment

Infrastructure and service provision	Users	Institution, policy, and planning	Finance
• Centralized wastewater reuse, using purple pipes for irrigation, are reducing demand on potable water use. • Sewer upgrades have minimized inflows to the sewer system while adapting to sea level rise. • Green infrastructure has reduced stormwater runoff and pressure on the sewer network. • Vulnerable wastewater assets are made more robust against sea level rise.	• Stormwater credits are incentivizing uptake of green infrastructure to private residents, reducing stormwater runoff. • Campaigns have motivated behavioral changes towards potable water conservation through uptake of reuse practices, including addressing public resistance to water reuse (i.e. combatting the 'yuck factor').	• Mandates have been introduced for new commercial and multifamily buildings (in excess of ~9,300 m^2 or 100,000 ft^2) to treat wastewater onsite and not discharge into the sewer system. This is reducing potable water demand and pressure on sewer networks. • Implementation of a Stormwater Management Ordinance has helped capture runoff from impervious surfaces of at least 2,000 m^2. • Financial penalties introduced for water users in breach of mandates and ordinance rules. • The SFPUC'S One-Water approach provides holistic and multi-system benefits.	• SFPUC is using green bonds to enable investment in climate adaptation and mitigation projects, such as flood control management and wastewater treatment projects. While these bonds may lower overall costs, SFPUC is transparent about the necessity of customer tariff/rate increases to cover capital investments and other expenses.

The Outcomes

SF has become a national and global pioneer for mainstreaming the uptake of wastewater reuse, as a result of a long-term and iterative planning, implementing and learning process.

The SFPUC has created a regulatory framework that has accelerated innovation, infrastructure upgrades and public acceptance/adoption, while creating a new service market for wastewater/blackwater/greywater water reuse.

The comprehensive monitoring of the sewer networks has ensured real-time and early detection of issues across the system, offering proactive solutions to climate related impacts, such as those resulting from heavy rainfall. SFPUC has also enhanced the accessibility of this data, prioritizing transparency by disseminating data through interactive maps to enable further public engagement. This has increased public awareness and facilitated informed decision-making for SFPUC and its customers regarding maintenance, management and behavioral change around water management and conservation.

In response to the challenge of sea level rise, vulnerable infrastructure has been identified, and SFPUC has increased focus on sewer backflow. In addressing the long-term challenge of sea level rise, multi-disciplinary projects involving multiple city stakeholders, such as the Ocean Beach Project, have demonstrated the need for a paradigm shift in governance to ensure that climate change effects are prioritized. This includes speaking a common climate language and understanding various city stakeholders' priorities.

Delving into the green bond market has created a further capital investment stream for the city, enabling infrastructure updates and the implementation of climate related infrastructure projects.

San Francisco is now influencing the sector nationally through the dissemination of lessons learned to national think tanks and other fora. In the context of direct peer-to-peer learning, New York city is in the early stages of direct knowledge sharing with San Francisco.

Key Capacities of Resilience

Absorptive Capacity
This case study demonstrates absorptive capacity through measures that enhance the system's ability to manage immediate climate impacts, such as extreme rainfall, drought, and sea level rise. Real-time monitoring and early warning systems allow the utility to prepare for and mitigate the effects of extreme weather events, ensuring the city's systems remain responsive to future uncertainties. Additionally, public education initiatives like the Rain Ready Project foster community preparedness.

Adaptive Capacity
This case study also showcases adaptive capacity through SFPUC's proactive adjustments to infrastructure, policies, and practices in response to evolving climate challenges. Upgrades to the combined sewer network, including the implementation of backflow stops and flood-proofing vulnerable infrastructure, enable the system to adapt to disruptions from coastal flooding and storm surges.

Transformative Capacity
SFPUC exemplifies transformative capacity through its adoption of a 'One Water' approach, which integrates water, wastewater, and energy management to address the interconnected impacts of climate change. This holistic strategy shifts traditional management paradigms and fosters systemic resilience by promoting circularity and innovation across sectors.

The following transformative efforts demonstrate a paradigm shift in urban water and sanitation management, enhancing the city's capacity to address both current and future climate challenges while delivering co-benefits, including environmental conservation, economic efficiency, and public engagement.

Photo (right): Newly upgraded digesters at the Oceanside Treatment Plant are an integral part of San Francisco's wastewater management (Credit: Robin Scheswohl).

1. Establishing decentralized and centralized wastewater reuse systems (e.g., the Onsite Water Reuse Program and the Sewer System Improvement Programmed), which reduce reliance on potable water and pressure on sewer systems.

2. Strategic cross-sector collaborations, such as the Ocean Beach Project, which align climate adaptation with public space development and environmental protection, demonstrating the value of integrating multiple city stakeholder priorities into a unified resilience strategy.

3. Financing mechanisms, such as green bonds, which secure sustainable capital while reducing costs for customers. This transformative approach to funding ensures the long-term viability of climate adaptation initiatives and creates a replicable model for other utilities.

4. Investing in nature-based solutions and green infrastructure through initiatives like the Stormwater Management Ordinance and Green Infrastructure Grant Program, which reimagine urban landscapes to address runoff, flooding, and water quality challenges.

2. Miami

KEY ASPECT

Connecting septic tanks to sewers through the *Connect 2 Protect* program is strengthening sanitation resilience against rising sea and groundwater levels and unpredictable storm surges. This initiative helps protect the Biscayne Bay Aquifer from contamination, while also reducing pollution into Biscayne Bay. These measures contribute to safeguarding the marine ecosystem, public health and the local tourism economy.

Key information

Location	• Miami, Florida, USA
Income Group	• High income country
Stakeholders	• Utility • Environment Agency
Hazards	• Flooding • Sea level rise • Cyclone
Sanitation Characteristics	• Mixed (sewered, non-sewered; centralized, decentralized)
Sanitation failures covered by the climate-resilient solution	• Wastewater delivery to treatment
Other sectors that benefit from the response	• Energy • Water supply
Resilience capacities displayed by the case study	• Adaptive • Transformative

Context and Challenges

Miami-Dade is the southeastern most county on the US mainland and with a population of 2.7 million makes it the country's seventh most populous county.

The county's sole water source—including potable water—is groundwater, abstracted from the Biscayne Aquifer via wells (MDC 2023). Miami-Dade County (MDC) operates three main wastewater treatment plant that discharge treated effluent either through two marine outfalls beyond Biscayne Bay or via deep injection wells into the region's boulder zone geology. Given the Biscayne Bay Aquifer is unconfined and the primary source of water supply for the county, both regulation and operational practices prioritize its protection.

The terrain in MDC is extremely flat, with only a 3-meter elevation drop across the basin. This low gradient poses significant challenges in the face of sea level rise, which is driving the inland migration of the saline intrusion front. These pressures are compounded by the increasing frequency and intensity of rainfall, placing further strain on wastewater collection systems. Major storms—especially when combined with hurricanes—can overwhelm drainage systems, leading to flooding and infrastructure damage (Arup 2018). These challenges are further exacerbated by ageing infrastructure, poor housing conditions and high unemployment rates, all of which undermine both infrastructure and community resilience.

MDC is surrounded by significant water bodies—including the Atlantic Ocean, the Biscayne Bay, and a network of rivers, lakes and canals. Biscayne National Park, located in the Bay, supports a vibrant tourism sector that is central to the local economy. However, the quality of these water bodies has deteriorated due to nutrient pollution from wastewater discharges, stormwater runoff, agricultural pollution and emerging contaminants.

The county's sanitation infrastructure consists of a combination of onsite systems and regional centralized sewerage systems. Onsite systems, primarily septic tanks, are used in areas without access to sewer networks. Currently, there are approximately 120,000 septic tanks in MDC, of which around 9,000 are considered vulnerable to failure under existing groundwater conditions. These vulnerabilities are being exacerbated by climate-induced sea level rise, which is raising groundwater levels.

High groundwater levels interfere with the functioning of septic tanks and their associated drain fields, reducing treatment efficiency and increasing the risk of system failure. This results in the discharge of nutrients, organic matter, and bacteria into groundwater and, ultimately, into marine environments. It also raises the risk of sewage backups into homes and businesses. These failures have generated serious public health concerns and contributed to environmental impacts, including a significant algal bloom and fish-kill event between 2017 and 2019.

Sea level rise has also caused saltwater intrusion into surface water bodies, which affects both the volume and quality of wastewater collected for treatment. Infiltration of seawater into sewer networks increases the volume of wastewater requiring pumping and treatment, thereby raising electricity consumption and operational costs.

MDC operates under a unique two-tier metropolitan system of government established in 1957, comprising both city and county authorities. The county includes 34 municipalities, with the City of Miami being the largest. The Florida Department of Environmental Protection (DEP), specifically its Division of Water Resource Management (DWRM), enforces state water quality laws. The Miami-Dade County Water and Sewer Department (WASD) provides sewerage services across all municipalities and unincorporated areas within the county.

At the state level, DEP is responsible for protecting the quality of Florida's drinking water, groundwater, wetlands, estuaries, lakes, and rivers. Florida's Resilient Utility Coalition (RUC) plays a key role in supporting utilities to assess and adapt operations to potential climate-related disruptions. RUC promotes improved water management decision-making through benchmarking, data management, and fostering partnerships with universities to support innovation and climate adaptation strategies.

To support economic growth and development, MDC has introduced the SMART Plan, which identifies strategic rapid transit corridors to concentrate new development. These areas are intended to accommodate a mix of land uses and represent high-value investment zones. Ensuring the climate resilience of these corridors is critical for sustaining long-term economic development and protecting infrastructure from future climate shocks and stresses.

The Responses

In response to a resolution by the MDC Board of Commissioners, an assessment of septic tanks vulnerable to sea level rise was conducted in 2016 (MDC 2018).

Using robust groundwater modelling, MDC identified areas most at risk and concluded that resilience should be prioritized by transitioning from septic tanks to centralized sewer systems. This led to the development of the Connect2Protect (C2P) program, which targets failing or vulnerable septic tanks that pose risks to public health, private property and the environment. The C2P program addresses two categories of properties:

1. Properties with access to existing sewer infrastructure (adjacent to a sewer main).

2. Properties without existing sewer access.

For properties with access, once an approved sewer main is deemed available and operational, property owners are required to connect within 90 days of receiving notice from the utility. However, due to the high capital costs involved, many property owners request waivers to extend the connection timeline—waivers that are generally granted.

The estimated cost of connecting all properties to the sewer system is approximately USD 4 billion in private infrastructure investment, individual connection costs ranging from USD 7,500 - 15,000. Costs vary depending on the septic tank's location property-specific factors, and how topography affects the installation of a gravity line to the sewer main (MDC n.d.). Since 2020, MDC has significantly accelerated efforts to expand sewer connections. As of September 2023, approximately 11,000 conversions were at various stages of planning, design, or installation—marking a substantial increase from the previous decade, during which only 436 conversions were completed (Harris 2023) Funding remains a challenge. While public financing is supported by grants and bonds, dedicated funding programs for household connections are still limited. Since 2020, MDC has aggressively pursued federal and state funding for the C2P program, securing nearly USD 488 million in grants as by September 2023 (Harris 2023). Private financial support is minimal but some assistance is available through NGOs and the US Environmental Protection Agency's Clean Water State Revolving Fund (CWSRF).

Recognizing the need for expanded private sector involvement, MDC is exploring alternative financing mechanisms, including a revised C2P loan program and the establishment of a trust fund to support residents with connection costs.

In commercial corridors, the WASD has committed to converting septic systems to county sewer services for 1,000 commercial properties, which will contribute 20,000 m3 per day of additional flow to the sewer network. These areas were selected based on criteria aimed at eliminating commercial and industrial septic tanks while supporting local economic development (MDC 2024).

For new developments, MDC prioritizes connections to the centralized sewer system. The definition of what constitutes a "feasible" connection distance has been expanded to include additional parameters such as proximity to surface waters, the vulnerability of water bodies, sea level rise, and saltwater intrusion (MDC 2020). As a result, septic tanks are now only permitted where centralized sewers are not available (MDC 2023).

Wastewater reuse is also being implemented to promote water conservation and circular economy principles. A major example includes piping treated wastewater to the Turkey Point nuclear power plant where approximately 739 million liters per day are used for cooling (IAEA 2020). However, reuse for domestic or irrigation purposes has not been considered feasible due to concerns over potential contamination of the Biscayne Aquifer. Nevertheless, wastewater must still be treated to potable standards to avoid polluting this critical water source.

Under state legislation, MDC is required to eliminate marine outfalls from domestic wastewater treatment plants and to recycle 60% of wastewater by 2025. In response, WASD is phasing out marine outfalls and replacing them with deep injection wells.

To coordinate long-term action on water quality and resilience, the Biscayne Bay Task Force was established in 2019. Comprising professionals and community members, the Task Force reviews data and reports to identify emerging challenges facing residents and property owners. Key focus areas include water quality, governance, infrastructure, marine debris, watershed restoration, education and outreach and funding. The Task Force serves as a central platform for stakeholder engagement on these issues.

At the regional level, Southeast Florida's Regional Climate Change Compact, established in 2009, represents a collaborative effort between Miami-Dade, Broward, Monroe, and Palm Beach counties. The Compact supports joint efforts to reduce greenhouse gas emissions, implement climate change adaptation strategies and enhance resilience across the region. It has developed tools such as unified sea level rise projections, ensuring that all counties rely on common, science-based data and consistent assumptions in their planning and interventions.

Table 3

Miami's climate-resilient sanitation responses and enabling environment

Infrastructure and service provision	Users	Institution, policy, and planning	Finance
· The Connect 2 Protect program requires the provision of sewer services to residents experiencing failing or vulnerable septic tanks. · Wastewater reuse for irrigation has not been considered feasible due to quality concerns. However, 739 million liters per day of treated wastewater effluent is used to cool a large nuclear power plant.	· Recent utility and county level efforts have created partnerships, coalitions and task forces to engage the community and other relevant stakeholders, including sector professionals, in mitigating water quality related challenges.	· Connection to sewer mains has been made mandatory through legislation. · The county is on track to eliminate marine outfalls from domestic wastewater treatment plants by the year 2025. · Professional and community decision-makers operate under the Biscayne Bay Task Force. Their work helps ensure that adequate monitoring is undertaken and data is shared. · A Climate Change Compact ensures science-based data is disseminated to all relevant authorities in the county.	· Reliance on traditional funding sources, including grants, for climate-related programs. · The utility set up a trust fund to support customer connections to sewer networks. · Gaps in the existing finance mechanisms for climate-resilient sanitation systems have been identified and new opportunities are being explored.

The Outcomes

MDC has achieved significant milestones in environmental stewardship, with a strong emphasis on protecting both groundwater and marine ecosystems from contamination by septic tanks and wastewater discharges.

These efforts are grounded in a recognition of the environmental, social and economic benefits of reliable sanitation services. As the Connect2Protect program evolves, improvements in water quality are being continually monitored and evaluated.

The county has adopted a OneWater approach and promotes circular water practices, including the reuse of wastewater in the energy sector. However, wastewater reuse for domestic or irrigation purposes remains infeasible due to the risk of contaminating the Biscayne Aquifer.

