ENGINEERING, WATER AND SMART CITIES

WORLD FEDERATION OF ENGINEERING ORGANIZATIONS

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ENGINEERING, WATER AND SMART CITIES

Editor

Jorge Emilio Abramian
Chairman of the WCCE Standing Committee on Water
Consejo Profesional de Ingenieros Civiles, CPIC, Argentina

Standing Technical Committee on Water (CW)
World Federation of Engineering Organisations (WFEO)
Chair: Ignacio González-Castelão Martínez-Peñuela

AUTHORS AND CONTRIBUTORS TO THE CHAPTERS

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1.0 INTRODUCTION

The question is how a city becomes a Smart City. For years, cities faced different challenges, mainly related to growth, both in population and extension. Many theories were developed; some encouraged densification, others, the enhancement of transportation and services or the creation of different "centralities". At the same time, climate change and social awareness are imposing new standards that cities must adopt. Extreme rainfall events overflow the existing drainage networks and invade streets. Sea level rise menaces unprepared vital infrastructure, like bridges, piers, and coastal protection works. Higher demand for energy stresses the electric grid. The community's current agenda also includes the need for green and recreational spaces, endangered or symbolic species protection, and poverty. Old, settled and well-established cities must adapt to the new demands and still would not be smart.

In addition to these shared urban problems, environmental protection and providing humans with basic needs are required. The 17 United Nations SDGs have clarified the vision of what cities must provide to their neighbours. Clean water, good health, affordable energy, responsible consumption and production, etc., are now objectives for the cities to pursue.

The task looks immense, especially when one realises that most cities must start from the back because they lack technical and monetary resources. However, new technologies have emerged, and they are handy and can help cities continue developing. Excellent tools allow for the remediation of today's problems and the conversion of old cities into smart ones.

This book, intended for engineers, urban planners, environmental scientists, policymakers, and anyone interested in shaping the cities of tomorrow, shows the tools available that can help them achieve development goals with less effort. It focuses very much on infrastructure and technology advances, all related to the significant part engineering plays in the future of civilisation, as it has played in the past. In that sense, this book also helps engineers to understand the importance of integrating innovative design, water management, and digital technology. This book explores the convergence of these critical domains, offering perspectives from academia, industry, and policy-making.

Engineering, Water and Smart Cities examines how cities can evolve into intelligent ecosystems. Topics covered include sustainable infrastructure, water-sensitive urban design, sensor networks, AI-driven resource management, and citizen engagement.

This volume brings together experts who present real-world case studies, theoretical frameworks, and cutting-edge solutions aimed at creating resilient, efficient, and livable cities. It is the result of the selfless effort made by engineers who live in different cities on the planet, with distinct development degrees and cultures. As we face the global pressures of climate change, urbanisation, and resource scarcity, the need for integrated thinking has never been greater. We invite readers to engage with these ideas and contribute to building smarter and more sustainable urban futures.

Jorge Emilio Abramian
Editor
Chairman of the WCCE Standing Committee on Water
Consejo Profesional de Ingenieros Civiles (CPIC), Argentina

2.0 SMART WATER FOR SMART CITIES

2.1 SUSTAINABLE DEVELOPMENT GOALS (SDGS) HISTORY, CONCEPTS, AND ENGINEERING

The Sustainable Development Goals (SDGs) were established at the 2012 United Nations Conference on Sustainable Development in Rio de Janeiro. The objective was to produce a set of universal goals that meet the urgent environmental, political, and economic challenges facing our world.

The SDGs coincided with another historic agreement reached in 2015 at the COP21 Paris Climate Conference. After that, the UN General Assembly approved the 2030 Agenda for Sustainable Development, which includes 17 Goals and 169 targets. Together with the Sendai Framework for Disaster Risk Reduction, signed in Japan in March 2015, these agreements provide a set of common standards and achievable targets to reduce carbon emissions, manage the risks of climate change and natural disasters, and build back better after a crisis.

The Sustainable Development Goals (SDGs) of Agenda 2030 are based on findings from the natural and social sciences and other fields regarding implementing necessary changes to ensure the survival and prosperity of all people and all life forms on the planet. Several human rights principles underpin the SDGs, including universality and indivisibility, participation and inclusion, equity and non-discrimination, accountability and the rule of law. These principles form the basis of a human rights-based approach.

The SDGs are unique in that they cover issues that affect us all. They reaffirm our international commitment to end poverty everywhere permanently. They are ambitious in making sure no one is left behind. More importantly, they involve us all in building a more sustainable, safer, and prosperous planet for all humanity.

The SDGs replace the Millennium Development Goals (MDGs), which started a global effort in 2000 to tackle the indignity of poverty. The MDGs established measurable, universally agreed-upon objectives for tackling extreme poverty and hunger, preventing deadly diseases, and expanding primary education to all children, among other development priorities. Water was not expressly present in the MDGs: it was only a target ("cut in half, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation"). That was not enough, so an international movement from water professionals and stakeholders introduced a specific SDG for water, SDG 6: "Ensure availability and sustainable management of water and sanitation for all".

The decision to incorporate a dedicated water goal (SDG-6) among the 17 SDGs recognises that water is not only part of many other SDGs but, in many aspects, their precondition. Within this goal are fundamental targets for drinking water provision, sanitation, and environmental sustainability. The water goal is expected to address the global water crisis as it unfolds, as evidenced by increased water scarcity, inadequate sanitation, widespread pollution, accelerated declines in freshwater biodiversity and the loss of vital ecosystem goods and services: water is essential for the survival and productivity of all life and ecosystems. Sustainable Development Goal 6, which ensures the availability and sustainable management of water and sanitation for all, underpins much of the 2030 Agenda for Sustainable Development.

Water engineering is a multidisciplinary profession involving the combined skills and collaboration of many engineering subdisciplines. To better understand how these engineers can contribute to achieving SDG 6, which aims to ensure the availability and sustainable management of water and sanitation for all, designs must be (locally) accessible, applicable, appropriate, and affordable.

The role of engineers in water projects (product development, planning, design, project management, construction, operation, maintenance, direction and management of institutions) will undoubtedly be pivotal for achieving SDG6 by ensuring the availability and sustainable management of water and sanitation for all. Engineers are professionals who are educated and trained to lead the work and subsequent management of the investments necessary to achieve the objectives of SDG6.

With only five years left to achieve the SDGs, we need an immediate and integrated global response to improve progress on SDG 6 rapidly. As we face the challenges related to SDG6 fulfilment, technological innovation, knowledge management, advanced research, and capacity development will generate new tools and approaches and, equally significantly, will accelerate the implementation of existing knowledge and technologies across all countries and regions. Therefore, engineering must be considered an accelerator to reach SDG 6.

From a water security perspective, the following must be considered among the vectors that move the world today: population growth, the unstoppable urbanisation process, and climate change. Consequently, it is of the utmost importance to focus on a virtuous water cycle that allows for securing water in cities and contributes to their sustainability and the well-being of their citizens.

Water Cycle with the SDG6 Targets (UN Water)

2.2 SUPPLY, TREATMENT AND DISTRIBUTION

The increasing population concentration in large cities and the demand for improved water services force engineers to look for higher efficiency. To reduce the economic efforts, it is crucial to take advantage of experiences and lessons learned in developed countries, where the urbanisation process has already occurred in recent decades. This process is now being intensified in developing countries.

Opening and closing a simple drinking water tap requires significant engineering and monetary efforts. Historical evidence indicates that with increasing income per capita, environmental quality deteriorates until a turning point is reached when citizens demand better ecological quality. Engineers face the dilemma of defining environmental levels consistent with the level of development feasible for their communities.