MDC is currently on track to eliminate all municipal wastewater outfalls by 2025, which will significantly reduce nutrient loads in coastal waters and improve the health of marine ecosystems.

Despite these advances, the Connect2Protect program faces challenges related to financing. The large capital investment required to connect vulnerable properties to sewer infrastructure places a heavy burden on communities. Without adequate funding, enforcement of connection requirements is difficult. To ensure the program's success and equitable implementation, alternative funding mechanisms are urgently needed to reduce the financial pressure on residents in high-risk groundwater areas.

Key Capacities of Resilience

Adaptive Capacity
MDC demonstrates strong adaptive capacity through its proactive response to sea level rise and the pollution risks associated with failing septic systems. By using real-time groundwater modelling to identify high-risk areas, interventions are tailored to changing environmental conditions. Collaborative initiatives at both utility and county levels—including partnerships, coalitions, and task forces—foster engagement from both professional and community stakeholders in addressing water quality challenges. These efforts support effective data monitoring and dissemination, which in turn enhance the county's overall resilience. The approach reflects a recognition of the social and economic benefits of reliable and safe sanitation services.

Transformative Capacity
The county also exhibits transformative capacity by adopting a One Water approach that applies circular economy principles—such as reusing treated wastewater for energy sector applications. This strategic shift integrates water management across sectors, emphasizing city-wide initiatives that optimize resource efficiency and sustainability. Investments in multipurpose infrastructure, such as reclamation systems that also support energy generation, exemplify a forward-looking strategy to reduce waste and maximize the use of limited resources.

Nonetheless, funding constraints remain a significant barrier to scaling these efforts. Addressing these gaps is essential to sustain transformative adaptation, ensure equitable access, and maintain long-term functionality of climate-resilient and resource-efficient sanitation systems.

3. Paraná State

KEY ASPECT

Climate risk management is considered a strategic priority for Sanepar, the water and sanitation utility serving the State of Paraná. It has been fully integrated into the company's business planning and operational processes to strengthen systems and enhance the resilience of its value chains.

Key information

Location	• State of Paraná, Brazil
Income Group	• Upper-middle income
Stakeholder	• Utility
Hazards	• Flooding • Water scarcity/drought
Sanitation Characteristics	• Sewered • Mixed (centralized, decentralized)
Sanitation failures covered by the climate-resilient solution	• Wastewater (WW) delivery to treatment • WW treatment
Other sectors that benefit from the response	• Energy • Solid waste • Water supply • Agriculture
Resilience capacities displayed by the case study	• Transformative

Context and Challenges

Sanepar has recognized climate change as a major business risk of strategic importance, prompting its action on adaptation and mitigation.

Sanepar is a state-owned utility company operating as a private entity since 1963 (SANEPAR & Governo do Estado do Paraná 2022). It is responsible for delivering water and sanitation services across 346 municipalities, including 345 municipal capitals in the State of Paraná and the municipality of Porto União in the neighboring state of Santa Catarina (SANEPAR & Governo do Estado do Paraná 2022). Grounded in research and innovation, Sanepar is implementing a range of measures, including GHG emissions assessments, the development of climate mitigation and adaptation plans, and the exploration of circular economy initiatives—such as the reuse of biogas for energy generation.

Sanepar's services include the collection, treatment, storage, and distribution of potable water, as well as the collection and treatment of wastewater. It also operates three solid waste landfills. The utility undertakes studies, design, and civil works for new infrastructure and network expansions in both water and wastewater systems. Additionally, it provides consultancy and technical assistance within its core areas of operation.

Sanepar also manages the separation, sorting, and appropriate disposal of organic solid waste and sludge from wastewater treatment plants, including biogas production and energy recovery (SANEPAR & Governo do Estado do Paraná 2022). Its operations are regulated, inspected, and controlled by the Regulatory Agency of Paraná (Agência Reguladora do Paraná, AGEPAR).

The State of Paraná, where Sanepar operates, is located in southern Brazil and is known for its abundant water resources, including the iconic Iguazu Falls and the Paraná River Basin, which hosts the Itaipu Bi-national Hydroelectric Plant—the world's largest in terms of clean and renewable energy generation (ITAIPU 2024).

Paraná is one of Brazil's most developed and urbanized states. It ranks as the fourth richest state, and the fifth most populous, with 11.4 million inhabitants (IBGE 2022). Despite its water wealth, the state is increasingly affected by climate change, experiencing both severe droughts and intense flooding, creating a cycle of too little or too much water. A prolonged water crisis experienced from 2020 to 2022 significantly impacted the region (SANEPAR & Governo do Estado do Paraná 2022). During this period average reservoir levels reached 27% of capacity, prompting the state government to declare a water emergency (SANEPAR 2023). This crisis heightened awareness of environmental vulnerabilities and accelerated efforts to strengthen monitoring systems and pursue long-term climate resilience through innovation and integrated basin-wide actions.

Simultaneously, the Covid-19 pandemic placed additional pressure on water and sanitation services, further exposing systemic risks. These converging crises were recognized by Sanepar as significant business risks under both current and future climate scenarios, leading the utility to adopt a strategic long-term vision centered on sustainability, resilience, and adaptive service delivery.

The Responses

Prompted by the 2020 water crisis, Sanepar now considers climate risk management a strategic priority.

As a result, Sanepar has integrated climate change and environmental considerations into its business planning, operations, and infrastructure development. A key enabling factor has been the utility's commitment to knowledge generation on sustainability issues—including environmental, social, and governance (ESG) matters—which now underpins its monitoring systems, strategic planning, and internal and external engagement processes.

As a state-owned enterprise operating with private sector principles, Sanepar has leveraged both public and private sector perspectives to enhance decision-making. At the regional level, it has promoted an integrated approach to the delivery of resilient water and sanitation services, aligning utility operations with broader environmental and climate resilience goals.

The key responses adopted by Sanepar have been grounded in research and innovation, enabling the utility to pilot efficient and market-competitive strategies to strengthen climate resilience. These efforts focus on: understanding climate risks and mitigating their impacts; adapting to the anticipated effects of climate change; and advancing cross-sectoral circular economy initiatives.

Sanepar's 4-pronged approach includes:

1. Expanding sanitation access through new technologies and business models.
2. A constant pursuit of innovation and operational efficiency.
3. Promoting social and environmental awareness to foster water conservation and accelerate climate adaptation.
4. Adopting circular economy practices and a low-carbon development paradigm.

Sanepar also draws on past experiences with climate and environmental challenges to guide future decisions. For example, it has developed greenhouse gas (GHG) assessments to monitor the environmental impact of its operations and infrastructure. These assessments have helped identify high-emission processes, enabling targeted GHG management, reduction, and even neutralization. The findings support internal decision-making and informed the development of the utility's Mitigation and Adaptation Plan, which was based on a diagnostic using the Task Force on Climate-related Financial Disclosures (TCFD) method, developed in collaboration with the International Finance Corporation (IFC) of the World Bank Group.

A GHG assessment identified wastewater treatment as Sanepar's most emission-intensive activity, with methane from treatment plants responsible for over 90% of the utility's direct emissions (SANEPAR & Governo do Estado do Paraná 2022). These findings prompted multiple responses, including changes to the design of existing and new treatment plants to optimize performance, comply with legislation and requirements for the improved preservation of water bodies, and further reduce treated effluent discharge parameters—thus contributing to the reduction of GHG emissions.

Another response to the GHG assessment was the incorporation of flaring in the utility's anaerobic reactors and sludge biodigesters, which resulted in a 27% reduction in methane emissions from wastewater treatment plants, equivalent to approximately 330,000 tons of CO_2 (SANEPAR & Governo do Estado do Paraná 2022). Other examples include the implementation of a full-scale thermal dryer and sludge combustion system (5 tonnes/hour) using biogas and biomass at the Atuba Sul WWTP, and a co-digestion facility at the Belém WWTP that produces 2.8 MW of clean electricity from biogas.

By integrating climate considerations into operations in a robust and resourceful way, Sanepar has minimized the environmental footprint of its activities while contributing to the protection of natural resources and ecosystems.

Sanepar also recognizes the importance of natural infrastructure, such as wetlands and forests, in enhancing water quality, regulating water flow, and reducing the risk of floods and landslides. Through the preservation and restoration of these ecosystems, the utility helps buffer communities against climate impacts while delivering co-benefits such as biodiversity conservation and recreational opportunities.

Sanepar has also participated in an initiative led by Movimento Viva Água, supported by GIZ's ProAdapta project, which aims to implement Brazil's national climate adaptation agenda across government levels, the private sector, and civil society (Moviemento Viva Água & SANEPAR 2022). As part of this initiative, a multi-stakeholder strategy was developed with Sanepar to improve water quality and availability and to increase climate resilience in river basins.

Sanepar has promoted the use of decentralized sanitation systems and natural conservation measures, including the rehabilitation of degraded areas, watershed management, revitalization of urban rivers, and the use of constructed wetlands, biofilters, and decentralized wastewater treatment plants in flood-prone areas or locations exposed to contamination of receiving water bodies.

An example is the Iguaçu Water Reserve, where 150 km of nature-based solutions have been implemented, including biodiversity corridors and natural water reservoirs. These not only offer an alternative water supply during periods of scarcity but also reduce regional vulnerability by minimizing flood risk. These systems are designed to be resilient to climate impacts, providing reliable water and sanitation services even under adverse conditions. This is achieved through the use of local species that improve soil infiltration, reduce flood impacts, and support groundwater recharge.

Sanepar is also adopting a systemic approach to urban resilience by promoting circular economy principles and integration across sectors and services. This includes research and innovation to advance biogas reuse and explore the potential of renewable hydrogen for energy generation. As part of this effort, Sanepar is partnering with Universidade Federal do Paraná, CIBiogás, the Brazilian government agency Finep, and Paraná State's energy utility Copel to implement a pilot project with a production capacity of 14.5 kg of hydrogen per day, equivalent to powering three electric cars per day. This will be the first renewable hydrogen production plant in Brazil focused on the dry catalytic reformulation of biogas from wastewater (Governo do Estado do Paraná 2023). Such efforts in renewable energy generation and supply contribute to maintaining the utility's services climate-resilient, efficient and competitive.

Another way in which Sanepar promotes a circular economy is through integration with agriculture. The utility supplies treated wastewater sludge for use as a soil conditioner to enhance nutrient content and improve soil properties. This practice aims to recycle nutrients, reduce production costs and increase crop productivity. In 2022, the program reached 157 farmers distributing approximately 23,000 tonnes of sludge (SANEPAR 2023b). Since 2023, Sanepar has been evaluating a new business opportunity involving the production of high value organic-mineral fertilizer from wastewater sludge.

Sanepar is also strengthening urban water and sanitation resilience through improved solid waste management. The utility treats approximately 65,000 tonnes of household solid waste annually through landfills in seven municipalities across Paraná. It also supports environmental awareness initiatives, including the installation of waste collection points in public areas—such as beaches along the Paraná coastline—and public education on the impacts of solid waste pollution on potable and recreational water sources (Governo do Estado do Paraná & SANEPAR 2019).

Through its solid waste management activities, Sanepar helps to preserve water bodies, reduce pollution, and enhance the resilience of water and sanitation systems by maintaining water quality and availability.

Water conservation and efficiency are key components of Sanepar's strategy to mitigate the impacts of droughts and water scarcity. The utility promotes water-saving technologies, implements leakage detection and repair programs, and encourages responsible water use among customers (SANEPAR & Governo do Estado do Paraná 2022). During the recent water crisis, Sanepar implemented a range of measures, including:

During the recent water crisis, Sanepar implemented a range of measures, including:

A.

Cloud seeding, using potable water dispersed via airplanes to induce rainfall in drought-affected areas—over 20 billion liters were dispersed through 60 flights.

B.

The "Meta20" campaign, which encouraged the population to reduce water consumption by 20%—a goal that was achieved, and sustained even after the crisis.

These measures are designed to increase flexibility and redundancy in the system, enabling it to better absorb and adapt to future water crises.

Sanepar also takes an inclusive approach to building urban resilience by engaging communities to raise awareness of climate change, sanitation, water challenges, and the importance of resilience-building actions. Through educational campaigns, the utility promotes a mindset shift—from relying solely on service providers to empowering citizens to become active partners in reducing climate risks and strengthening resilience. As part of this approach, Sanepar also utilizes citizen-generated data to identify and monitor issues in the system, including water levels and pollution events (SANEPAR & Governo do Estado do Paraná 2022).

Photo: Biogas storage from anaerobic domestic sewage treatment at Atuba Sul WWTP, Curitiba, Brazil. Clean energy from methane and biomass (dried sludge and wood chips) is used to generate heat for a full scale sustainable thermal drying and combustion sewage sludge system (Credit: Sanepar).

Table 4

Sanepar's climate-resilient sanitation responses and enabling environment

Infrastructure and service provision	Users	Institution, policy, and planning	Finance
• Service delivery adapted to too little and too much water (e.g. water saving measures during droughts, and nature-based solutions for wastewater treatment and flood mitigation. • Integration across the water and sanitation cycles and other sectors, such as energy, agriculture, solid waste, to promote circular economy approaches and build systemic resilience (e.g., biogas reuse and renewable hydrogen for energy generation; wastewater sludge for soil nutrients improvement; solid waste management to reduce water pollution). • Monitoring system in place with indicators for regular review and annual reporting, providing a baseline to inform strategies and decision-making towards climate resilience.	• Promoting environmental awareness initiatives with communities, including educational programs in schools, and public campaigns to reduce water wastage to foster a mindset shift and encourage proactive environmental action. • Gathering community-generated data to monitor pollution and water levels, with the aim of empowering the population to report on climate-related issues and contribute to resilience-building.	• Sanepar produces internal documents such as its GHG inventory, Adaptation and Mitigation Plan, Integrated Report (Environmental and Climate Risk Management), which are listed in the ISE B3 (Brazil's Corporate Sustainability Index) and reports on climate change (Disclosure Insight Action) (SANEPAR & Governo do Estado do Paraná 2022). This evidence and knowledge production is used to inform climate-resilient actions.	• Investment in knowl edge generation through research and innovation to assess and implement prevention and adaptation measures (e.g. nature-based solutions in river basins) and to support disaster response efforts (e.g. water-saving actions during the scarcity crisis). • Since 2022, all capital raised by Sanepar in the financial market has received a green or blue label, with investments aligned to sustainable bond guidelines. To date, Sanepar has raised USD 320 million in compliance with IFC, SBP, GBP and SBG requirements, helping to reduce its cost of equity and to ensure its financial stability. The utility is rated AAA(bra) by relevant credit rating agencies.

The Outcomes

Sanepar has built its climate risk management approach on a foundation of research, innovation, and a mature internal strategy.

It's an approach aimed at maintaining the quality and availability of water resources across its operations. Through close monitoring of environmental and climate risks, the utility has generated high-quality data, evidence, and knowledge that informs internal decision-making and contributes to broader sectoral discussions. Sanepar plays a thought leadership role in Brazil on ESG issues in the water and sanitation sector, demonstrated through its participation in national climate action planning for municipalities, cross-learning with other utilities, and collaboration with international stakeholders—including projects on climate resilience with GIZ and the World Bank Group.

Sanepar's initiatives have also delivered resilience co-benefits across sectors, including the generation of energy from methane and hydrogen, the use of treated wastewater sludge to improve soil health in agriculture, and solid waste management that helps prevent contamination of water bodies. These actions have produced measurable environmental impacts, including reductions in GHG emissions from wastewater treatment processes and effluent discharges, while contributing to broader ecosystem resilience.

Sanepar's efforts to address climate change and build resilience have also enhanced its reputation for ESG leadership. The utility has received multiple awards and certifications, including:

- A Gold Stamp for its GHG inventory from the Brazilian GHG Protocol Program
- A 'Classification A-' rating from CDP Disclosure Insight Action for climate change reporting
- Recognition as the most innovative utility in Brazil's infrastructure sector for the last three years through the Brazil Innovation Award (SANEPAR & Governo do Estado do Paraná 2022).

Key Capacities of Resilience

The case study of Sanepar illustrates elements of absorptive, adaptive, and transformative capacity.

The strongest emphasis is on transformative capacity due to the systemic, forward-looking, and innovative approaches embedded in its strategies.

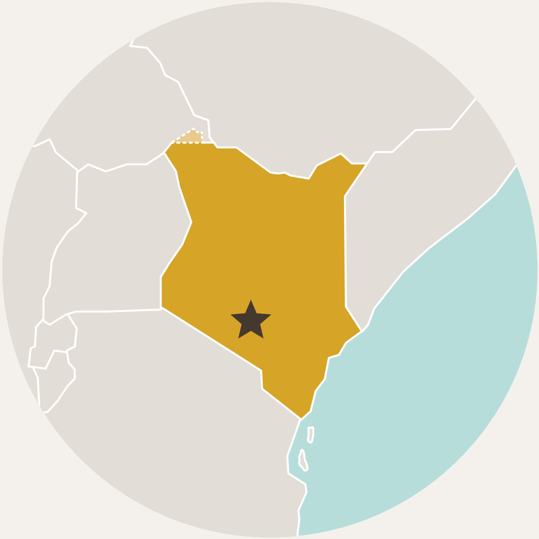
Transformative Capacity
Sanepar exemplifies transformative capacity by integrating climate considerations into its strategic planning, operations, and infrastructure development at a systemic level. Through the development of GHG assessments, the utility has identified the primary sources of emissions within its operations, enabling targeted management, reduction and neutralization of these emissions. The adoption of circular economy principles, such as biogas reuse for renewable hydrogen production, sludge recycling for agricultural applications, and integrated solid waste management, reflects a fundamental reimagining of the water and sanitation system. These efforts extend beyond short-term responses to climate risk, laying a foundation for long-term resilience and sustainability. Initiatives such as nature-based solutions in the Iguaçu Water Reserve and the deployment of decentralized wastewater treatment systems represent transformative shifts in infrastructure design, addressing both water scarcity and flooding.

Transformative Adaptation
Sanepar's development of partnerships with research institutions, the private sector, and international stakeholders to pilot advanced technologies, such as renewable hydrogen production, further demonstrates its commitment to transformative adaptation. These systemic innovations not only build climate resilience but also contribute to reducing GHG emissions, ecosystem health, and generate additional social and economic co-benefits, including support to the agriculture and energy sectors.

Transformative Financing
Finally, Sanepar's ability to leverage green and blue capital market funding aligns with a transformative financing model, reducing dependency on traditional mechanisms and enabling sustained investments in climate-resilient infrastructure.

Photo (right): Iguaçu Wastewater Treatment Plant (Credit: Sanepar).

4. Nairobi



KEY ASPECT

Home to some of the largest and most vulnerable informal settlements in Africa, Nairobi is where residents face significant challenges related to basic services and heightened climate change risks. Recent improvements in water supply and sanitation have been implemented as part of broader slum upgrading programs. This integrated approach has created space for innovation and demonstrated the impact and scalability of climate-resilient sanitation solutions.

Key information

Location	• Mukuru (Nairobi, Kenya)
Income Group	• Low-income country and informal settlements
Stakeholder	• Utility • Local government • Social enterprise
Hazards	• Flooding • Water scarcity/drought
Sanitation Characteristics	• Mixed (sewered, non-sewered; centralized, decentralized)
Sanitation failures covered by the climate-resilient solution	• Containment • Wastewater (WW) delivery to treatment • WW treatment • Fecal Sludge (FS) delivery to treatment • FS treatment
Other sectors that benefit from the response	• Water supply • Agriculture
Resilience capacities displayed by the case study	• Absorptive • Adaptive

Context and Challenges

Nairobi is a fast-growing capital city whose population rose from 4.4 million in 2019 (KNBS 2019) to an estimated 5.5 million in 2024 (Macrotrends 2024).

The city is experiencing significant climate change impacts including rising temperatures combined with more erratic rainfall leading to longer and more frequent droughts, as well as extremes in precipitation resulting in a greater risk of flooding, especially in low lying areas of the city. Demand for water currently outstrips supply and government efforts to tackle this water crisis are focused on diversifying water sources and reducing pollution by investing in improved sanitation.

Article 43(1)b of the 2010 Kenyan Constitution stipulates that “Every person has the right to accessible and adequate housing and to reasonable standards of sanitation”. Kenya Vision 2030 provides the national development framework through 2030, including a commitment to conserve and diversify water sources, and achieve universal access to water supply and sanitation services. It requires mandate holders to work towards the equitable distribution of water, sewerage and sanitation services within their jurisdiction.

As of 2020, sewerage coverage in Nairobi City stood at approximately 51% (Cytonn Investments 2022). However, not all wastewater entering the sewer network is treated, resulting in untreated discharges into the environment. In informal and low-income settlements, where an estimated 60%-70% of the city’s population resides, access to improved sanitation remains limited. These areas rely heavily on onsite sanitation facilities, and open defecation remains a common practice.

The Nairobi City County Government (NCCG) is working to increase sanitation across the city through a combination of approaches aimed at enhancing the resilience of low-income communities and reduce their social, economic and environmental vulnerability. These include the expansion of the conventional sewer network and the adoption of alternative service delivery models, such as simplified sewers, onsite sanitation (OSS) and fecal sludge management (FSM) systems (NCCG 2018), particularly in areas where traditional sewerage is not feasible or prohibitively expensive.

The Responses

Mukuru is one of the largest informal settlements in Nairobi and one of the most affected by climate change impacts.

It is situated in a low-lying area that is vulnerable to heavy flooding and this, combined with indiscriminate solid waste dumping and inadequate sanitation and drainage, significantly increases the public health risks faced by its inhabitants.

Upgraded Slum Development and Simplified Sewerage Systems

Improvements to sanitation have been prioritized by Mukuru residents for over a decade. In 2013, women and girls demanded improved sanitation through the 'Too Pressed to Wait' campaign. However, it wasn't until 2017, when NCCG and the National Government created the Mukuru Special Planning Area (SPA), that significant progress in upgrading sanitation was initiated. 'Water, Sanitation and Energy' was grouped as one of eight priority sectorsto be included in the settlement upgrading plan.

Involving residents was central to the planning process. They were engaged in a two-year process to profile and "enumerate" their needs and vulnerabilities and to develop appropriate solutions through a participatory and multisectoral planning process. This created critical local ownership and leadership, reduced the need for displacement, and resulted in integrated solutions for intersecting problems.

Community-led mapping found that there were only 3,800 toilets, mostly pit latrines, serving a population of 400,000 people. This equates to more than 105 people per toilet; far exceeding the recommended standard of a maximum of four families, or 20 people, per toilet to maintain adequate hygiene. Latrines were generally emptied manually, with fecal waste dumped uncontrolled into the environment. To address this issue, residents proposed the construction of additional shared toilets and connecting them to the sewer network.

In practice, conventional sewers require substantial space and are costly to build. They are also vulnerable to blockages when water availability is reduced. Simplified sewer systems (SSS) have been piloted in Mukuru as a more climate-resilient alternative to conventional sewers, alongside shared toilet facilities. Simplified sewer systems offer a lower-cost, flexible sanitation solution that requires less water to function, making them well-suited to water-scarce contexts. They are appropriate for densely populated low-income urban settlements since they can be laid in close proximity to users' properties, allowing for higher household connection rates to be achieved.

The SSS pilot constructed 5 km of simplified sewers; a further project, funded by the African Development Bank, is constructing an additional 35 km of sewers. The settlement upgrading plan for Mukuru targets a total of 170 km of simplified sewers. However, securing funding to build this additional infrastructure remains a key barrier to replicating the model in other informal settlements. The pilot was undertaken within the framework of the SPA process. and there is currently little evidence that Nairobi Water and Sewerage Company (NWSC) plans to mainstream SSS in other parts of Nairobi (GCA 2022).

Sanitation Improvements were made alongside upgrades to water supply, solid waste management, and drainage. The combination of interventions developed through the SPA process has led to a clear improvement in living conditions in the settlement. Residents have played an active role in monitoring progress on the upgrading plan and in assessing the impact of water supply and sanitation improvements.

Container Based Sanitation (CBS)

Another effort to introduce climate-resilient sanitation and support universal access in Nairobi is the container-based sanitation (CBS) services provided by the social enterprise Fresh Life/Sanergy. This model offers a waterless toilet for clusters of households and in public areas, which are properly managed by local residents. Fecal waste is regularly collected, treated, and reused—ensuring it is not discharged untreated into the environment.

Fresh Life works with municipalities, utilities and residents to deliver safe, equitable and sustainable sanitation, particularly in underserved, low-income areas. The model involves deploying low-cost container-based toilets, and providing regular collection and waste treatment services managed by Fresh Life's sister company, Regen Organics, which converts waste for agricultural use. This system closes the sanitation loop, returning nutrients to soil that would otherwise be lost. In addition, actively managing fresh waste reduces the likelihood of bad odors and methane emissions. The system also uses less water than conventional onsite toilets or flushed sewer systems.

The CBS service model was developed in collaboration with users to understand their needs and acceptability of different service steps, in response to a perceived gap in the market. The company maintains ongoing communication with users through mobile technology, such as logging maintenance data. Expansion into new locations begins with a pilot phase to facilitate feedback from users and communities.

In Nairobi, Fresh Life operates as a private service offered in parallel to municipal water supply and sanitation services. In contrast, in Kisumu, a city adjacent to Lake Victoria, Fresh Life is sub-contracted by the Kisumu Water and Sewerage Company (KIWASCO) and is therefore a component of KIWASCO's broader plan to achieve citywide sanitation coverage.

When Fresh Life established operations in Kenya, it needed to demonstrate proof of concept before partnering with utilities. This was achieved with the County's support, but was implemented independently of the city's sanitation improvement plans. In the case of Kisumu, Fresh Life was able to offer a proven service model that aligned with and contributed to addressing sanitation challenges identified by KIWASCO and other local stakeholders in their planning processes.

The two main barriers to further expansion of the CBS model, both in Nairobi and in other cities, are institutional and financial. Although the Kenya Environmental Sanitation and Hygiene Policy allows for the use of container-based sanitation (FAO 2016), the system has not been explicitly recognized or regulated by the Water Services Regulatory Board (WASREB). This lack of clarity regarding the acceptability of the service delivery model for both users and service providers creates a barrier to its further rollout.

Fresh Life continues to engage with national stakeholders, municipalities and utilities to build more understanding of the model and to advocate for its recognition and adoption in support of climate-resilient sanitation. Financially, although user fees cover the operating and maintenance costs of the Fresh Life service, initial investments—such as the purchase of the toilets and other aspects of managing the full sanitation service chain—still require public, private, or development partner support.

Fresh Life is working with the Container Based Sanitation Alliance (CBSA) to develop a methodology for calculating the climate mitigation potential of CBS services, with the aim of unlocking climate finance through credit mechanisms.

Table 5

Nairobi's climate-resilient sanitation responses and enabling environment

Infrastructure and service provision	Users	Institution, policy, and planning	Finance
· Two sanitation technologies have been piloted in Nairobi to increase climate resilience and help climate mitigation in low-income settlements: **Simplified sewer systems (SSS)** SSS have a reduced risk of failing during flooding compared to conventional sewerage systems. This lowers the risk of the spread of water- and excreta-related diseases, and provides a viable alternative in water scarce contexts. **Container-based sanitation** Delivered by Fresh Life and Regen Organics, these services are actively managed and follow a circular model, with treated waste products reused in agriculture. They also require less water than conventional toilets.	· Service users (households) were actively involved identifying priority issues and designing solutions included in the Mukuru upgrading plan; they also participated in monitoring progress and outcomes of water supply and sanitation investments. · The CBS model is co-designed with users to ensure it meets their needs and is socially acceptability; mobile technology is used to log and monitor maintenance issues.	· Kenya Vision 2030 commits to conserving and diversifying water sources and achieving universal access to WSS. It requires mandated holders to work toward equitable WSS service provision. · WASREB recommends simplified sewer systems for urban sanitation. Container-based sanitation is not yet formally recognized or regulated by WASREB but has received specific permissions from NEMA and WASREB, and is permitted under the Kenya Environmental Sanitation and Hygiene Policy. · Climate-sanitation linkages remain limited in county and utility-level planning. In 2023, Nairobi City County's Water and Sanitation Services Policy was reviewed to align with the National Water Policy 2021 (NCC 2023). However, the County Integrated Development Plan lacks concrete links between climate adaptation and sanitation, and NCWSC's investment plans include only limited, general references to sanitation-climate linkages.	· Models such as CBS services require some level of external funding (as do many conventional sanitation systems, including sewerage and wastewater treatment). The majority of associated costs would need to be covered by the public sector or through a sanitation surcharge to reduce dependence on external funding. · The potential to leverage carbon credits for CBS service provision is currently being explored by container-based sanitation entrepreneurs.

The Outcomes

Integrated slum upgrading in the Mukuru Special Planning Area in Nairobi City County has facilitated holistic improvements in basic service provision in this low-income area.

The applicability and scalability of SSS has been demonstrated, leading to further investment for its expansion within the settlement. Because SSS uses reduced amounts of water, its application also supports efforts to address water scarcity and enhance climate resilience in the city. WASREB has formally adopted SSS as an alternative to conventional sewerage in urban contexts, enabling other cities facing similar water scarcity issues to consider SSS within their jurisdictions.

Other efforts to promote climate-resilient sanitation in Nairobi have focused on the active management of fecal waste. The Fresh Life model, a CBS approach, ensures the regular collection, treatment, and conversion of fecal waste into agricultural reuse products as well as compressed fuel briquettes. This model not only improves sanitation outcomes but also contributes to climate change mitigation. By actively managing waste, it reduces methane emissions, while the reuse products serve as sustainable alternatives to traditional fuels and chemical fertilizers, further reducing carbon emissions.