It is up to the engineers to transform the increasing scarcity of safe water and social demands into a virtuous circle of water that ensures the quantity and quality of drinking water, the coverage of essential sanitation services, the conservation and recovery of watercourses as well as the management of the extreme phenomena such as droughts and floods, with full awareness and community collaboration. Also, great efforts will have to be taken to achieve peaceful solutions to disputes over the use of shared water resources.

To complete all these actions, engineers should consider integrating urban watercourses in city planning as an improvement factor to increase the quality of life of the city's inhabitants.

In their design, wastewater treatment systems must consider minimising their impact as generators of greenhouse gases, either by implementing the treatment systems using less energy or lower emissions or by reusing these gases and electric power generators.

After studying the urbanisation process and population growth experienced in several developing countries during the last decades, a think tank held over the past decade within the WCCE (World Council of Civil Engineers) reached several conclusions:

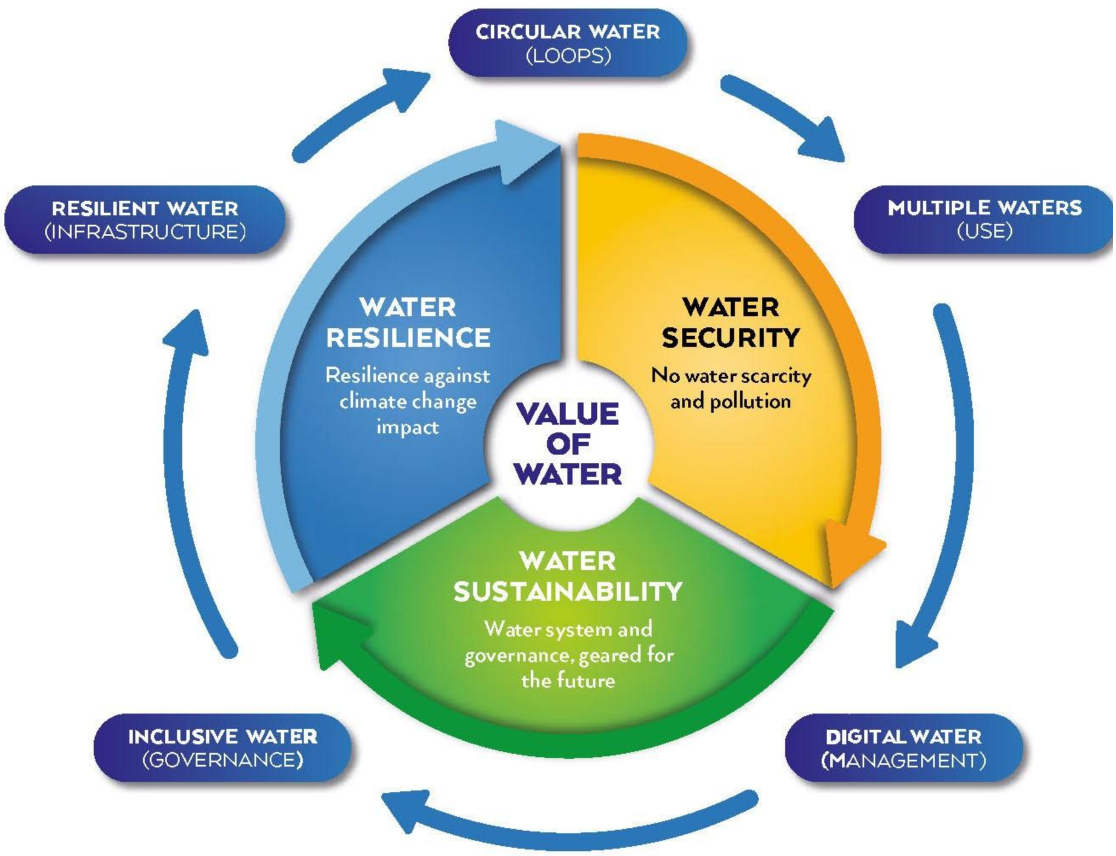
- To ensure the availability of sound water cycles in the cities, without adverse conditions, and sustainability requires:
    - Prior and rigorous planning, with a time horizon of 10 or 20 years, allowing:
        1) The introduction of the required prior restraints based on environmental grounds
        2) The reservation and protection of better-quality sources to provide a human supply as the first priority

    - Sufficient and stable funding, at medium and long term, legal and financial security
    - Demanding engineering efforts to build and manage infrastructures before and after the use of water in the city
    - Capacity to intervene and to decide in territorial and urban planning
    - To act at the right level, as comprehensive as possible, higher than the local one and with well-defined competencies, to obtain the necessary economies of scale and scope that cover the service efficiently
- Alternative resources (desalination, regeneration, and reutilization) are valuable for achieving water security or solving qualitative problems. However, they are more expensive and increase energy dependence, so they should generally be considered complementary sources, not replacement alternatives.
- It is necessary to control and monitor the quantity and quality of resources. There is no reliable information about supply amounts or supply typologies in each city. Even less reliable information is on wastewater typologies (septic tanks, sewage, sewage and wastewater treatment plants)
- Network Sectorization (for consumption control, leakage control, and investment planning) and connections and distribution rings are very beneficial.
- Sanitation and wastewater treatment are as crucial as the supply. They affect the resource's sustainability and the population's health conditions. Supply systems cannot exclude or make them outdated when the population exceeds the minimum subsistence level.
- If separate sanitation networks cannot be implemented, at least SUDS (sustainable urban drainage systems) and storm tanks should be used to reduce the necessary capacity of wastewater treatment plants significantly, their operating costs, and the discharge of contaminated water into rivers or aquifers.
- Demand management is the best and cheapest alternative resource to meet the supply.
- In a broad scope, we cannot adequately respond to droughts and population growth if we have not foreseen the needed infrastructures and the efficient operators of facilities, so new resources should be looked at through currently available technologies unless this would lead to unaffordable increased costs.
- Knowledge management should be incorporated into the management and operation of the systems.
- It is very important to technify the systems and provide them with "intelligence" that enables better operation and management through R&D+I and knowledge transfer.

Water resource management involves many parties, including utilities, authorities, regulators, and end-users. Although many planning, monitoring and optimisation tools have been developed and implemented by engineers –like hydrologic and hydraulic models, real-time monitoring systems and control systems for water treatment and distribution, and decision support systems for reservoir and hydraulic infrastructure operations– these systems usually do not communicate with each other and thus raises a need to have a framework that integrates all these applications. The lack of water ICT (Information and Communication Technologies) standards prevents effective interoperability and increases the cost and maintenance of such applications.

Thus, the necessary step forward would be a Water-Smart society, one in which the value of water is recognised and realised to ensure water security, sustainability, and resilience. All available water sources are managed so that water scarcity and pollution are avoided, water and resource loops are primarily closed to foster a circular economy and optimal resource efficiency, the water system is resilient against the impact of climate and demographic change, and all relevant stakeholders are engaged in guaranteeing sustainable water governance.

The model for reaching a water-smart society includes three key objectives that need to be achieved to realise the core value and five specific innovation concepts crucial to realising the objectives. The following figure indicates how the innovation concepts and key objectives are interrelated, generating a 'flying wheel' effect that drives the process towards the Water-Smart Society.



Concept Model to build a Water Smart City (Water Europe – Water Resilience Strategy/Vision 2024)

Clearly, results in actual cases show a need to combine structural (e.g., innovative water technologies/SWT) with non-structural measures (e.g., SUDS) with the perspective of capturing and utilising stormwater as a potential complementary solution to address water scarcity and flood risk simultaneously. The feasibility of these measures should be examined at three geographical scales: the watershed, the sub-watershed (the city), and the site level (the urban zone considered) in line with the national water strategy and the city's urban growth development strategy.

Smart water management aims to achieve water security at all levels (building, city, and regional) in a sustainable and self-sufficient manner through information technology, monitoring and control technology, and the implementation of a holistic system of all the processes in the water cycle. It also benefits water utility companies economically by reducing non-revenue water losses and detecting illegal connections and water theft.