Fresh Life estimates that its CBS services offset 24,000 tCO_2eq annually, which over five years would be equivalent to removing 36,000 cars from the road. Recognizing this environmental impact, Sanergy's circular sanitation model has been accredited for carbon credit issuance, creating an additional financing stream to support further expansion. These carbon credits are certified under the Verified Carbon Standard, reinforcing Sanergy's commitment to quantifying, verifying, and scaling its climate benefits.

Key Capacities of Resilience

The Nairobi case study highlights elements of absorptive, adaptive, and transformative capacity in its sanitation-related climate responses.

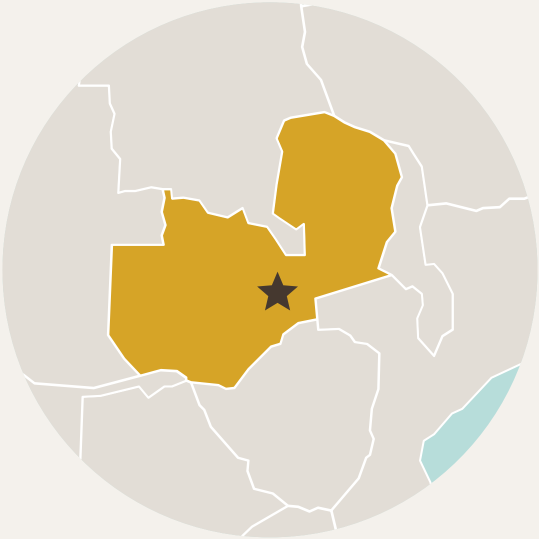
Absorptive Capacity
The CBS model ensures the regular removal and treatment of fecal waste, preventing environmental contamination and reducing immediate public health risks in informal settlements.

Adaptive Capacity
The implementation of SSS and CBS in Mukuru represents an adaptive response to water scarcity, as both systems require less water and are more cost-effective than conventional sewer networks. The Fresh Life CBS model also exemplifies adaptive innovation, filling gaps in traditional service delivery in underserved areas. By applying circular economy principles, CBS addresses resource constraints while delivering co-benefits, including climate mitigation—thus overlapping with transformative capacities, as described below.

Transformative Capacity
The SPA designation facilitated an integrated, multi-sectoral upgrading approach, combining improvements in sanitation, housing, drainage, and solid waste management. This reflects a shift toward systemic thinking and integrated urban development. The successful development of circular economy products and carbon credits for CBS services demonstrates a forward-looking approach that could unlock new funding streams for sanitation.

However, these transformative adaptation efforts remain nascent and face significant barriers, including limited institutionalization and funding challenges for scaling adaptive infrastructure, such as SSS and CBS, in low-income areas.

5. Lusaka



KEY ASPECT

Strategic investment in sanitation in Lusaka has allowed the water and sanitation utility to actively manage onsite sanitation and fecal sludge management services in peri-urban areas, reducing the risk of groundwater contamination and the potential for disease outbreaks.

Key information

Location	• Peri-urban areas of the city of Lusaka, Zambia
Income Group	• Low-income country
Stakeholder	• Utility • Local government • National government • Lusaka Sanitation Programmed-Project Implementation Unit (LSP-PIU)
Hazards	• Flooding • Water scarcity/drought
Sanitation Characteristics	• Mixed (sewered, non-sewered; centralized, decentralized)
Sanitation failures covered by the climate-resilient solution	• Containment • Fecal Sludge (FS) delivery for treatment • FS treatment
Other sectors that benefit from the response	• Water supply • Solid waste
Resilience capacities displayed by the case study	• Adaptive

Context and Challenges

Climate change is having a direct and pronounced impact on Lusaka, the capital of Zambia.

Rising temperatures and more frequent and prolonged droughts—in a country heavily reliant on hydropower—has caused serious water shortages as well as power outages. Lusaka also depends on groundwater for up to 60% of its water supply, making the protection of this resource critically important.

According to the latest census, Lusaka is growing at around 2% per year, driven by both natural population growth and inward migration of people from rural areas affected by climate change. Around 70% of Lusaka's 2.4 million people live in peri-urban areas (PUAs), where access to improved water and sanitation services is limited. Ninety percent of Lusaka's population relies on onsite sanitation (OSS) for their sanitation needs.

Flooding is a regular challenge in the PUAs due to a combination of intense rainfall, poor drainage and network blockages linked to inadequate solid waste management. Flooding impacts sanitation infrastructure by causing the collapse of pit latrines, overflow of fecal sludge from containment structures, and other forms of untreated waste discharge, including wastewater, into the environment (AfDB 2015). As a result, Lusaka experiences annual disease outbreaks including cholera, typhoid and dysentery with a major cholera outbreak reported in early 2024 (AfDB 2015).

Improving sanitation and solid waste management has been consistently prioritized in the city's development plans, and climate resilience is recognized as a cross-cutting issue. Key stakeholders, Lusaka City Council (LCC) and Lusaka Water Supply and Sanitation Company (LWSC), in collaboration with development partners—including the World Bank (WB), the African Development Bank (AfDB), the European Investment Bank (EIB), KfW and the Bill & Melinda Gates Foundation (BMGF—have designed and are implementing the Lusaka Sanitation Program (LSP). Alongside investments in offsite sanitation infrastructure, the LSP also aims to improve environmental sanitation conditions in PUAs by introducing climate-resilient onsite sanitation systems and promoting the active management, treatment, and safe disposal of septage and fecal sludge.

The Responses

Maintaining potable water quality has become a top priority in Lusaka.

The city relies heavily on groundwater, and while the aquifer is shallow and recharges rapidly, this also makes it highly vulnerable to contamination. This vulnerability is especially acute in areas where the aquifer is most shallow—coinciding with the city's largest PUA—where most households rely on unlined pit latrines, and where the risk of flooding is high. As a result, sanitation improvements to have become a central component of Lusaka's recent multi-sectoral development plans aimed at enhancing urban and climate resilience.

Responsibility for improving urban sanitation and protecting groundwater lies with the LWSC. Universal sanitation coverage is a key goal of Zambia's 'Vision 2030' plan and is reflected in LWSC's Master Plan, which aims to achieve citywide sanitation coverage by 2035. To meet this target, LWSC has undertaken two major initiatives:

1. Integration of OSS and FSM into its core business, formalized by the approval of OSS strategy in 2017.
2. Design and implementation of the LSP to help meet their Master Plan targets. The LSP includes interventions to improve both on- and off-site and sanitation, including the rehabilitation of sewer networks, upgrading of two wastewater treatment plants, household and institutional toilet upgrades in PUAs, and improvements to FSM services.

A key focus of the LSP has been reducing the vulnerability of onsite sanitation facilities to flooding in high-risk PUAs. Users were consulted, and their preferences were reflected in the design and costing of sanitation facilities. To reduce flood risk, toilets were elevated above ground and containment units were fully sealed and impermeable. The facilities were also designed to allow for easy emptying. A range of models at different price points was developed and demonstrated, and subsidies were offered to households upgrading their toilets. Over 5,500 household toilets were constructed in the PUAs of Chawama, George and Kanyama, where Water Watch Committees continue to support community-based monitoring of water and sanitation situation services.

In parallel, LWSC established an FSM Unit and began collaborating with the private sector to actively manage fecal sludge. The unit ensures that sludge is safely and routinely removed from PUAs and treated at fecal sludge treatment plants (FSTPs). Two such plants were constructed at Manchinchi and Matero.

To facilitate FSM service delivery, Lusaka was divided into three operational zones (North, Centre and South). Private operators competed for performance-based contracts with LWSC. Twelve emptying teams (four per zone) were selected. Customers were encouraged to use these services through the introduction of a subsidized, affordable fee. Private operators were compensated for the difference between the user fee and the actual cost of service provision—including a reasonable profit margin—through a subsidy provided by LWSC, funded by the World Bank and, more recently, the Gates Foundation. This innovative financial mechanism led to a notable increase in FSM service uptake, which has been sustained even as the subsidy has been progressively reduced, with households now paying a larger share of the total cost.

Nevertheless, LWSC recognizes that affordability remains a key challenge, particularly for residents in PUAs. The utility is exploring different mechanisms to support regular use of FSM services, including the introduction of a sanitation surcharge. This issue mirrors challenges seen in other LIC contexts, including those using CBS services, and has led to increased recognition among practitioners and utilities of the need for additional funding from sources such as sanitation surcharges. These have already been implemented in Mozambique, and Zambia now plans to introduce a similar approach.

Beyond the direct outcomes, the LSP has also created opportunities for LWSC to develop new service delivery models and to demonstrate the feasibility of toilet upgrades and FSM services in PUAs across Lusaka. However, several constraints to scaling these models remain:

1. An estimated 60,000 additional climate-resilient toilets are needed.
2. A financial gap persists between the cost of FSM service delivery and household ability to pay. LWSC is considering applying a sanitation surcharge to water bills, allowing households to spread payments over time and receive scheduled emptying services.
3. Enforcement of existing standards remains weak even though the regulator, the National Water Supply and Sanitation Council (NWASCO), has published a technical framework to regulate OSS and the National Building Code includes standards for OSS.

Table 6

Lusaka's climate-resilient sanitation responses and enabling environment

Infrastructure and service provision	Users	Institution, policy, and planning	Finance
· 5,500 climate-resilient toilets have been built under the LSP, with an estimated additional 60,000 toilets still in need of upgrading. · Investment in emp tiable toilets and active FSM market management by LWSC has led to greater uptake of emptying and transport services among households that can afford those services. · Additional FS treatment capacity has been introduced—two plants each with the capacity to treat 25 m³/day of sludge and 160 m³/day of septage. However, the volume of sludge currently emptied and transported manually to these sites is around 67 m³/day,[3] highlighting the need for further expansion of treatment facilities.	· Users were consulted during the toilet design process and provided with physical examples at the selection stage through demonstration centers. · Subsidies are provided to enable households to complete toilet upgrades. · Users are involved in the on-going monitoring of water and sanitation services in their areas through Water Watch Committees.	· Zambia's 'Vision 2030' includes a goal of universal access to water supply and sanitation. · NWASCO has devel oped a technical framework for Urban Onsite Sanitation and Faecal Sludge Management; utilities are required to provide OSS and FSM services within their jurisdictions. · Sanitation is included in urban development plans for Lusaka, and climate resilience is considered a cross-cutting issue. · LWSC's Master Plan aims to achieve universal access to improved sanitation by 2035. · Capacity to enforce Onsite Sanitation standards and Fecal Sludge Management standard operating procedures remains weak.	· The FSM service subsidy mechanism has increased household willingness to empty containment structures. Even as the subsidy has been reduced, customers who can afford the service continue to use it; however, subsidies remain necessary to ensure continued uptake by lower-income households. · Ability to pay remains a challenge. Scheduled emptying, combined with a sanitation surcharge on water bills, is being considered as a means for customers to spread payments over the year.

3 Key informant interview.

The Outcomes

Over the last 10 years, LWSC has worked to improve OSS and FSM in peri-urban areas of Lusaka.

At the same time, Lusaka City Council (LCC) has focused on improving solid waste management and drainage. Together these efforts have contributed to enhancing the overall climate resilience of these communities and reducing the risk of groundwater contamination.

LWSC progressively took on its OSS and FSM mandate, beginning with the development of an OSS strategy through which these services were formally incorporated into the utility's master plan. With this foundation, the utility was able to secure funding from multiple donors for the Lusaka Sanitation Programmed (LSP). This support enabled the utility to build institutional capacity for active management of OSS and FSM, expand access to improved sanitation in targeted PUAs, and ensure the safe treatment of collected fecal waste and septage.

LWSC has developed context-appropriate service delivery models that reflect the needs of its customer base and hold potential for scaling. However, with the end of the LSP, LWSC now faces the challenge of developing sustainable financing mechanisms to continue investing in improved sanitation facilities and to support further development of the fecal sludge and septage emptying and transportation market.

Key Capacities of Resilience

Adaptive Capacity

Adaptive capacity is the strongest dimension demonstrated in Lusaka's responses, reflecting the city's efforts to modify and expand sanitation systems in response to evolving climate challenges and urban growth. Examples include:

1. The construction of 5,500 raised, fully sealed toilets in flood-prone peri-urban areas (PUAs), which reduces contamination risks during flooding. These facilities help protect groundwater and public health by safely containing fecal waste under challenging environmental conditions.
2. LWSC's integration of OSS and FSM services into its business model and master plan, addressing the widespread reliance on pit latrines in PUAs. The establishment of FSM services, including the construction of two fecal sludge treatment plants and performance-based contracts for private emptying operators, ensures the regular removal and treatment of waste. This shift represents an important adaptation to the realities of Lusaka's urban landscape and climate risks.

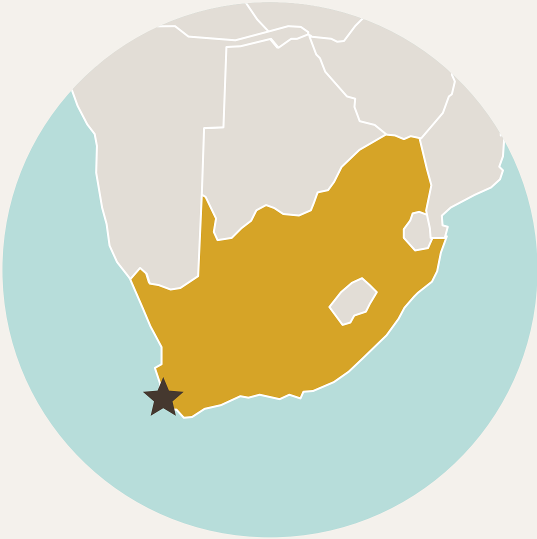
These adaptive measures have strengthened Lusaka's ability to address the systemic and climate-induced challenges facing its sanitation system. However, affordability constraints and regulatory enforcement gaps continue to limit their scalability and long-term impact.

Transformative Capacity

While less prominent, there are emerging signs of transformative capacity in Lusaka's sanitation initiatives. For example, the Lusaka Sanitation Program (LSP) includes interventions across the entire sanitation chain, from household toilets to treatment plants, reflecting an integrated citywide approach to sanitation services. However, financial and regulatory barriers limit the potential for broader impact. The city's reliance on external funding for infrastructure and service subsidies underscores the need for sustainable financing mechanisms to support scaling and long-term resilience.

Photo (right): Rehabilitated stormwater drainage channel (Credit: Lusaka Water and Sewerage Company).

6. Cape Town



KEY ASPECT

Cape Town's Water and Sanitation Department has implemented new climate-resilient strategies to address the impacts of water scarcity and flooding on the city's sanitation systems. These efforts are supported by the department's ongoing transformation into a more customer-oriented and financially stable utility.

Key information

Location	• Cape Town, South Africa
Income Group	• Upper middle-income country
Stakeholder	• Utility • Local government
Hazards	• Flooding • Water scarcity/drought
Sanitation Characteristics	• Mixed (sewered, non-sewered; centralized, decentralized)
Sanitation failures covered by the climate-resilient solution	• Containment • Wastewater (WW) delivery to treatment • WW treatment
Other sectors that benefit from the response	• Water supply • Stormwater
Resilience capacities displayed by the case study	• Absorptive • Adaptive • Transformative

Context and Challenges

Treated wastewater reuse has been prioritized to support the city's goal of diversifying water sources, while ensuring safe access to sanitation in informal settlements remains a key focus under Cape Town's water resilience strategy.