Experts have proposed the following overall framework for a smart water city based on the characteristics of smart water. The proposed framework has seven main components, which can be categorised into three main compartments. The first is Hardware (Sensors and Sensors Adapters), which deals with data acquisition, monitoring, conversion and transmission. The second is the Water Information System (Big Water Data Management and Analysis), which deals with data processing and storage. The third one is software (support services and applications), which deals with modelling and analytics, real-time monitoring and control systems, decision support systems, visualisation, and dissemination of information to stakeholders.

2.3 HOW RECYCLING IS INHERENT TO SMART CITIES

The International Water Association has published "The IWA Principles for Water-Wise Cities" to assist leaders in developing and implementing their vision for sustainable urban water. These principles remark four actions based on the base principle that all citizens can access water and sanitation services. The first level (Regenerative water services for all) explains that the main goal is to ensure public health while protecting the quality and quantity of water resources for future generations by ensuring the efficient production and use of water, energy and materials. Regenerative water services are essential to climate change adaptation and mitigation strategies, leading to city carbon neutrality. Five principles underpin regenerative water systems:

- REPLENISH water bodies and their ecosystems within the basin by taking from or discharging them only what the environment can give or absorb. Protect the quality of these same water sources from wastewater and urban run-off to ensure ecosystem health.
- REDUCE the amount of water and energy used per capita. Minimise the energy used in moving and treating urban waters, including rainwater.

1. Sensing Devices Layer

Sensors: Water flow (level, velocity, discharge, pressure), pressure, quality sensors, remote sensing/geospatial tools.

Outputs: Captures raw water quantity, water quality, and geographical data.

2. Sensor-Adapter Layer

Data loggers: Onsite units, vehicle-mounted, buoy-mounted—each with storage/display capabilities.

Connectivity: Short-range wireless (HAN/NAN) or wired networks.

3. Data Layer

Communication: Wired networks or long-range wireless (FAN, IAN, WAN).

Central DB: 'Water Information System (Database)' powered by Big Data Analytics and Standardization.

Embedded in the broader Smart City Information System.

4. Service-Support Layer

Forecast systems, hydraulic/hydrological modeling & simulation, feeding into an Operation Center.

Visualization tools: Dashboards, alerts, reports/analysis, and overall system orchestration from the control center.

5. Application Layer

Decision-Support Systems: For planning, optimization, resource allocation.

Warning Systems: Early detection of leaks, floods, anomalies.

Dissemination Applications: Community alerts, dashboards, stakeholder communications.

Overview of the SWM architecture framework (adapted from L.G. Ler and P. Gourbesville)

- REUSE and use diverse sources of water with treatment that matches the use, applying the "fit for purpose" water quality approach and Integrated Water Resources Management (IWRM); RECOVER energy from water, whether through heat, organic energy or hydraulic energy; RECYCLE and recognise the value of "upcycled" materials, such as nutrients or organic matter, using these materials within the systemic approach;
- Use a SYSTEMATIC APPROACH integrated with other urban services. Consider the different parts of a water system as one system and connect water to other services such as health, transport, food production, waste or energy as a whole system to enable solutions which reduce and reuse while improving service costs efficiently. In several countries, wastewater control has been used as an alert network for early detection of COVID-19.
- INCREASE THE MODULARITY and ensure multiple resource, treatment, storage, and conveyance options are available throughout the system to ensure service levels and resilience of urban water systems in the face of either gradual or sudden changes—gradual changes as a result of persistent stresses, sudden changes as a result of shocks to the system, and failure to cope any longer with persistent stresses.

Moreover, Earth's cities buzz with activity and growth while urban lights boldly shine from space. Although human societies are growing and thriving, water scarcity is a persistent problem plagues cities worldwide. Effectively managing water-scarce towns has been a notoriously challenging puzzle through the ages and is increasingly difficult.

In the face of drought and increasingly scarce conventional water sources, several cities have begun diversifying their water portfolio by adding nonconventional sources. They are either incorporated by increased local capture, such as stormwater in Los Angeles or Tucson, or "sponge cities" in China (in which green infrastructure enables the management, filtering, and retention of stormwater) or are generated by new technological advances such as wastewater reuse and desalinated seawater. Indeed, advances in membrane filtration and energy recovery are increasing the attractiveness of indirect or even direct potable reuse, which are pioneered in places including Orange County, San Diego, Windhoek, Singapore, and India. These provide more flexibility, particularly in the face of climate change. A fit-for-purpose use philosophy and corresponding infrastructure can support their optimal use, promoting energy-efficient and low-cost local water sources for non-potable uses.

Reuse and desalination already make obtaining more water at very reasonable prices possible, which will tend to drop substantially in the coming years due to the reduction in energy costs and the expected improvement in treatment processes' efficiency. There are examples of full-scale applications of direct reuse of urban wastewater, which have long been done in space stations where price is not a decisive factor, but also in Namibia and

Singapore. Public acceptance was challenging in these cases, requiring a long communication process until confidence levels were established regarding this freshwater source. In reality, indirect reuse is the current practice in most supply systems that capture freshwater in natural systems, where effluents were previously discharged, and existing water treatment plants are not as efficient as those created for direct reuse.

Reusing water treated by reverse osmosis technology remains less expensive than that from desalination plants. The higher salinity of the ocean water requires more pressure to be applied in the reverse osmosis process, and advanced water treatment requires under a third of the energy needed for desalination. Therefore, cities have begun to see wastewater as a strong ally in dealing with droughts while avoiding significant infrastructure costs: a previously untapped source is an important resource not to be thrown away.

Using treated municipal wastewater for drinking is not quite common, though it is well-established in some places. Some countries, namely Australia, Namibia and Singapore, are already drinking treated wastewater, as are some populations in the USA, including California, Virginia and New Mexico. It is usually safe, but public opinion is swayed by those who refer to ‘toilet to tap’ reuse as a way to discourage use. The reuse has focused on non-drinking applications, such as landscape irrigation and industrial processes, or urban non-drinking purposes, such as toilet flushing and cleaning. These are initial steps in most reuse experiences because they demand lower levels of treatment. Recycling wastewater near where it is generated provides another approach to save on transportation infrastructure to the central water treatment plant.

The United States Environmental Protection Agency (US EPA, 2004) gives a good account of urban reuse systems that provide partially treated (fit-for-purpose) wastewater for various non-potable purposes, including:

- Irrigation of public parks and recreation centres, athletic fields, school yards and playing fields, highway medians and shoulders, and landscaped areas surrounding public buildings and facilities;
- Irrigation of landscaped areas surrounding single-family and multi-family residences, general washdown, and other maintenance activities;
- Irrigation of landscaped areas surrounding commercial, office and industrial developments;
- Irrigation of golf courses;
- Commercial uses, such as vehicle washing facilities, laundry facilities, window washing, and mixing water for pesticides, herbicides and liquid fertilisers; and
- Ornamental landscape and decorative water features, such as fountains, reflecting pools and waterfalls.

Two main issues govern the potential for using municipal and urban wastewater: the level of sewage cross-contamination and the application and location. Water scarcity and the cost and availability of new water sources are also essential factors. It is better to restrict the discharge of hazardous substances to sewers, particularly those that render the wastewater difficult to treat. Urban runoff, for example, could be directly reused for specific purposes, but once combined with blackwater, it would require additional treatment. The drivers for reuse are legislative and principally driven by economics. If used water is available at a lower or a similar price (including the cost of conveyance), it will be considered over and above conventional freshwater sources. In some water-scarce countries or regions, necessity dictates and favours high levels of reuse.

Reusing water in agriculture is a promising area. Many countries have already practised it formally and informally. Reusing water in peri-urban areas offers the opportunity to produce food close to the consumption area.

In addition to new water sources in urban supply systems, future approaches will include separate networks with different water qualities depending on their use. In fact, only about 1 to 2% of the water we use needs to be potable, so separate systems would reduce the treatment levels for most of the water we use daily. The widespread use of this approach will imply the resizing of buildings and public systems, something disruptive in the years to come. Separate networks, including one for wastewater reuse, may also be considered at the scale of housing and communities. In low-density areas, more or less autonomous houses may be justified. As for sanitation, dry toilets may also be used, with incineration or composting, since it is much easier to reuse shower water and wash clothes and dishes if the sanitary sewer is previously separated.

Urbanisation and urban development have significantly impacted the permeability of most cities' surfaces and, thus, have generally increased runoff and reduced groundwater recharge in urban areas. Most cities have implemented separate drainage systems that convey stormwater runoff directly to a nearby water body. These systems try to avoid the problems faced by those relying on combined sewers. Another possibility is implementing a system that allows rainwater to be retained in storm tanks before it reaches the treatment plants. Storm tanks are huge underground tanks designed to store the first rush of rainwater, which is also the most polluting, even more than sewage, because it carries away all the dirt accumulated on streets and pavements. In this way, these tanks prevent treatment plants from becoming overloaded and having to discharge excess untreated water into receiving watercourses. On days of heavy rainfall, these waters are held in the storm tanks until the rain stops. That’s when it’s gradually fed into the purification plants. This not only prevents it from polluting the rivers but also prevents flooding and environmental damage. Once purified, the water can be discharged back into the rivers under better conditions without threatening the ecology of the water flow.

Traditionally, the recommended solution to stormwater pollution was intercepting contaminated stormwater and conveying it to the municipal stormwater treatment plant before discharging it to natural water bodies. In general, stormwater is perceived as a form of wastewater to be disposed of, though it presents different quality characteristics from sewage. It does not include human waste and requires less treatment to achieve the quality needed before being used as an alternative water source. But as the drought years dragged on and water scarcity intensified, capturing stormwater for the water supply before it was polluted and then using or storing it made sense. With the treatment capacity installed to control pollution in Los Angeles County, the city and the county are now looking into the best ways to capture these resources through aquifer infiltration and other methods. This way, the cities responsible for reducing stormwater pollution could address water quality issues and benefit from additional water supply or ancillary benefits, such as parks that could capture and infiltrate stormwater.

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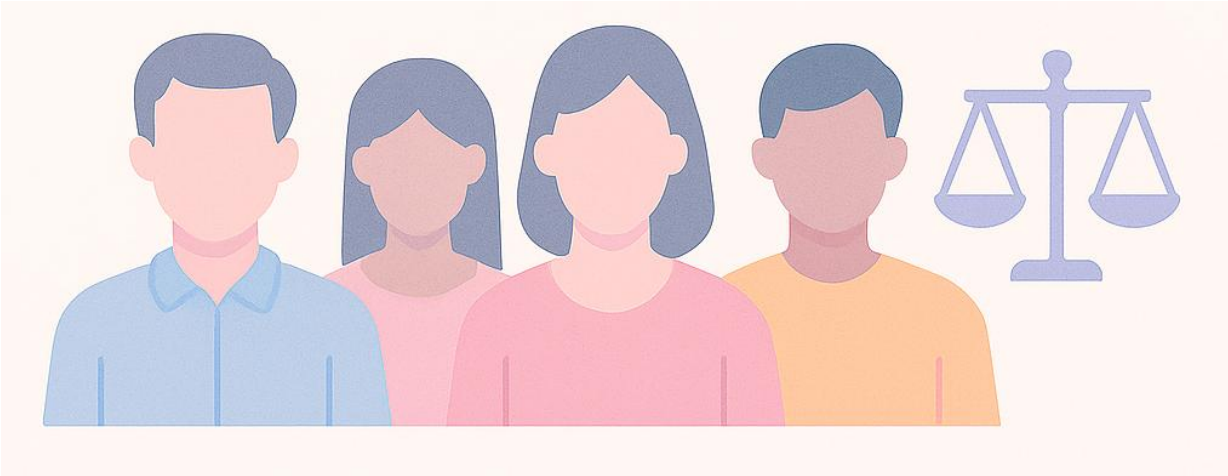

3.0 POLICIES, REGULATIONS AND FINANCING

3.1 POLICYMAKERS AND REGULATORS

3.1.1 Introduction

Access to clean water and sanitation is a cornerstone of sustainable urban development, and achieving this goal is increasingly linked to the concept of smart cities. By 2008, 50% of the world's human population was living in urban areas (United Nations, Department of Economic and Social Affairs, n.d.). Urban areas hold significance as places where approximately 70% of the world's GDP is currently held (United Nations: Department of Economic and Social Affairs, n.d.). It is imperative to safeguard water resources in cities. There are issues of equitable access to clean drinking water, as well as many other considerations encompassed by the global Sustainable Development Goal (SDG) 6. SDG 6 aims to ensure sustainable management of clean water and sanitation for all people (United Nations, Department of Economic and Social Affairs, n.d.).

3.1.2 Achieving the sustainable management of clean water and sanitation

Progress towards achieving SDG 6 has been inadequate. The United Nations World Water Development Report (2023) emphasises the importance of transformative partnerships in supporting water-related interventions. These partnerships are crucial for generating political will, fostering innovation, and ensuring the peaceful and sustainable management of water resources (UN Water, 2023). According to the UN-Water 2030 Strategy's theory of change, the SDG 6 Global Acceleration Framework (GAF) aims to deliver faster results as part of the Decade of Action towards 2030 (UN Water, 2020). This strategy is grounded in the idea of integrated and coordinated action among different governments worldwide, as well as among water and sanitation actors and users at all levels of governance and participation (UN Water, 2020).

With the world experiencing rapid urbanisation, Wu et al. (2020) assert that urban water supply systems are currently the most critical infrastructure (Wu et al. 2020).

Smart and sustainable cities of the future need smart water supply systems that use technologies such as integrated sensors, controllers, and cloud computing (Wu et al., 2020). The lack of safe drinking water impacts millions worldwide (Wu et al., 2020).

The United Nations World Water Development Report 2023 highlights the need to explore opportunities through cooperation and partnerships among parties interested in supporting water-related interventions (UN Water, 2023). Partnerships and coordination at all levels can be powerful agents of change towards improved water governance and decision-making (UN Water, 2023). According to the SDG 6 GAF, these partnerships aim to generate sustainable political will, encourage innovation within the sector, promote peaceful management of water resources and avoid conflict (UN Water, 2020).

3.1.3 Water management in smart cities

According to Budge et al. (2022), the water, sanitation and hygiene sectors are still unresolved regarding the best way to achieve environmental health in living environments (Budge et al., 2022). There are several transformative water and sanitation management interventions that, when scaled up, can deliver healthy environments (Budge et al., 2022).

Digitisation of urban water infrastructure using reliable information and communication technologies (ICT) is a critical solution for factors that impact urban water, including climate change, urbanisation, and water infrastructure maintenance (Oberascher, 2022).

According to the Arup City Water Resilience Approach (CWRA), policymakers and regulators have important roles in ensuring the successful implementation of sustainable water resilience initiatives. These include:

- Strategic planning: Developing long-term visions for water resilience to guide sustainable resource use.
- Policy and regulation: Creating and enforcing laws that promote resilient water use and integrated land-use planning.
- Interagency coordination: Fostering collaboration among government agencies and water actors across local, regional, and national levels.
- Stakeholder engagement: Facilitating robust dialogue among public and private sectors, civil society, and communities to ensure inclusive decision-making.
- Innovative financing: Allocating resources strategically and exploring financing mechanisms to encourage private sector investment in water resilience initiatives.

The responsibility of policymakers is to ensure that marginalised communities are not left behind.