The legislative capital of South Africa and home to more than 4 million people (Western Cape Government 2022), Cape Town is already experiencing the effects of climate change on water supply and sanitation service provision. Located in a water scarce region, drought has been an ongoing challenge for the city. In 2018, Cape Town narrowly avoided 'Day Zero', when it was projected to run out water, by reducing its water consumption by nearly 50% (Arup 2018b).

Water scarcity has also impacted the city's sanitation systems. During extreme drought periods, reduced flows in the city's water supply have led to blockages in communal toilets and failures in the centralized sewer networks. Wastewater treatment plants have struggled to operate effectively under the higher influent loadings associated with these reduced flows (Mikhael et al. 2021).

Climate change is also causing rapid-onset flooding, particularly in informal settlements, many of which are located in flood-prone areas. When flood waters flow into the sewer networks, they pose public health and environmental risks due sewer overflows and the inability of wastewater treatment plants to cope with the increased flows.

In addition to these climate-related challenges, Cape Town's sanitation systems face existing constraints. Three of the city's wastewater treatment plants are at capacity limiting further urban development in their service areas. Failures in aging sanitation infrastructure (including pumping stations, sewers and wastewater treatment plants) along with sewer blockages caused by illegal garbage dumping and/or stormwater discharge have resulted in spills that pollute inland water bodies (CCT 2022).

Water and sanitation services are provided and regulated by the City of Cape Town. The city's Water and Sanitation Department is responsible for onsite sanitation, fecal sludge management and wastewater management, including conveyance and treatment. The department manages 9,000 km of sewers, 17 wastewater treatment plants and six smaller wastewater systems, collectively providing centralized sanitation services to the 89% of city residents who use flush toilets, and onsite services for the 2% who rely on septic tanks.

In line with the city's water resilience strategy, Our Shared Water Future (2019), Cape Town has committed to ensuring safe access to water and supply sanitation services for all, including those in informal settlements. While the city reports adequate access to sanitation for all households in informal settlements, this is based on the National Basic Sanitation policy definition, which requires at least one shared toilet per five households. The city has prioritized the installation of flush toilets connected to the sewer system, and wherever this is not feasible, has provided container-based solutions.

The Responses

The threat of Day Zero prompted the City of Cape Town to increase the climate resilience of its water supply and sanitation services.

This process began with the development of a water resilience strategy, built on five commitments, three of which are particularly relevant to this case study:

1. Safe access to water and sanitation—with particular care for communities in informal settlements.
2. Sufficient reliable water from diverse sources—which includes water reuse.
3. A water-sensitive city—optimizing the use of stormwater and urban waterways for flood control, aquifer recharge, water reuse and recreation.

The strategy applies a systems approach to the water cycle and includes clear commitments to sanitation. City authorities recognized that delivering on the strategy's vision would require collaboration between citizens and institutions, grounded in trust, transparency and accountability. This principle has been key to Cape Town's success in advancing climate resilience in water and sanitation systems.

To operationalize the strategy, the City began transforming the traditionally engineering-focused Water and Sanitation Department into a modern, customer-oriented and financially stable utility (CCT 2019). Several new branches were created, including a Commercial Services arm focused on customer service, capital and contract management, and finance. This Department also incorporated catchment, stormwater and river management into its mandate and established a dedicated Informal Settlements Basic Services branch.

Under Commercial Services, a new customer services team was created to regain customer trust and improve customer satisfaction—seen as essential to the sustainability of service provision. Measures introduced included:

1.

Updating the Customer Relations Management policy for water and sanitation services.

2.

Implementing multi-platform, multi-language communication with customers.

3.

Enhancing the performance of the department's Contact Centre.

4.

Improving customer surveys and accessibility of results.

To improve financial stability, the Department revised its water tariff model. The previous model was based solely on the volumetric charges, whereas the new structure includes a fixed charge (based on water meter size) and a volumetric component. The fixed charge currently covers around 25% of fixed service costs. This new system has improved revenue predictability and ensured sustained funding for capital and operational costs, even during drought periods. Combined with improved customer satisfaction, the new tariff system increased the revenue collection ratio to 93%, bolstering the Department's financial stability and enabling continued investment in climate-resilient initiatives.

In contrast, the sanitation tariff remains based on a percentage of metered water use varying by residence type. Recognizing the vulnerability of this model to fluctuations in consumption, the city is exploring more resilient sanitation tariff structures.

One of Cape Town's key strategies for addressing water scarcity has been the diversification of water sources, including treated wastewater reuse for non-potable, potable, and aquifer recharge purposes. Thirteen wastewater treatment plants are equipped to produce treated effluent suitable for non-potable reuse. A 230 km non-drinking water network conveys this water to customers for irrigation and industrial use, delivering 50 million liters per day (MLD). Treated wastewater is priced below potable water to encourage uptake (CCT 2018).

The city is also piloting potable reuse. At the Zandvliet demonstration plant, commissioned in 2019, up to 10 MLD of advanced purified water is produced. An independent expert panel supports plant operations and advises on plans for a large-scale 70 MLD facility at the Faure Water Treatment Plant and reservoir (CCT 2023).

To meet its commitment to safe sanitation for all, the city provides multiple sanitation options in informal settlements. Wherever possible, shared flush toilets connected to the sewer network are prioritized. Where this is not feasible, non-sewered solutions are offered: chemical toilets, container toilets, or portable flush toilets (PFTs). Challenges to installing shared flush toilets include flooding, water supply constraints, dense urban layouts, land tenure issues, and physical site conditions (e.g., rocky soil, water bodies, high water tables) (GreenCape 2023).

The non-flushing toilets are not explicitly driven by climate goals but do offer climate resilience benefits. Being above-ground, sealable, and regularly emptied, they are less vulnerable to flooding. The city uses GIS mapping to identify informal settlements at risk and prioritize deployment accordingly.

Among non-sewered options, only PFTs are used at the household level; chemical and container toilets are shared facilities. All are managed by private service providers, who are also responsible for daily cleaning of the shared units. PFT tanks are collected three times weekly. Providers must employ local labor from the served communities. All waste is transported to wastewater treatment plants, with no reuse currently taking place. The services are free to users, and costs are covered by the city. PFTs and container toilets are owned by the city, while chemical toilets are rented.

While generally accepted, challenges remain. Design flaws in imported containers and PFTs—such as insufficient sturdiness for heavier users and poor performance when full—have been reported. Only one PFT design exists, which is not adapted for children. Community consultations have called for better reporting channels to raise complaints. The city is exploring alternative toilet models and developing service provider standards. A National Water and Sanitation Servicing Standards document has been released for public comment. These initiatives aim to ensure service quality, even as contracts rotate (contract durations are governed by the Municipal Financing Management Act and are typically 36 months).

The Water Resilience Strategy also addresses existing infrastructure challenges. The Department is rehabilitating 100 km of sewer lines per year to reduce spills and blockages, and improve inland water quality. It is upgrading wastewater treatment plants, enhancing energy efficiency, and modernizing pumping stations. Improved monitoring and reporting systems now support rapid response and preventive maintenance, including sediment removal from sewers. In areas where treatment capacity limits development, the city allows developers—under a standard operating procedure—to install decentralized (package) treatment plants, while continuing to expand citywide capacity.

The development and implementation of Cape Town's Water Resilience Strategy was made possible by strong support from city leadership, particularly the Mayor's Office. The office convened stakeholders to develop an integrated drought response and established new structures for inter-departmental coordination. It began by creating a Strategy Policy Branch to lead resilience planning across departments. This has since evolved into the Future Planning and Resilience Office, which now oversees the integration, coordination, and monitoring of citywide resilience plans, ensuring Cape Town remains responsive to both immediate risks and long-term challenges.

The Outcomes

The transformation of Cape Town's Water and Sanitation Department into a commercially oriented and trusted utility has provided the financial stability needed to implement the climate-resilience measures required across water and sanitation systems.

With the establishment of a new commercial arm, the department has improved its overall financial performance, and measures aimed at improving customer management have led to positive outcomes, including increased customer satisfaction, as indicated by a decrease in customer complaints. The collection ratio improved to 93% in 2022, up from 80% in 2018, and—together with the new tariff system—this has contributed to the department's financial sustainability.

The reorganized department has also joined GWI's 'Leading Utilities of the World', a global network of the most successful and innovative water and sanitation utilities. Membership provides a platform for knowledge exchange with other leading utilities internationally. The climate resilience initiatives implemented by the department have brought Cape Town closer to the goals outlined in its Water Resilience Strategy. The city is now on track to deliver 300 million liters per day (MLD) of additional water by 2030 through the diversification of water sources. Currently, 8% of all water used in the city is recycled. The use of treated wastewater for non-potable and potable purposes is gaining public acceptance.

The success of the pilot potable reuse purification plant has led to the design and planning of a large-scale permanent plant, supported by an expert advisory committee. Meanwhile, sanitation system upgrades are also contributing to the city's resilience goals: there has been a 25% reduction in sewer spills between 2020 and 2022, and the increased capacity of wastewater treatment plants is helping the city manage higher flows, thereby reducing impacts on inland water quality.

Table 7

Cape Town's climate-resilient sanitation responses and enabling environment

Infrastructure and service provision	Users	Institution, policy, and planning	Finance
• Thirteen wastewater treatment plants produce treated effluent suitable for non-potable reuse, helping to reduce reliance on potable water. • Piloting wastewater reuse for potable purposes, with plans to develop a large-scale plant. • Treated wastewater is injected into the Cape Flats Aquifer to store water and create a barrier against sweater ingress and pollutant intrusion. • Alternative sanitation solutions, including container toilets, chemical toilets and portable flush toilets, are provided in flood-prone informal settlements where full-flush toilets are not feasible. • Upgrades to the centralized sewer network, pumping stations and wastewater treatment plants are improving system resilience while addressing existing non-climate related issues.	• Proactive customer management approach implemented to regain customer trust. • Indigent residents receive a monthly free allocation of water supply and sanitation. • Rebates on water and sanitation rates are available for domestic customers, as well as for schools, churches, charities, homeless shelters, facilities for the physically/mentally challenged, old age homes, and other vulnerable groups. • Engagement with residents of informal settlements to understand how sanitation infrastructure and services can be improved. • Public awareness campaigns focused on the causes of sewer blockages and promoting wastewater reuse. • The City Connect platform provides a collection of useful guides on how city processes work, including a dedicated section on water and sanitation.	• Developing a Water Resilience Strategy. • Implementing a new WSS Dept. structure and Commercial Services branch to enhance customer focus and financial sustainability. • Establishing the Informal Settlements Basic Services (ISBS) branch. • GIS mapping used to identify flood-prone settlements and prioritize flood-resilient toilets. • Integrating catchment, stormwater, and river management under Water and Sanitation for a holistic approach. • National Water Research Comm. statements endorsing water reuse to support public and inst. acceptance. • Forming International Advisory Panel to guide development of the wastewater-to-potable water purification plant. • Releasing Nat'l Water and Sanitation Servicing Standards for public comment. • SOPs for decentralized wastewater treatment in areas lacking centralized WWTP capacity.	• Water tariff model modified to enhance financial sustainability; a similar revision is proposed for the sanitation tariff. • Treated wastewater is sold for irrigation and industrial use at a lower price than regular municipal water, making it more cost-effective and appealing.

Key Capacities of Resilience

Cape Town's approach combines absorptive, adaptive, and transformative capacities to build a climate-resilient sanitation system.

Absorptive measures address immediate disruptions, adaptive strategies adjust infrastructure and governance to evolving risks, and transformative initiatives drive systemic changes in water and sanitation management.

Absorptive Capacity

Cape Town demonstrates absorptive capacity through measures that mitigate immediate disruptions and stabilize the existing water and sanitation system. Key examples include:

1. Day Zero crisis response
   During the severe 2018 drought, the city reduced water consumption by 50%—a rapid and effective measure to prevent service collapse.
2. Flood-resilient sanitation solutions
   GIS mapping is used to identify informal settlements vulnerable to flooding, prioritizing the installation of container, chemical, and portable flush toilets that are less susceptible to flood damage.
3. Proactive system maintenance
   Actions such as sediment cleaning, sewer rehabilitation, and a rapid incident response protocol minimize blockages and spills, ensuring system functionality during periods of stress.

Adaptive Capacity

Cape Town also displays significant adaptive capacity by modifying systems, policies, and practices to address evolving climate challenges—for instance, by investing in diverse water sources, including treated wastewater reuse for irrigation, industrial use, and potable purposes.

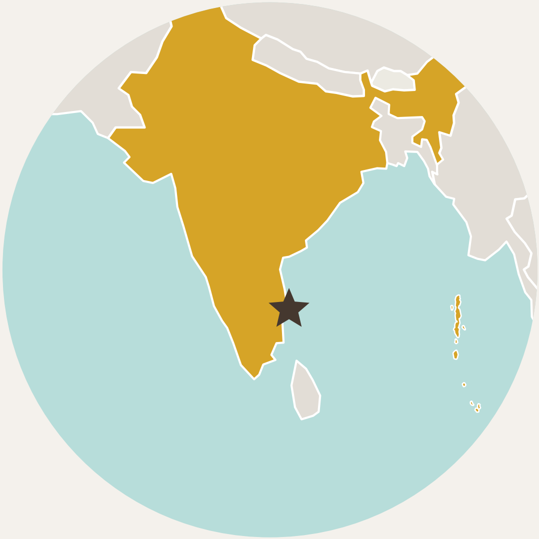
Transformative Capacity

Cape Town's efforts to build transformative capacity are evident in its systemic, forward-looking initiatives that aim to fundamentally reshape water and sanitation systems. Examples include:

1. Integrated water resilience strategy
   The City of Cape Town reflects on challenging past experiences (Day Zero) and has used the learnings to evolve into a utility that embraces innovative solutions to diversify water sources and provide climate-resilient sanitation for all. The city's water resilience strategy applies a holistic approach to the urban water cycle, emphasizing safe access to water and sanitation, diversified water sources, and a water-sensitive city that optimizes stormwater and urban waterways. The use of treated wastewater to recharge aquifers and the development of advanced purification facilities for potable water reuse represent transformative shifts in water management, addressing long-term water scarcity and promoting circular resource use.
2. Institutional reform
   The transformation of the Water and Sanitation Department into a modern, customer-oriented entity demonstrates a systemic shift in governance. The establishment of the Future Planning and Resilience Office ensures coordinated, long-term resilience planning across city departments. In addition, engagement and coordination with other sectors within the city, through the established structures, are facilitating effective decision-making and aligning actions toward overall city resilience.

Photo (right): An aerial view of the newly upgraded Zandvliet wastewater treatment plant in Cape Town, South Africa (Credit: City of Cape Town).