There are good examples of how adaptive governance, citizen cooperation, smart technologies, and coordinated action have worked to avert crises caused by severely restricted access to water.

In 2018, Cape Town faced a "Day Zero" event when taps were predicted to run dry. The city implemented a comprehensive strategy, including (SIWI, 2020):

- Public awareness campaigns to promote water conservation and reduce water consumption.
- Installation of water-saving devices across households and industries.
- Development of alternative water sources such as desalination and groundwater extraction.
- Implementation of a tiered water tariff system to incentivise conservation.

Singapore has worked towards achieving 40% of the city’s water demand through wastewater recycling, utilising its NEWater initiative (Smart Water Magazine, 2024).

3.1.4 Conclusion

As cities grow and climate challenges intensify, smart water management becomes indispensable. Policymakers and regulators play a central role in shaping resilient water systems through strategic planning, innovation, and partnerships. By investing in these areas, cities can secure a sustainable future where water and sanitation contribute to health, prosperity, and environmental harmony.

3.2 COSTS AND FINANCING

Implementing smart water systems in cities is often perceived as costly due to the need for advanced technologies, infrastructure upgrades, and real-time monitoring solutions. However, while initial investments may be high, the long-term benefits of efficiency, sustainability, and cost savings can outweigh these expenses.

In urban areas, traditional water systems have been crucial in providing clean and reliable water for various purposes, including drinking, irrigation, sanitation, and industrial use. Still, many face significant challenges as cities grow and environmental pressures increase. Centralised Water Distribution Systems are the most common system in modern cities, where water is sourced from rivers, lakes, or reservoirs, treated in water treatment plants, and then distributed to households and businesses through an extensive network of pipes and pumps (van Duuren et al., 2019). These systems provide a continuous and stable water supply to a large number of people. Centralised systems are cost-effective for large populations because the well-maintained infrastructure can serve many people. Centralised management allows for more effective monitoring of water quality, pressure, and treatment processes. However, as water moves through a vast network, it can be susceptible to contamination from leaks, pollution, or ageing infrastructure. Water loss due to leaks, ageing infrastructure, or theft can be significant in some cities, wasting valuable resources. Maintaining a large infrastructure, including treatment plants and pipelines, can be expensive. Many cities rely on external sources, such as rivers or aquifers, which can be vulnerable to droughts, pollution, or overuse.

In some urban areas, especially in older cities or informal settlements, rainwater is collected from rooftops and stored in cisterns or tanks for later use, such as irrigation or non-potable water needs (Bouramdane, 2023). Rainwater harvesting can reduce the dependency on municipal water supplies, especially during heavy rainfall. It reduces water bills and can be a cost-effective solution, especially in areas with frequent rainfall. It uses a renewable natural resource, reducing the environmental impact of extracting water from other sources. However, rainwater collection depends on the amount of rainfall, making it unreliable during dry seasons or periods of drought. Storing rainwater requires large tanks and regular cleaning to avoid contamination. In many cases, rainwater requires filtration or treatment before it is safe for drinking.

Some coastal cities rely on desalination plants, which convert seawater into freshwater, to address water scarcity, especially in areas where freshwater sources are limited (Bouramdane, 2023). Desalination provides a consistent and reliable source of ocean water, regardless of weather patterns or freshwater availability. For cities near the coast, desalination can be a viable long-term solution to supplement freshwater supplies. However, desalination requires large amounts of energy, making it expensive and contributing to environmental impacts if not powered by renewable energy sources. Discharging brine into the ocean can harm marine ecosystems and affect local fisheries. Desalination plants are costly to build, maintain, and operate, making them unsuitable for many cities.

Smart water systems are advanced, technology-driven solutions designed to enhance water management in urban environments. These systems integrate digital tools, sensors, data analytics, and automation to monitor, control, and optimise water distribution, consumption, and treatment.

Predictive analytics leverages historical data, weather patterns, and artificial intelligence (AI) algorithms to forecast water demand, allowing utilities to optimise water distribution, especially during peak usage times. By analysing trends and integrating real-time weather data, these systems enable utilities to adjust supply in advance, preventing shortages. The primary advantages of predictive analytics include optimised water distribution, which ensures that water resources are allocated efficiently and shortages are avoided during periods of high demand, and cost savings, as utilities can reduce waste, optimise energy consumption, and prevent the unnecessary purchase of additional water from external sources. Additionally, accurate predictions support improved resource planning by aligning the water supply with future population needs. However, predictive analytics comes with specific challenges, such as data dependency, as it requires large volumes of accurate historical data, which may not always be readily available or complete. Building these models can also be complex and require specialised knowledge and computational resources. Furthermore, the accuracy of forecasts can be compromised by unpredictable factors, such as extreme weather events or sudden shifts in consumption patterns (Stańczyk et al., 2022).

Cities like Cape Town, South Africa, have faced severe water shortages, with the possibility of reaching "Day Zero," a situation where the city's taps would be turned off due to extreme water scarcity. To prevent this, the city used predictive analytics to forecast water demand and adjust the water supply accordingly (Carmody 2018). By analysing historical data and real-time consumption patterns, Cape Town could predict periods of high water usage, such as during hot weather or peak times. These insights enabled the authorities to implement targeted water-saving measures, including restricting usage during peak hours, enforcing water rationing, and encouraging residents to reduce their consumption. The city also adjusted the reservoir supply based on these predictions, ensuring that the available water resources were used as efficiently as possible (ITWeb 2018; Kotzé 2018). This proactive approach helped delay "Day Zero" for a significant period, buying time to implement further water-saving strategies, such as expanding desalination capacity and recycling wastewater. Ultimately, predictive analytics played a critical role in helping the city manage the crisis and avoid a complete water shut-off.

Smart water meters use sensors and communication technologies to measure water usage in real-time, automatically sending data to utility companies for remote monitoring and billing. This provides accurate data, helping utilities identify inefficiencies, reduce waste, and detect leaks early, preventing costly issues and water loss. Additionally, it eliminates estimated bills, reduces human error, and encourages consumers to monitor their usage, promoting responsible water consumption. However, the initial setup can be expensive for utilities, especially when retrofitting existing infrastructure. Continuous water usage monitoring raises potential privacy issues, particularly if data is not anonymised (Bouramdane 2023). Malfunctions or technical issues can disrupt the monitoring and metering process.

Climate change intensifies California's water scarcity through prolonged droughts, erratic precipitation patterns, and extreme heat. In response, the state has adopted smart meters to enhance resilience, with the Los Angeles Department of Water and Power (LADWP) at the forefront of innovation. LADWP utilises SAS Energy Forecasting, an AI-powered tool, to model the impacts of climate change and predict water demand under extreme weather scenarios (SAS, 2023). Over 230,000 smart meters are being installed across San Jose (completed by 2026), providing hourly usage data to residents and utilities. Through real-time alerts, pilot projects reduced water use by 7% and leak durations by 38% (Starr, 2022). Similar systems in LA enable dynamic pricing and rapid leak detection (LADWP, 2018; Huang, 2020). Startups like Phyn deploy AI-driven smart valves (e.g., Phyn Plus) that automatically shut off water in the event of a leak. Installed in homes and businesses, these devices have cut water waste in commercial settings by up to 25% (Huang, 2020). The LA Stormcatcher Initiative uses Internet of Things (IoT) sensors and collaborative data platforms to redirect stormwater into groundwater basins, where it can be naturally filtered and stored. This project aims to capture 3.8 billion gallons of rain per half-inch, addressing scarcity and pollution (Tree People, 2025). California has allocated $880 million to water resilience projects since 2023 (City of Los Angeles Planning Department, 2008). Precision agriculture technologies (e.g., soil moisture sensors) have reduced agricultural water use per unit output by 40% since 2000 (Ecojobs Contributor, 2024). Every 1,000 gallons saved in LA reduces energy use by 6–10 kWh, lowering greenhouse gas emissions (WaterWorld Staff, 2023). While smart meter installations cost $100 million, they yield long-term savings by curbing non-revenue water losses (Starr, 2022).

Many cities worldwide, including Mexico City, face significant losses due to outdated and leaky water infrastructure. In Mexico City, the smart water network employs IoT sensors to monitor pipes in real-time, detecting leaks that would otherwise go unnoticed. This allows for immediate repairs, reducing water wastage and minimising inefficiencies. For example, the city has reduced water loss by implementing smart leak detection systems that pinpoint problem areas, helping maintain a more reliable water supply (Qualcomm, 2021).

Digital water metering enables utilities to implement more equitable and efficient pricing strategies, encouraging responsible water consumption. In Singapore, the Smart Water Metering System (SWMS) is used to gather data on household water usage. This information allows the government to charge based on actual consumption rather than flat rates, promoting water conservation among residents. Additionally, the system sends alerts to users about high water usage, giving them the opportunity to adjust their behaviour before receiving higher bills. This digital metering ensures that users are charged fairly and promotes long-term, sustainable water use (SDWM, 2025).

Bouramdane et al. (2023) evaluate smart city water management strategies using Multi-Criteria Decision Making (MCDM), a methodology that assesses various strategies based on multiple criteria. The study employs the Analytic Hierarchy Process (AHP) to assign weights to these criteria and score strategies accordingly. The goal is to identify the most effective and sustainable strategy for managing water resources in the face of global urbanisation and rising water demand. The criteria used in the study are critical in evaluating the effectiveness of different water management strategies. The Effectiveness and Risk Management criterion, which carries the highest weight (15.28%), measures how well a strategy manages water resources and mitigates risks such as water scarcity, system failures, or extreme weather events.

Another important criterion is Resource Efficiency, Equity, and Social Considerations (10.44%), which focuses on how efficiently water is used and whether the strategy ensures equitable access to water for all communities. The Integration with Existing Systems, Technological Feasibility, and Ease of Implementation criterion (10.10%) assesses how well a strategy can be incorporated into existing infrastructure and how easily it can be implemented. Environmental Impact (9.84%) evaluates the strategy's ecological effects, particularly in reducing pollution and its overall environmental footprint.

The Community Engagement and Public Acceptance criterion (9.79%) recognises the importance of involving the community in decision-making and ensuring public support for the strategy. Other criteria, such as Scalability and Adaptability (9.35%), measure the ability of a strategy to scale and adapt to changing conditions, while Return on Investment (9.07%) evaluates the financial benefits and cost-effectiveness of the strategy. Regulatory and Policy Alignment (8.8%) assesses whether the strategy aligns with existing laws and policies. The Data Reliability criterion (8.78%) emphasises the importance of accurate data in guiding strategy decisions. In comparison, Long-Term Sustainability (8.55%) looks at whether the strategy can deliver lasting benefits without depleting resources or causing harm. The strategies evaluated in the study vary in their effectiveness and weight. Highly weighted strategies, such as Smart Metering and Monitoring, Demand Management, and Behaviour Change, are particularly effective in optimising water usage by monitoring consumption and encouraging responsible behaviour.

Smart Irrigation Systems are also highly effective, as they use sensors and weather data to optimise irrigation and reduce water waste, particularly in agricultural and urban landscapes. Medium-weight strategies include Educational Campaigns and Public Awareness, which focus on raising awareness about water conservation, and Policy and Regulation, which involves implementing and enforcing policies to manage water use. Rainwater Harvesting (collecting rainwater for non-potable uses) and Offshore Floating Photovoltaic Systems (solar panels on bodies of water) are medium-weight strategies for water management. Collaboration and partnerships, greywater recycling and reuse, and distributed water infrastructure are strategies that improve resilience and optimise resource use.

Low-weight strategies, such as Water Desalination, are considered less effective due to their high costs, environmental concerns, and energy requirements. Despite their lower weight, these strategies still contribute to water management and can be combined with higher-ranked strategies to create tailored solutions for each city’s unique needs. The significance of this study lies in its comprehensive, multi-criteria approach to evaluating water management strategies, which provides a more holistic view than traditional methods that focus on a single criterion. The research provides a framework for resource allocation based on weighted criteria, helping smart cities make informed, sustainable decisions. It acknowledges that results may vary depending on each city's specific needs and constraints and suggests future research on the impact of climate change on water management and the use of alternative MCDM methods, such as TOPSIS or ELECTRE, to further refine strategy evaluation.

Smart water systems, while highly efficient and capable of optimising water use, often come with higher upfront costs. These costs are primarily associated with installing advanced infrastructure, such as smart meters, sensors, and communication technologies, which require significant capital investment. For example, the startup costs for a smart water management system can range from $185,000 to $2,300,000, depending on the system's complexity and scale (Finmodelslab Team, 2024). Additionally, ongoing maintenance and data management expenses may add to the overall cost. Ongoing expenses, including software maintenance, updates, and hosting, can account for 5-10% of the total software development budget annually. Additionally, monthly cloud-based hosting and data storage fees can range from $1,000 to $5,000 (Finmodelslab Team, 2024). Utilities also incur costs for electricity, water, and internet services to operate smart water systems, with electricity costs averaging $50 to $200 per month and internet costs ranging from $50 to $150 per month (Finmodelslab Team, 2024). However, in the long term, smart water systems can result in substantial savings through improved efficiency, reduced water wastage, and optimised demand management. By preventing leaks, minimising water loss, and promoting responsible consumption, these systems help utilities reduce operational costs and increase revenue through more accurate billing and demand-based pricing (Marchment Hill Consulting Pty Ltd., 2010).

A financially sustainable water management system, especially in the context of smart cities, strikes a balance between affordability for users, cost recovery for utilities, and long-term investments in infrastructure and innovation. Achieving this balance requires well-designed policies and investment models that promote the efficient use of resources while ensuring that water remains accessible to all. Effective funding strategies include Public-Private Partnerships (PPPs), where governments and municipalities collaborate with private entities to share the financial burden of infrastructure development and technology deployment. These partnerships enable the integration of cutting-edge technologies, such as smart water meters, into existing systems without solely relying on public funds (Avalon Consulting, 2024). Additionally, tariff structures are vital in maintaining affordability while encouraging responsible water use. For example, basic water needs can be subsidised to ensure that vulnerable populations are not burdened, while excessive consumption can be priced at higher rates to incentivise conservation. This tiered pricing model ensures equity while promoting sustainability (Bouramdane, 2023).

Incentives also play a critical role in fostering innovation and ensuring water systems remain financially viable. These include grants, low-interest loans, and tax benefits for public and private sector water management and technology deployment entities. Furthermore, decentralised water solutions such as rainwater harvesting, localised desalination, and treatment plants offer cost-effective alternatives to traditional centralised systems. By decentralising water management, cities can reduce the strain on central infrastructure, enhance resilience, and lower costs associated with large-scale distribution networks (Avalon Consulting, 2025).

Access to water in smart cities can be achieved through a combination of inclusive policies, technological innovations, and equitable funding strategies. Smart cities can ensure universal water access by implementing tiered pricing structures, ensuring that low-income households are protected while incentivising higher-income users to adopt more efficient practices. Public-private collaborations can expand infrastructure to underserved areas. At the same time, decentralised solutions like rainwater harvesting can be deployed in specific neighbourhoods or sectors, ensuring that no one is left behind. By leveraging technology and sustainable financing models, smart cities can achieve the dual goals of efficient water management and universal access, ensuring that water remains a shared resource for all residents, regardless of income or location (IWRA, 2021).