7. Chennai



KEY ASPECT

Chennai faces the dual pressures of rapid urbanization and increasing water scarcity due to climate change. To address these challenges, city authorities are promoting wastewater recovery and reuse and have developed a market for treated wastewater. These strategies are central to reducing pressure on freshwater supplies and enhancing the city's long-term water resilience.

Key information

Location	• City of Chennai, India
Income Group	• Lower middle-income country
Stakeholder	• Utility • Local government
Hazards	• Flooding • Water scarcity/drought • Sea level rise
Sanitation Characteristics	• Mixed (sewered, non-sewered; centralized, decentralized)
Sanitation failures covered by the climate-resilient solution	• Wastewater treatment
Other sectors that benefit from the response	• Water supply • Energy • Industry
Resilience capacities displayed by the case study	• Transformative

Context and Challenges

India is a water-scarce country, with over 54% of the covered area facing high to extreme water stress..

There is a growing gap between water supply and demand and, given current population growth trends, this is only expected to worsen over the coming years. The Government of India is promoting treated wastewater reuse as one way to deal with this crisis. The National Urban Sanitation Policy (2008) recommends the reuse of a minimum of 20% of wastewater produced in every city (MoHUA 2008). Examples of wastewater reuse in industry and agriculture date back to the 1960s and 1970s. However, as the country begins to feel the full impact of climate change, the market for the reuse of treated wastewater is growing rapidly.

Chennai is one of the cities in India significantly impacted by climate change. It is the capital of the State of Tamil Nadu and has an estimated population of 5.3 million (IndiaCensus.net 2024). It is a low-lying coastal city, and climate change is leading to sea level rise, increases in temperature and intensity of extreme weather events, as well as more erratic rainfall patterns. It has no perennial rivers, and water scarcity—caused by reduced groundwater availability and increased pollution of urban water bodies—is the key water challenge facing the city (Resilient Cities Network 2019).

Periods of drought are interspersed with periods of high rainfall, leading to widespread flooding in the city. In 2015, catastrophic flooding from a 1-in-100-year rainfall event cost hundreds of lives and millions of dollars in damage to property and infrastructure (The Quint 2015). Impacts to sanitation systems and public health were recorded, although the direct impact of failing sanitation on public health was not quantified. In the immediate aftermath, an additional 2,000 sanitation workers were deployed to the city as part of a large-scale emergency response to prevent large outbreaks of disease. Drainage was noted as one of the immediate areas to improve in the aftermath of the floods, with poor maintenance of the drainage system a contributing factor to flooding in low-lying areas (Narasimhan et al. 2016).

The need for additional water supply to industry was the initial driver for investment in wastewater recovery and reuse in Chennai in 2005 (World Bank 2016). Recent droughts have prompted a renewed focus on wastewater recovery and increased efforts to expand capacity and strengthen the market for its reuse. Alongside these efforts, measures have also been introduced to reduce pollution to urban water bodies through improved septage and fecal sludge management.

The responsibility for ensuring water and sanitation services are climate resilient is shared between the Greater Chennai Corporation (GCC) and the Chennai Metropolitan Water Supply and Sewerage Board (CMWSSB). The GCC is responsible for ensuring access to sanitation, solid waste management, and stormwater management services in the city. The CMWSSB is responsible for water supply, sewerage, and wastewater treatment (TWAD 2024).

The GCC, in collaboration with the CMWSSB and other national and state level actors, developed the Resilient Chennai Strategy (2019) which "prioritized protecting and strengthening its green and blue assets to ensure that investing in resilience delivers for our future generations". Water supply and sanitation are covered under Pillar 2; Goal 2.1 focuses on fostering sustainable water use and wastewater reuse practices in the city. The strategy is a city-focused document and does not explicitly deal with onsite sanitation, despite its widespread use in Chennai.

The Responses

Chennai experienced a 'Day Zero' event in 2019, with all five water reservoirs supplying the city reaching critical levels.

This crisis prompted the city to diversify its water sources, rationalize water use and renew its focus on wastewater recovery and reuse. The GCC developed the Chennai Resilience Strategy (2019), which includes actions designed to promote water saving and encourage wastewater recovery and reuse. GCC aims to restore 210 urban water bodies to be used for water storage, while other initiatives have included the introduction of rainwater harvesting and encouraging businesses and residents to reduce water consumption using water saving devices. Wastewater recovery and reuse is central to the Chennai Resilience Strategy, and several legal and regulatory tools have been introduced to support its implementation and mainstreaming.

Wastewater recovery is included in building permitting for new developments. Specifically, the Tamil Nadu Combined Development Building Rules (2019) require new housing developments of more than 50 houses, or with a footprint of greater than 2,500 m2, and new commercial developments where there is no sewerage network, to include their own wastewater treatment plant using Zero Liquid Discharge Technologies (ZLD).

The Treated Wastewater Policy for Tamil Nadu (2019) aims to create a framework to help develop extensive treated wastewater grids, providing treated wastewater as a reliable, sustainable, and additional water source to industrial, institutional, commercial, agricultural, and domestic customers. It requires CMWSSB to include tertiary treatment phases in its wastewater treatment plants (WWTPs).

The CMWSSB, together with some private companies, has been central in the development of the reuse market for treated wastewater from wastewater treatment plants. Their WWTPs co-treat wastewater from sewers with septage from onsite facilities, most commonly septic tanks. In 2015, CMWSSB established two tertiary treatment and reverse osmosis plants in the North and South of the city, each with a 45 MLD capacity, and began to supply high-quality treated water to industry (World Bank 2016). It is currently estimated that a combined total of 130 MLD of treated wastewater is supplied to industry.

A key barrier to the uptake of treated wastewater is pricing. Where treated wastewater costs the same as, or more than, the potable water supply, customers usually prefer the latter. To overcome this, the Treated Wastewater Policy includes clauses that make the use of treated wastewater mandatory for all non-drinking and process-water requirements, for users with a water requirement of over 100 KLD (GCC 2019).

In addition to wastewater recycling, resilience and circular economy principles are being built into WWTPs through the inclusion of energy recovery capacity in seven out of CMWSSB's 12 plants. Specifically, biogas is recovered from sludge through anaerobic digestion and is used in gas engines to generate energy. This activity contributes 60-70% of the plants' energy requirements, reducing dependence on the electricity grid and improving the financial sustainability of wastewater treatment operations (World Bank 2016). CMWSSB is also exploring the possibility of producing wastewater sludge derived products for onward sale at the WWTPs.

CMWSSB's success in incorporating wastewater and energy recovery components into its wastewater treatment facilities has been attributed to the willingness of its leadership to create space for its engineers to innovate through piloting and scaling of successful approaches. The utility has been active in establishing partnerships with universities and technical institutions to undertake the related research, and has been successful in identifying and securing funding to support this work–for example, the Gates Foundation is supporting the utility in developing technology to further improve energy recovery at their plants. The utility will need to remain flexible and retain this ability to innovate to tackle emerging climate impacts and corresponding changes to the policies, institutions, regulations, and financing (PIRF) framework under which it operates, for example, when wastewater effluent standards change.

Table 8

Chennai's climate-resilient sanitation responses and enabling environment

Infrastructure and service provision	Users	Institution, policy, and planning	Finance
• CMWSSB treats and sells wastewater for industrial use. • Wastewater recycling and reuse are included in new housing and commercial developments, and are stipulated in the building permits issued by GCC. • Wastewater recycling and reuse are carried out in parallel to rainwater harvesting and water saving initiatives for domestic users, with the private sector promoting low usage taps and shower heads.	• Tamil Nadu Combined Development Building Rules legislation requires rainwater harvesting to be pursued at the household level, supported by annual communication campaigns to encourage ongoing maintenance (although there is limited interaction with users/households). • An online platform, Chennai City Connect, strengthens coordination between stakeholders allowing for integrated planning and cohesive promotion with communities.	• The 2019 Resilient Chennai Strategy's second Pillar, Water Systems, Goal 2.1 focuses on sustainable water use and wastewater recycling but does not include explicit reference to onsite sanitation or sewerage. • The 2019 Treated Wastewater Policy makes the reuse of treated wastewater mandatory for large-scale water users. • Changes to the building code make wastewater recycling mandatory in new housing and commercial developments. • Changes to wastewater effluent standards may limit the types of wastewater treatment plants that can be used.	• Industry investment in wastewater recycling. • The utility has been successful in attracting diverse funding for innovation, including from BMGF and academic partners for pilots. • Biogas generation contributes 60-70% of the WWTPs' energy requirements reducing dependence on the electricity grid and improving the financial sustainability of wastewater treatment operations.

The Outcomes

The State of Tamil Nadu is rapidly urbanizing and industrializing in a context of increasing water scarcity.

Rising industrial demand for water was the initial driver for the development of wastewater recovery and reuse. The State has created its own Treated Wastewater Policy to ensure that urban local bodies (ULBs) incorporate wastewater recovery and reuse into their sanitation services, and mandate industrial and other users to use the treated wastewater.

In Chennai, a market for treated wastewater has been developed. The CMWSSB treats and sells around 130 MLD of recycled wastewater to industry, and is seeking to further expand this capacity. The use of treated wastewater in industry reduces the demand for potable water from this sector, and thereby increases the water available for other users, including domestic, institutional, and commercial. CMWSSB has also introduced energy recovery facilities at seven of its 12 WWTPs in the city, reducing demand for electricity from the grid and increasing the financial sustainability of the WWTPs. The utility has adopted a flexible, innovative approach to infrastructure development and has built climate resilience into its wastewater treatment services.

Key Capacities of Resilience

Adaptive capacity is the most strongly demonstrated dimension in Chennai's responses.

Adaptive Capacity
The Chennai resilience strategy promotes modular treatment systems enabling the city to adapt to changing stresses such as drought and flooding. This flexibility enhances the city's ability to respond to evolving climatic challenges. Integrated processes, including the in-house capacity for innovation within CMWSSB to develop mechanisms for selling treated wastewater, demonstrate how service providers can build adaptive capacity by offering new services and diversifying their business models.

Transformative Capacity
The challenges of water scarcity coupled with a supportive national and state-level enabling environment empowered the service provider to establish a market for treated wastewater. The development of a treated wastewater reuse market has helped diversify water sources for industry reducing dependence on limited potable water supplies. This initiative is supported by the 2019 Treated Wastewater Policy, which mandates the use of treated wastewater for non-potable and industrial purposes. This represents a fundamental shift toward circular resource use, reducing stress on potable water supplies and enabling sustainable industrial growth.

8. Bangladesh

KEY ASPECT

The Government of Bangladesh is developing an enabling environment for urban sanitation that addresses the immediate impacts of climate change, as well as secondary impacts such as climate migration from the national to the city level. The national government's prioritization of climate adaptation and mitigation is being translated into local action by municipal authorities and utilities.

Key information

Location	• Bangladesh with examples from the capital, Dhaka, and coastal communities
Income Group	• Lower middle-income country
Stakeholder	• Utility • National government • Local government • NGOs/International organization—UNICEF and WaterAid
Hazards	• Flooding • Sea level rise • Temperature rise
Sanitation Characteristics	• Mixed (sewered, non-sewered; centralized, decentralized)
Sanitation failures covered by the climate-resilient solution	• Containment • Wastewater treatment
Other sectors that benefit from the response	• Energy
Resilience capacities displayed by the case study	• Adaptive

Context and Challenges

Bangladesh is one of the most populous countries in the world with around 170 million inhabitants (BBS 2023) living in or near low-lying and coastal areas.

Situated in the largest delta in the world, Bangladesh is already impacted by climate change with nearly a third of the country susceptible to tidal flooding and storm surges, and up to 70% of the country being flooded during monsoons (GFDRR 2011).

There are multiple climate change hazards impacting sanitation service provision in Bangladesh. This includes sea level rise, increased temperatures and more intense monsoons, leading to saline water intrusion into groundwater in coastal areas and increased incidence of flooding. When combined with damage to infrastructure, including sanitation facilities, this leads to an increase in the prevalence of disease including cholera (MoH 2019) and dengue (Bhowmik et al. 2023).

The loss of agriculturally productive land in areas affected by climate change hazards has led to an influx of climate migrants from rural and coastal areas to Bangladesh's major cities, including the capital Dhaka. The Government estimates that by 2050 one in seven Bangladeshis will be a climate migrant (World Bank 2018). Estimates suggest that over 2,000 migrants from coastal areas currently arrive in Dhaka every day, putting pressure on existing basic services which in many cases are failing to keep up with this increasing demand (Khan and Islam 2021).

The Government of Bangladesh has prioritized climate change as a national issue and is promoting a shift from an approach based on disaster response to one that includes wider preparedness and risk management. The 2009 Bangladesh Climate Change Strategy and Action Plan (BCCSAP) was updated in 2022 to include the urban dimensions of climate change. This has a pro-poor focus and adopts an adaptation and disaster risk reduction (DRR) approach. The National Adaptation Plan was published in the same year. The National Plan for Disaster Management, which was updated in 2017, also recognizes the risks linking urbanization and climate change. The National Strategy for Water Supply and Sanitation, updated in 2020, focuses on the vulnerability of these services to climate change.

Bangladesh has made advances in improving water supply and sanitation services, with open defecation, for example, having been reduced to almost zero. However, challenges remain regarding water quality and safe excreta disposal. There are also significant variations in service levels nationwide. In urban areas, access to water supply and sanitation services is significantly lower in low-income communities and among vulnerable groups (Ahmed et al. 2023). Key sanitation challenges include: upgrading of inadequately designed sanitation facilities in flood prone areas and effective fecal sludge management in densely populated urban slum areas.

Current national efforts to overcome these sanitation challenges are focused on translating the policy framework for climate-resilient sanitation to action, through the development of a supporting legal and regulatory framework, as well as appropriate resourcing, capacity building for improved OSS and FSM services, and improved coordination for stakeholders at all levels.

The Responses

Bangladesh is ahead of many other low- and middle-income countries in facing the impacts of climate change and incorporating a climate focus into its sanitation planning and service provision.

Early efforts to mainstream climate resilience in sanitation included the Accelerated Sanitation and Water for All (ASWA) II program, which was financed through the UK's Foreign Commonwealth and Development Office (FCDO) and implemented by the Department of Public Health Engineering (DPHE), with the support of UNICEF.

In Bangladesh, the Ministry of Local Government, Rural Development and Cooperatives (MLGRDC) is responsible for ensuring access to sanitation services and water supply. The Department of Public Health Engineering (DPHE) is responsible for increasing the capacity of organizations and communities to implement sanitation facilities and water supply. DPHE has further set out guidance for municipalities to assess climate risks and select climate-resilient water supply and sanitation services, as well as to implement flood resilient sanitation facilities. This includes strategies for improving the financial and institutional resilience of service providers as well as the strategic design of sanitation services.

ASWA II supported the uptake of climate-resilient sanitation through community awareness raising, capacity building and installation of climate-resilient sanitation facilities which have remained functional after climate events (UNICEF 2022). Rural and coastal communities and other sector stakeholders constructed climate-resilient latrines in flood-prone areas, replicating and scaling up the climate-resilient sanitation program within and outside of the ASWA II project areas. This approach has now been adopted in almost all of the districts in Bangladesh.