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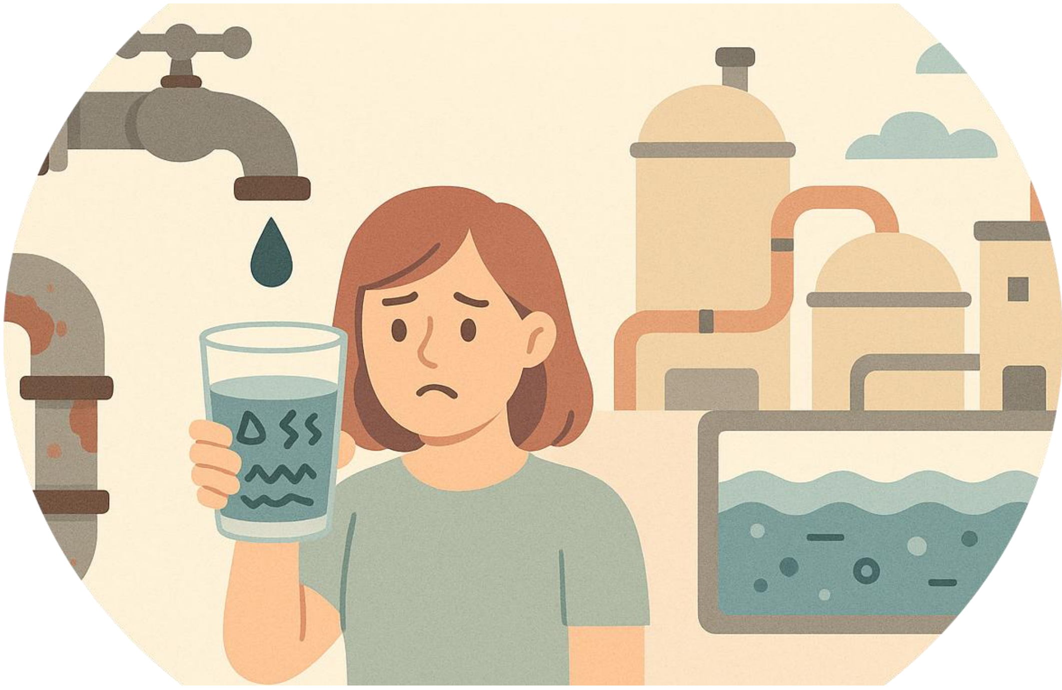


4.0 THE CHALLENGE: AGEING INFRASTRUCTURE

4.1 WATER QUALITY STANDARDS

Water is essential for life. Ensuring it is safe and clean is very important for everyone's health. Today's water quality standards come from groups like the World Health Organisation (WHO) and the Environmental Protection Agency (EPA). These rules help make sure drinking water is free from dangerous pollutants. But, as cities grow and infrastructure falls apart, it's clear these standards might need to change. A major worry is how ageing systems can affect water quality. Old pipes and treatment plants can put drinking water at risk in many cities. Some key factors heavily impacting water quality within distribution networks are discussed below.

4.1.1 Ageing Infrastructure Water Quality Issues

Corrosion and Water Quality:

A significant yet often overlooked danger to our drinking water comes from the pipes that bring it to us. As pipes age, especially those made of iron, they start to rust, which can get into our water supply. In older cities, corroded pipes are common, and they cause serious problems. When these pipes corrode, they create rust (iron oxides), turning the water reddish-brown. While some iron isn't usually bad for health, rust makes the water taste strange and look unappealing.

The real danger? Rusty pipes can let in even worse pollutants. For example, lead pipes are still present in many old neighbourhoods. They can release lead particles into the drinking water, creating serious health issues for children, such as brain damage or developmental delays.

Network Design-Related Issues:

Some water distribution and service pipelines run near or under contaminated areas like sewages in older urban layouts. This design flaw poses a significant risk to water quality, mainly when leakages occur in these pipelines. When water distribution pipelines leak in areas close to sewer lines or contaminated water zones, the reduced pressure in the damaged pipe can create a phenomenon called back-siphonage. This allows untreated sewage, contaminated groundwater, or industrial pollutants to seep into the water supply system. Even minor cracks or breaks in water pipes can cause this dangerous backflow, introducing harmful contaminants into the water supply.

To mitigate this risk, clear policies should be implemented on network designs (both water and sewer) to prevent future contamination. In addition, overhauls and realignments of the existing networks should be undertaken.

Ageing Treatment Facilities: Challenges in Meeting Contemporary Needs

Many cities still depend on water treatment offices developed in the early years, when the demand for water supply was small and poisons were restricted or not expected. Although these offices may still meet administrative guidelines, they frequently find it troublesome to address present-day contaminants not considered in the early design.

Obsolete Technology

Many of the more seasoned treatment offices utilise less effective advances in disposing of more up-to-date toxins. Conventional treatment approaches target organic contaminants (microscopic organisms and infections) and particulates. Still, they may be lacking in tending to develop contaminants like endocrine disruptors, which can pose long-term health dangers at negligible concentrations.

Dilapidated Pipelines:

In addition to eroded channels and obsolete treatment plants, the condition of pipelines that convey water plays an essential part in deciding water quality. Numerous cities depend on water dispersion frameworks that are over 50 years old; there are cases featuring pipelines that have not been replaced for over a century. This may lead to contaminants in the arrangement, which influences water quality.

Physical Deterioration

As pipelines age, they become susceptible to cracks, leaks, and breaks. These vulnerabilities create pathways for contaminants, such as soil, bacteria, and chemicals, to enter the water supply. Leaking pipelines lead to the introduction of contaminants into the treated water.

For example, cracked or broken pipes can allow stormwater runoff, which may contain harmful pollutants like fertilisers, pesticides, and waste products, to mix with treated drinking water during heavy rainfalls or natural disasters. This can lead to the spread of waterborne diseases and pose a significant health risk to the population. In addition, during network maintenance, like leak repairs, particles such as sand or silt can enter the network, causing health problems.

4.1.2 Updating Water Quality Standards

Given the challenges posed by ageing infrastructure, there is a growing need to revisit current water quality standards to ensure they remain effective in protecting public health. The question arises: Should changes be made to current water quality standards in light of these growing risks?

Water quality standards must be updated regularly as new contaminants and threats emerge. Standards should incorporate modern pollutants like microplastics, pharmaceuticals, and endocrine disruptors, which are increasingly found in water supplies but are not adequately regulated under current guidelines. Additionally, standards should focus on minimising contaminants that result from corroded pipes, such as lead and other heavy metals.

4.1.3 Infrastructure modernisation

Governments and water utilities should implement policies that mandate regular assessments of infrastructure conditions, including pipelines and treatment plants. These assessments can help identify areas where the risk of contamination is high and upgrades or replacements are needed.

The future of water quality will also depend on investment in smart water systems. Technologies such as real-time water quality monitoring sensors can detect changes in water quality as it travels through pipelines, providing early warnings of contamination or infrastructure failures. These technologies will allow cities to respond more quickly to emerging issues and ensure that water remains safe from the treatment plant to the tap.

4.2 THE ISSUE OF LEAKAGE IN AGEING INFRASTRUCTURE

Leakages within water distribution systems pose a significant challenge, particularly in older urban areas where the infrastructure has exceeded its intended lifespan. Pipelines installed many decades ago –sometimes over a century– are now showing signs of deterioration, leading to the wastage of millions of litres of treated water each day. This issue of ageing water infrastructure is prevalent in cities worldwide, spanning from developing regions with limited maintenance resources to advanced nations that have postponed necessary infrastructure investments.

4.2.1 Factors Leading to Leakages

- **Obsolete Pipelines:** A considerable portion of the infrastructure established in earlier decades (1960s) was not designed for longevity beyond a few decades. As materials deteriorate over time, they develop cracks and breaks, resulting in water leakage.
- **High-Pressure Systems:** Many cities operate high-pressure water systems to accommodate increasing urban demands. These systems can exacerbate minor cracks, eventually leading to larger leaks.
- **Urban Growth:** As cities expand and populations rise, the existing water infrastructure is often pushed beyond its original capacity, further straining ageing pipes.