The government's initial focus on climate resilience in the mainly rural coastal areas is now shifting to deal with the increasing impact of climate migration into cities. The mass influx, combined with existing constraints in the provision of basic urban services, is having a direct impact on the quality of life of urban residents, particularly those settling in the dense slum areas of large cities, such as Dhaka.

The National Adaptation Plan (NAP), updated in 2022, includes the goal of building climate-smart cities and prioritizes integration of adaptation into wider planning processes and capacity building. The current challenge is to ensure this policy framework is mainstreamed and translated into action at all levels of government.

The Citywide Inclusive Sanitation-Fecal Sludge Management (CWIS-FSM) Support Cell is a dedicated technical assistance unit, established under DPHE to deliver inclusive sanitation in partnership with development partners, local authorities, NGOs and academic institutions, including the International Training Network-Bangladesh University of Engineering and Technology (ITN-BUET). The Support Cell provides strategic guidance to DPHE and municipalities to develop CWIS investment plans which identify and include adaptation and disaster risk reduction measures. Technical assistance is being supported by national government and water utilities, but implementation of onsite sanitation systems remains with city corporations (CWIS-FSM Support Cell 2024).

Climate financing for the sanitation sector is still underdeveloped but the CWIS-FSM Support Cell seeks to link government partners with potential funders. The unit is also advocating for the inclusion of sector plans for adaptation, mitigation, capacity development, financing and technology transfer based on the existing National Adaptation Plan and other national development policies (CWIS-FSM Support Cell 2024).

Locally, cities are working towards climate-resilient sanitation service provision through the adoption of CWIS. Whereas previously, authorities focused on sewerage and wastewater treatment to meet the city's sanitation needs, it is now accepted that a mixture of sewered and non-sewered solutions is required. To support this transition, the 2017 Institutional and Regulatory Framework for Faecal Sludge Management (IRF-FSM) served to clarify mandates for FSM service provision. Three framework documents were prepared: one for rural areas; one for urban areas; and one for the metropolitan area of Dhaka (CWIS-FSM Support Cell 2024).

In Dhaka, only 20% of the population are connected to the sewer network. The remaining 80% rely on onsite sanitation. The IRF-FSM states that Dhaka Water and Sewerage Authority (DWASA) is responsible for providing water supply and sewerage services and the Dhaka North and Dhaka South City Corporations are responsible for FSM services provision.

These organizations are responsible for accelerating sanitation provision in low-income communities that are disproportionately affected by climate migration. In practice, although DNCC and DSCC are experienced in providing other waste management services, including solid waste collection and street sweeping services, they have no previous experience in delivering FSM services and have been slow to embrace their responsibilities under the IRF-FSM (CWIS-FSM Support Cell 2024).

Locally, cities are working towards resilient sanitation service provision in different ways. In Dhaka, DWASA's main sanitation focus is on the extension of the sewer network and the construction and operation of wastewater treatment plants in the city. The Sewerage Master Plan (2013) is the key document guiding the development of this infrastructure. It divides the city core into five sewer catchment areas with their corresponding wastewater treatment plants (WWTPs). Since the Master Plan was developed, Dhaka has experienced significantly higher population growth than forecasted due, in no small part, to climate migration. IRF-FSM has therefore introduced a requirement to develop FSM services in areas not covered by centralized sewerage networks, demonstrating the need for continuous work to operationalize climate considerations within utilities' longer-term planning.

UNICEF is supporting DWASA in updating the Sewerage Master Plan including incorporating climate resilience strategies into the sanitation and sewerage systems. The utility itself has recently set up its own CWIS Cell to lead this work. DWASA is also in the early stages of undertaking research into the potential to mitigate emissions at its WWTPs through energy recovery initiatives. This research is being supported by the Gates Foundation (UNICEF 2022).

Several international organizations and NGOs, including UNICEF and WaterAid, have also mainstreamed climate resilience into their sanitation programming in Bangladesh. Both have introduced it as a cross-cutting issue in their development and emergency response programs and have prioritized it in their country strategies.

Users are also playing an important role in the design and implementation of climate-resilient sanitation programmed in Bangladesh. The importance of user acceptance is recognized within the Bangladeshi sanitation sector, with sanitation marketing and information education campaigns advised during the development of climate-resilient sanitation facilities by NGOs and, to a lesser degree, by the government.

Table 9

Bangladesh's climate-resilient sanitation responses and enabling environment

Infrastructure and service provision	Users	Institution, policy, and planning	Finance
• Climate-resilient sanitation facilities have been constructed in the coastal region of Bangladesh (including raised toilets and improved containment units). • Interventions by UNICEF and WaterAid have focused on improving school sanitation; schools, which often serve as cyclone shelters, benefit from improved sanitation that enhances overall community resilience. • Utilities have increased their focus on climate-resilient sanitation and are undertaking research to determine the applicability of different technologies and models.	• The inclusion of grass root organizations in the development of local adaptation plans is not a widespread practice at present. Some civil society organizations and NGOs use inclusive planning methodologies. This is less common in government projects, though some respondents recognize a gradual shift towards greater community consultation. • The importance of community consultation is growing for both government- and civil society-led projects, including having the community identify needs and areas for intervention. • Information, education and communication (IEC) and behavior change campaigns are still needed to ensure urban migrants adapt to urban sanitation options, such as shared instead facilities rather than individual ones.	• A comprehensive policy framework for climate-resilient sanitation has been developed. The next step is to create a legal and regulatory framework to support implementation through clear mandates, adequate resourcing, capacity building and improved coordination. • Policy has changed from a focus on disaster response to one focused on wider preparedness and risk assessment. • The National Adaptation Plan includes the development of climate-resilient WASH facilities for improved wellbeing and livability in cities. • The CWIS-FSM Support Cell was established to provide strategic guidance to implement Citywide Inclusive Sanitation (CWIS) in Bangladesh; the Support Cell is hosted by DPHE and currently receives funding from the Gates Foundation.	• Some NGOs are working with microfinance institutions to provide services, including sanitation for climate migrants in Dhaka, although barriers remain. • As a more comprehensive way of measuring the positive impacts of a project, trials to quantify social capital as an alternative to economic capital have begun, which include elements of sanitation. • The current practice is to collect 10-20% of project costs from the community to pay for CAPEX of new sanitation projects; efforts are underway to repurpose this practice to improve ongoing maintenance and create an O&M fund. • Further research is needed to establish sanitation as a priority funding area for climate finance.

The Outcomes

Climate change impacts have already been felt in Bangladesh for some years.

The inclusion of a climate focus in a range of national and sectoral policies reflects the importance of this issue at the country level. Local governments increasingly recognize the need to operationalize national policies and plans, with the National Adaptation Plan currently being translated into Climate Action Plans by around 2,500 local authorities, including Dhaka South and Dhaka North in the capital. This work is still in its early stages but is evidence of a growing shift in approach to mainstreaming climate adaptation into urban planning, including into urban sanitation planning. Nevertheless, to fully translate these policies into action, the supporting legal and regulatory framework needs to be further developed, institutional mandates clarified, and additional resources allocated to these activities.

For example, the IRF-FSM has led to the establishment of the CWIS-FSM Support Cell and the inclusion of FSM in sanitation projects, which had previously focused solely on the expansion of sewerage and wastewater treatment. This will require utilities to move beyond mandates only focused on water supply and sewerage to work more closely with City Corporations in the development of OSS and FSM services. Utilities report an increased focus on climate-resilient sanitation and have commissioned research to better understand the application of climate-resilient technologies and approaches within their respective contexts.

Bangladesh has received significant international support from organizations including UNICEF and the Gates Foundation to fund the introduction of climate-resilient sanitation and build the institutional capacity of local organizations and the national government to plan, implement and operate these sanitation systems. WaterAid and UNICEF have reported improved resilience of sanitation facilities after both localized flooding and larger monsoon events.

Key Capacities of Resilience

As one of the countries most affected by flooding worldwide, Bangladesh exhibits notable absorptive capacity.

Absorptive Capacity
By improving sanitation in schools that double as cyclone shelters, interventions ensure essential services are available during disasters, thereby enhancing community resilience.

Adaptive Capacity
Bangladesh's efforts as presented in the case study are most strongly aligned with adaptive capacity, demonstrating an ability to adjust sanitation systems and policies to respond to evolving climate challenges. There is a long tradition of constructing raised toilets and improved containment units in coastal and flood-prone areas, which helps to maintain sanitation services during extreme weather events, preventing contamination and disease outbreaks. The inclusion of climate resilience in national policies, such as the updated Bangladesh Climate Change Strategy and Action Plan (BCCSAP) and the National Adaptation Plan (NAP), reflects an adaptive approach to managing climate risks in sanitation. National adaptation plans are being used to create local adaptation plans that are aligned to national aspirations. This is supported by government ministries, international organizations and academics. The DPHE has created guidelines for developing climate-resilient sanitation (CRS), while the Green Climate Fund (GCF) is funding a national center of excellence to support the implementation of climate-resilient infrastructure at different levels.

Transformative Capacity
In addition, there is evidence of transformative capacity in Bangladesh's approach to sanitation, but it is still in its early stages and requires further strengthening. The development of comprehensive national policies such as the NAP and the IRF-FSM represents a systemic shift toward integrating climate resilience into sanitation planning. However, these policies require further operationalization through legal frameworks and resource allocation.

9. Singapore

KEY ASPECT

The Republic of Singapore is a city-state located at the southern tip of the Malay Peninsula. As a small, low-lying island country, Singapore uses integrated water management through its national water agency, the Public Utilities Board, to explore high-grade reclaimed wastewater (NEWater) as an alternative water source.

Key information

Location	• Singapore city state
Income Group	• Upper-middle income country
Stakeholder	• Utility • National government
Hazards	• Flooding • Sea level rise • Water scarcity/drought • Extreme heat
Sanitation Characteristics	• Sewered • Centralized
Sanitation failures covered by the climate-resilient solution	• Wastewater (WW) delivery to treatment • WW treatment
Other sectors that benefit from the response	• Energy • Stormwater • Water supply
Resilience capacities displayed by the case study	• Transformative

Context and Challenges

Singapore, a low-lying island city-state, faces unique climate change vulnerabilities.

Current and projected climate hazards, including intense rainfall, flooding, sea-level rise, drought and extreme heat, pose significant challenges to the nation's infrastructure and safety. For water supply and sanitation service provision, prolonged dry spells threaten water availability, while increased rainfall exacerbates flood risks, and rising sea levels pose a threat to coastal areas (PUB 2024a).

Despite Singapore's abundance of rainfall, the absence of groundwater and natural freshwater bodies presents a challenge. Compounding this issue is the limited availability of land for rainwater capture and storage, further straining water resources. Furthermore, historical reliance on external water sources, such as imported water from Malaysia, underscores the need for enhanced national water security measures (Tan; Lee, and Tan 2009).

The impacts of climate change are further compounded by Singapore's growing population and expanding economy. Since its independence in 1965, overall water consumption has increased more than six-fold, placing additional stress on already-strained water resources (PUB 2015). Given Singapore's distinctive geomorphological and socioeconomic characteristics, addressing these challenges necessitates a resourceful and innovative approach to climate resilience.

The Public Utilities Board (PUB), as the national water agency under the Ministry of Sustainability and the Environment (MSE), plays a central role in managing Singapore's water supply, catchment areas and wastewater. Additionally, PUB has assumed responsibility for safeguarding Singapore's coastline since April 2020. It leads coordinated government efforts to protect against rising sea levels and manages inland and coastal flood risks, further highlighting its integral role and proactive approach to climate resilience efforts (IAHR 2024). Singapore's susceptibility to climate change, coupled with its demographic and environmental characteristics, underscores the necessity for innovative solutions to ensure climate resilience in urban sanitation and water service provision.

The Responses

To address Singapore's growing water demands, integrated water management has been implemented.

Four National Taps

Singapore's efforts are grounded in three core strategies:

- Maximizing water collection
- Promoting continuous water reuse
- Expanding seawater desalination (PUB n.d.)

Singapore has further developed the 'Four National Taps' strategy to diversify water supply in a sustainable way that includes the four primary sources of water supply: local catchment water, imported water, high-grade reclaimed water known as NEWater, and desalinated water.

During Singapore's early independence in the 1960s and 1970s, the country relied primarily on local catchment water and imported water from Malaysia. However, to enhance national water security, the government began exploring alternative sources in the 1970s, eventually introducing NEWater and desalinated water in the early 2000s (NLB 2019). With water demand projected to double by 2065, NEWater and desalination are expected to grow as future sources of water for Singapore. In order to ensure water security for the country, long-term strategies and infrastructure plans under the Water Master Plan have been put in place to grow these climate-resilient sources of water.

NEWater and Deep Tunnel Sewerage System

NEWater, a critical component of Singapore's water strategy, allows for multiple rounds of water reuse. It has positioned Singapore as a key global leader in water reclamation and associated technology. Through advanced treatment processes such as microfiltration, reverse osmosis, and ultraviolet disinfection, PUB transforms used water into ultra-clean, high-grade NEWater, ensuring reliability and climate resilience. While primarily utilized for industrial and commercial purposes, NEWater also replenishes and sustains local reservoirs during dry months. The blended raw water is further treated at local waterworks before it is supplied to consumers.

NEWater was introduced to the Singapore public more than 20 years ago, and currently receives overall acceptance and trust. To optimize Singapore's integrated water system to deliver NEWater, the Deep Tunnel Sewerage System (DTSS) Phase 1 was completed in 2008, allowing used water from the northern and eastern parts of Singapore to be conveyed by gravity to centralized water reclamation plants (WRPs) in Kranji and Changi. When completed in 2026, the DTSS Phase 2 will collect used water from the southern and western parts of Singapore and direct it towards the new water reclamation plant in Tuas, further boosting the capacity to produce NEWater and enhance Singapore's long-term water sustainability. To meet the projected increase in water demand, PUB is also redeveloping the Kranji WRP and Kranji NEWater Factory, in addition to constructing Changi NEWater Factory 3. Together, the new facilities will further strengthen NEWater production, enhance water supply and support Singapore's water resilience against growing water demand and climate change.

When NEWater was first introduced, in 2003 (Global Water Forum 2018), there were challenges concerning the cost and reliability of the technology used to clean the wastewater, which in turn influenced its acceptance. A Public Communications Plan for NEWater was developed to communicate the technical considerations for NEWater through public outreach activities. Through this plan, the government was able to engender broad acceptance of NEWater. The public were informed that: wastewater reclamation was not new and had been practiced in other countries such as the United States; the quality of NEWater was comparable to or even exceeded international drinking water standards; and NEWater was a cost competitive source of water supply. Several factors have since contributed to building trust with the public, including political support, public education, scientific/technical rigor, external recognition, certification and communications efforts (Horizon International 2011).

Photo (right): In Singapore, used water is transported via the DTSS (Deep Tunnel Sewerage System) to the water reclamation plants for treatment (Credit: Singapore's National Water Agency).

PUB has sought to be at the forefront of technological developments in global water research, development and innovation for water solutions. Since 2004, a dedicated technology department has driven PUB's efforts on this matter and invested in technologies that are required, applicable and valuable to its operations. PUB has worked closely with collaborators and research partners such as local universities (the National University of Singapore and Nanyang Technological University) to develop and scale up promising technologies. In addition, PUB actively engages with the private sector and international partners to test and commercialize innovative water technologies. These collaborations provide opportunities for companies to validate their technologies at PUB's facilities, such as water reclamation plants and NEWater factories, under real-world conditions.

Water recycling for increased climate resilience

Water recycling for increased climate resilience
PUB seeks to partner with consumers and industry to conserve precious water. With Singapore's total water demand expected to double by 2065, a collective effort to ensure that water is used in a responsible and sustainable way is critical to ensuring long-term water security. To manage water demand, water is priced to reflect its scarcity value, with the aim of recovering the full costs of its supply and production. The price also incorporates the higher cost of producing water from unconventional sources, specifically NEWater and desalinated water. In addition, PUB sets and reviews water efficiency standards to ensure efficient water use. Finally, people and businesses are engaged through water conservation programs and initiatives.

In particular, PUB has put in place mandatory recycling in Singapore for the non-domestic sector, focusing on the projected water demand growth areas. Water-intensive industries such as the wafer fabrication, electronics and biomedical industries are amongst the largest water users, accounting for more than 17% of non-domestic water demand, with expected growth in the future. For industries that consume at least 60,000m3 of water per annum, a minimum of 50% recycling rate for wafer fabrication/semiconductor plants is mandated, while for electronics and biomedical facilities, the recycling of specified waste streams will also be mandated. PUB has supported these regulations with funding support to defray costs.

3R strategy, resource circularity, water management, and sustainability framework

To achieve sustainable operations, PUB is considering the '3R Strategy' of 'Reducing' carbon emissions by enhancing energy efficiencies, 'Replacing' fossil-fuel based energy with renewable resources such as solar power, and 'Removing' carbon through carbon capture and utilization solutions (CCUS). While technologies such as NEWater and desalination offer climate-resilient sources of water, they are membrane-based and hence energy intensive, and require between 5 and 17 times more energy compared to the conventional treatment of rainwater (MoSE 2020). The generation of the energy needed results in GHG emissions which pose environmental challenges. PUB and the Singapore National Government are investing in research and innovation to improve the energy and carbon efficiency of their desalination and NEWater plants. Examples include using electro-deionization and biomimicry to improve desalination, membrane flow reversal technology, as well as electro-dialysis reversal to improve NEWater recovery.

PUB's resource circularity plan aims to make the utility's overall supply chain more efficient and circular by looking at operations that generate waste. PUB seeks to reduce waste sent to landfill, recover value from waste streams, and maximize synergies with parallel processes. The Tuas Nexus is a multi-agency effort which integrates the operations of PUB's Tuas WRP and the National Environment Agency (NEA)'s Integrated Waste Management Facility (IWMF). For example, the co-digestion of wastewater sludge and food waste increases biogas production, which can be processed in high-efficiency superheaters at IWMF to generate more electricity. Electricity generated will be used for plant operations and any excess will be exported to the grid.

Table 10

Singapore's climate-resilient sanitation responses and enabling environment

Infrastructure and service provision	Users	Institution, policy, and planning	Finance
• Through PUB's '4 National Tap' approach, facilities are being redeveloped and constructed to bolster NEWater production, augment water supply and strengthen Singapore's water resilience against growing water demand and climate change. • A multi-pronged approach regulates the design, maintenance and enforcement of sewerage systems and ensure that the used water collected is fit for recycling, with the DTSS a central part of NEWater delivery. • The integrated approach towards water management includes the management of other systems including the water supply, stormwater drainage and coastal protection systems.	• NEWater has received broad level acceptance and trust from the public for over two decades. Several factors have contributed to public buy-in of NEWater, including political support, public education, scientific/technical rigor, external recognition/certification and communication efforts. • Other stakeholders, including academia and the private sector, are actively engaged in the development of technologies and solutions to bolster and optimize NEWater production and delivery.	• The Water Master Plan is a 50-year long-term plan. Solutions will not become a reality without long-term planning to identify opportunities and critical paths to realize them. • PUB has a Sustainability Framework aligned with Singapore's Green Plan 2030. PUB publishes an annual sustainability report that informs and engages the public on the role that the utility plays as Singapore's National Water Agency, managing activities and impacts responsibly and sustainably. • Mandatory recycling regulations have been imposed on non-domestic water users to reduce water consumption, enhance long-term competitiveness, and deliver sustainability outcomes.	• PUB and the Singapore Government are investing in research and innovation to improve the energy and carbon efficiency of the NEWater plants and desalination technologies. • PUB receives revenue from water tariffs, supplemented by grants from the government. PUB's business practices balance financial prudence with environmental responsibility

Rising sea levels and extreme rainfall brought on by climate change pose an existential threat to Singapore and to water management infrastructure, including sewers, drains, tunnels and treatment plants. Singapore has distinct and separate wastewater sewerage and stormwater drainage systems, allowing for better management and added resilience in their operations. PUB is currently developing the coastal-inland flood model to assess the combined flood impact from intense rainfall and extreme coastal events. In addition, there are ongoing coastal site-specific studies, and development of coastal protection policies and a code of practice for coastal infrastructure. PUB is also investing in the building of expertise in coastal protection and flood management. These efforts will, in due course, further add resilience to Singapore's response to its climate risks.

To advance PUB's sustainability agenda, a Green Financing Framework has been established to guide the raising of green financing to meet capital needs for identified green projects. In August 2022, USD 800 million in green bonds with a 30-year maturity were issued to support PUB's investment in green infrastructure. Moreover, PUB has a sustainability framework in place that serves to guide the organization, as it strives to be a responsible and trusted public agency contributing to Singapore's nationwide sustainability movement under the Singapore Green Plan 2030. This also further contributes to building a positive public perception (GoS 2024; PUB 2024b).

The Outcomes

The efforts of PUB and Singapore on research and innovation have facilitated water sustainability, resulting in increased water supply capacity.

Currently, Singapore has five NEWater plants located in Bedok, Kranji, Ulu Pandan and Changi, collectively capable of producing around 170 million gallons per day. This capacity represents approximately 40% of the country's current water demand, which stands at 430 million gallons per day (CNA 2024). Moreover, working with large water users in the non-domestic sector to improve water consumption efficiency resulted in mandatory 50% recycling for wafer fabrication/semiconductor plants, as well as for selected waste streams in electronics and biomedical facilities. The utilization of reclaimed water from wastewater has enabled its reuse to bolster Singapore's water supply. Primarily, water produced by these plants is utilized in industrial applications such as cooling at wafer fabrication plants, industrial estates and commercial buildings (PUB 2024c). During periods of drought, NEWater is also introduced into reservoirs to blend with raw water. Subsequently, it undergoes treatment at waterworks to ensure it is suitable for human consumption before being distributed to consumers. As part of PUB's Water Master Plan, more NEWater production capacity is planned to meet future demand.

Beyond this, PUB recognizes that new challenges need to be overcome to ensure water security for future generations. Climate change threatens the availability of water from reduced rainfall, affects energy generation and consumption as well as carbon emissions, and impacts the operability of infrastructure through rising sea levels and extreme rainfall. Singapore continues to look for sustainable solutions to ensure water security.

Key Capacities of Resilience

By reclaiming and reusing high-grade wastewater, Singapore has integrated water security into its national strategy, creating a sustainable and circular urban water system.

Transformative Capacity
Singapore's NEWater approach exemplifies transformative capacity in building resilience by reimagining the urban water cycle to address geomorphological and socioeconomic challenges such as land and water scarcity, a growing population, and an expanding economy. The "Four National Taps" strategy diversifies water sources, enhancing redundancy and safeguarding against water scarcity-related disruptions, while adhering to a "One Water" approach. Initiatives such as The Tuas Nexus, a multi-agency effort integrating the operation of PUB's Tuas WRP and NEA's Integrated Waste Management Facility (IWMF), exemplify system-wide transformative adaptation across sectors. Co-digestion of sludge and food waste increases biogas production, which is processed in high-efficiency superheaters at IWMF to generate electricity.

3

Photo: Seedlings, like the one shown here, are planted in newly constructed wetlands adjacent to decentralised treatment plants that are designed to serve more remote communities (Credit: Juliet Willets).

Conclusion

Overall, these case studies highlight the diverse strategies cities and utilities worldwide are adopting to enhance the resilience of their sanitation systems. While contexts and capacities vary, common lessons and opportunities emerge.

Looking Back and Looking Ahead

A key takeaway is the importance of a system-wide approach to urban (waste-) water management and linked urban services in building resilience.

In Singapore, an integrated approach that combines long-term planning, continuous investment in technology, and oversight of the entire water loop has enabled large-scale water reuse. Similarly, San Francisco's "One Water" approach has allowed for a holistic view of water, wastewater, and energy services, fostering system-wide resilience. In Nairobi, integrated urban development (IUD) projects have demonstrated that tackling multiple basic services together—such as sanitation, solid waste management, drainage, and water supply—reinforces outcomes and amplifies overall impact. Paraná State in Brazil has further shown that considering climate risk management as a strategic business area strengthens decision-making and improves operational resilience.

However, integrating climate resilience into sanitation requires robust policy, governance, and institutional support. The experience from Bangladesh underscores that policies alone are not enough; they must be backed by robust legal and regulatory frameworks to ensure the mainstreaming of climate-resilient sanitation. Miami has demonstrated the effectiveness of coordinated task forces in integrating community priorities into infrastructure planning, while San Francisco highlights the need to establish governance structures early in the adaptation process, ensuring relevant city agencies are engaged in decision-making. In Cape Town, strong support from local authorities, along with mechanisms to coordinate stakeholders, has been essential in implementing climate resilience measures.

Building public trust and stakeholder engagement has also emerged as a fundamental enabler of successful climate adaptation. Singapore's experience with NEWater highlights the importance of public perception, as well as collaboration with academia and the private sector, in ensuring acceptance of wastewater reuse. In Cape Town, customer trust and satisfaction have been key to improving revenue collection, which in turn provides the financial stability necessary for further investments in climate resilience. Meanwhile, Lusaka has shown that involving users in the design of sanitation services leads to greater acceptance and sustained use of improved solutions.

Financial sustainability is another critical factor, with case studies emphasizing the need for diverse financing mechanisms and economic incentives. San Francisco has successfully leveraged green bonds to attract investors while reducing financing costs. Miami's experience highlights the importance of exploring alternative funding sources to accelerate large-scale adaptation programs. In Paraná State, embedding climate risk into business strategy has strengthened a utility's reputation and attracted investment. Chennai's case study further illustrates how pricing structures impact wastewater reuse, showing that treated wastewater must be competitively priced compared to potable water to ensure uptake.

The role of innovation, technology, and research in climate-resilient sanitation has been widely recognized. Singapore's continuous investment in technology has been instrumental in maintaining water security and expanding wastewater reuse. The National Water Agency works closely with partners to support the translation and commercialization of promising technologies, including through the Singapore Water Exchange to incubate start-ups in water technologies and through the Global Innovation Challenge, which invites companies, researchers, and innovators to propose solutions to address Singapore's challenges. In Chennai, strong leadership and space for technical innovation within utilities have driven major advancements in wastewater treatment and reuse. Paraná State's experience highlights how research-driven decision-making can generate evidence to support climate risk management. Meanwhile, Nairobi has demonstrated that piloting and showcasing new sanitation models have accelerated recognition and regulatory uptake.

Enhanced data collection and comprehensive monitoring enable authorities and utilities to better understand and respond to the impacts of climate change on urban sanitation systems. In Chennai, the water and sanitation utility collaborates with universities and technical institutions to advance research on wastewater and energy recovery, securing funding to support these efforts. Similarly, RUC in Florida strengthens climate adaptation strategies by improving data management, benchmarking, and fostering partnerships with universities to enhance decision-making in water management. In San Francisco, SFPUC's real-time sewer network monitoring enables early detection of issues, allowing proactive responses to climate-related impacts such as heavy rainfall. Prioritizing transparency, SFPUC disseminates data through interactive maps, enhancing public engagement, raising awareness, and informing decision-making on maintenance, management, and water conservation. In Paraná State, Sanepar integrates community-driven data collection to monitor pollution and water levels, empowering residents to report climatic issues. This participatory approach strengthens the utility's ability to maintain reliable and informed operations in the face of climate challenges.

A recurring theme across case studies is that climate or environmental risk can serve as a catalyst for learning and resilience action. In Cape Town, the looming 'Day Zero' crisis significantly raised public awareness and engagement, providing momentum for climate-resilient interventions. San Francisco's cost-benefit analysis of adaptation investments versus a "do-nothing" scenario demonstrated that inaction would be far more expensive in the long run. Chennai's case study similarly shows that acute water scarcity can drive transformative change, particularly in the acceptance of wastewater reuse for industrial applications. In Miami-Dade County, the threat of environmental pollution from failing septic systems compounded by sea-level rise led to the Connect to Protect program, which aims to transition from septic to sewer systems, reducing contamination risks and improving water quality and protecting the vital ecosystem of Biscayne Bay.

Collaboration across different sectors and governance levels has proven to be a powerful tool in enabling resilience. In Paraná State, multi-level partnerships—spanning local, regional, national, and international actors—have played a key role in strengthening urban resilience. Miami's regional collaboration has facilitated the development of unified climate data sets, enabling consistent adaptation planning across multiple agencies. Cape Town's partnership with international experts has increased confidence in trialing and scaling up new wastewater reuse technologies.

Developing effective service delivery models and adapting infrastructure has also been critical in ensuring that sanitation systems remain resilient to climate impacts. Nairobi's case study highlights the need for a broader range of service delivery models to meet citywide climate-resilient sanitation targets. Lusaka has demonstrated that sanitation improvements yield greater impact when combined with solid waste and drainage services, helping reduce environmental contamination and public health risks. Meanwhile, San Francisco's targeted adaptation of sewer networks has strengthened resilience to drought, flooding, and sea-level rise.

Many case studies have emphasized the role of market and regulatory mechanisms in scaling climate-resilient sanitation. In Chennai, municipal by-laws mandating treated wastewater use have encouraged industrial adoption. Nairobi has shown that formal recognition and regulation of sanitation technologies, service models, and reuse by-products are essential to mainstreaming them. In Miami, targeted ordinances in commercial corridors have successfully incentivized private investment in sewer connections.

Finally, the case studies underscore the benefits of circular economy approaches and sustainable development. Singapore is actively incorporating decarbonization, circularity, and green financing into its climate resilience strategy. Paraná State demonstrates that cross-sectoral circular initiatives generate environmental and socioeconomic returns beyond the sector.

Overall, these case studies highlight the diverse strategies cities and utilities worldwide are adopting to enhance the resilience of their sanitation systems. While contexts and capacities vary, common lessons and opportunities emerge.

Photo (right): In Nairobi, Kenya a Fresh Life worker collects waste in the Mukuru community (Credit: Fresh Life).

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