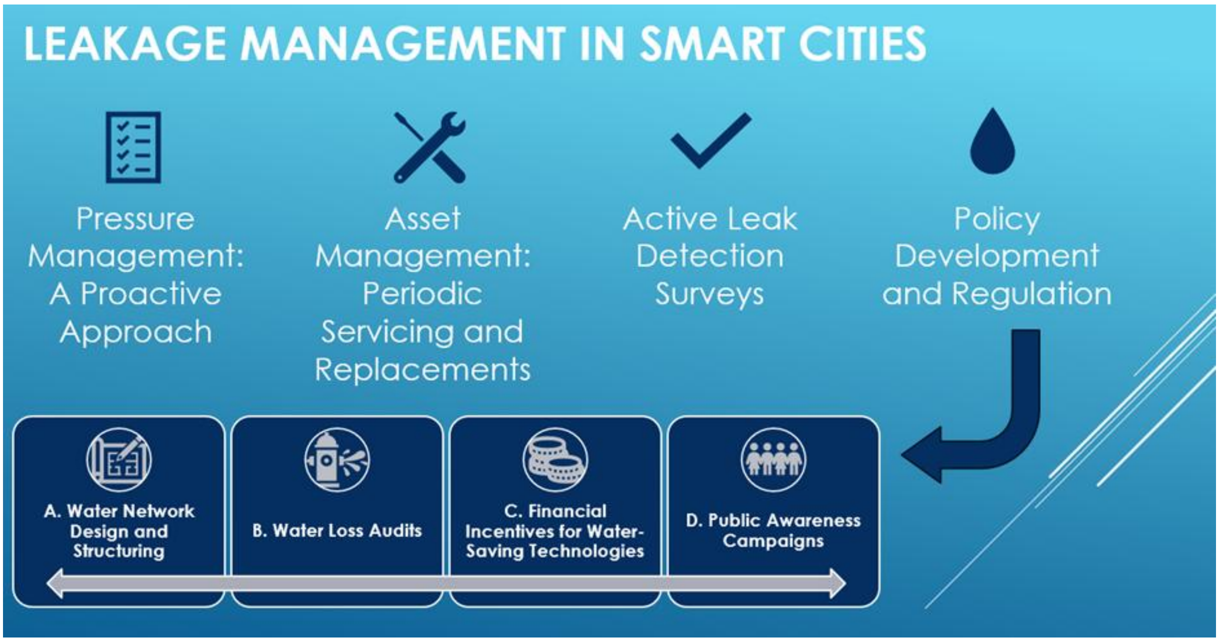
The repercussions of neglecting leakages are substantial, both financially and environmentally. In many cities, approximately 20-30% of treated water is lost through leaks before reaching consumers. This not only results in increased operational costs, which are often transferred to residents through elevated water tariffs, but also leads to the wastage of a finite resource that is becoming increasingly scarce.

4.2.2 Advanced Strategies for Managing Leakages in Smart Cities

To effectively mitigate water leakage, cities must implement a combination of cutting-edge technologies, strategic asset management, and supportive policy frameworks. While traditional approaches such as manual leak detection and reactive maintenance are essential, they must evolve to meet the requirements of a smart and sustainable urban environment. The following is a brief description of a leak management alternative.

- Pressure Management: A Proactive Approach

One of the main reasons urban water distribution systems leak is high water pressure in the pipes. Although this approach helps satisfy cities' increasing demands, increased pressure deteriorates ageing infrastructure, leading to pipe cracking and bursts over time.



World Health Organisation (WHO) & International Water Association (IWA). (2014). Guidelines for Drinking-water Quality: Leakage Management and Control. WHO Press. Adapted for illustrative purposes

Pressure control techniques can drastically improve the distribution network's lifespan and decrease leaks.

- **Dynamic Pressure Management:** Using smart sensors and automated valves, cities can dynamically adjust water pressure based on real-time demand. This reduces strain on ageing pipes and minimises the chances of leaks.
- **Zonal Pressure Control:** Dividing the water distribution network into zones allows for better control over water pressure in specific areas. Zones with lower demand can be operated at lower pressures, preventing unnecessary stress on pipes.

- Asset Management: Periodic Servicing and Replacement

Upgrading and maintaining water distribution systems requires a comprehensive approach to effective asset management. As time passes, the demand for prompt repairs, routine maintenance, and replacement of aged infrastructure increases.

- Periodic Servicing: Scheduled inspections and maintenance of pipelines, valves, pumps, and other appurtenances help identify potential problem areas before they become major leaks. Regular servicing ensures equipment operates efficiently and reduces the risk of unplanned failures.
- Replacement of Appurtenances: Key components of the water network, such as valves and meters, deteriorate over time and must be periodically

replaced. Appurtenances that are overused or obsolete are more prone to malfunction, leading to leaks and inefficiencies.

- Lifecycle Monitoring: Implementing a system that tracks the lifecycle of infrastructure assets allows water utilities to anticipate when pipes and other elements will need replacement. By addressing deteriorating network sections before they fail, cities can prevent leaks and improve water service reliability.

- Active Leak Detection Surveys

Traditional leak detection methods often involve waiting until leaks are visible or reported. However, by employing Active Leak Detection Surveys, water utilities can identify and fix leaks before they cause substantial water loss.

- **Acoustic Leak Detection:** This method uses specialised sensors that detect the sound of water escaping from pipes underground. Regularly conducting acoustic surveys can help cities identify leaks in areas that might not be visible from the surface.
- **Ground-penetrating radar (GPR):** GPR technology can detect changes in the soil caused by water leakage. This is especially useful in locating leaks in large, complex systems, such as those under roads or urban infrastructure.
- **Smart Leak Detection Sensors:** Smart technologies such as IoT (Internet of Things) sensors can continuously monitor water flow and detect anomalies that signal the presence of leaks. These sensors allow cities to locate leaks in real-time, significantly reducing the time it takes to initiate repairs.

- Policy Development and Regulation

Effective policy development is essential for managing water leakages and ensuring that smart cities remain resilient and sustainable. Beyond operational solutions, well-crafted policies create the framework to guide public and private sectors in minimising water loss. These policies should address leak detection and response, and tackle the structural and design challenges that lead to leakages, primarily due to vandalism during urban projects such as road construction.

- Water Network Design and Structuring:

A significant source of water leaks and infrastructure damage is accidental or deliberate vandalism during road construction, building projects, and other urban development activities. Developing policies that govern the design and structuring of the water distribution network can minimise these risks:

- Clear mapping and documentation of pipelines: Cities should maintain up-to-date, detailed digital maps of all water pipelines, valves, and critical infrastructure. These maps should be readily accessible to urban developers, utility companies, and city planners to prevent accidental damage during construction projects. Mandating Geographic Information Systems (GIS) can ensure accurate mapping and tracking.
- Vibration and impact-resistant materials: Encourage the use of vibration-resistant or impact-tolerant materials for water pipelines in high-risk areas, such as those frequently affected by heavy construction. Installing flexible, durable materials reduces the chances of cracks and breaks caused by construction equipment or ground movement.
- Regular inspections during and after urban developments: Policymakers should mandate that water networks be inspected during and after construction projects to check for potential damage. This can help ensure that leaks or compromised infrastructure are promptly addressed before they escalate into significant issues.

o Water Loss Audits:

Regular water loss audits should be mandated to evaluate the effectiveness of existing water infrastructure and identify areas prone to leaks. These audits provide data-driven insights that enable utilities to detect patterns, understand the root causes of water loss, and develop targeted interventions.

o Financial Incentives for Water-Saving Technologies:

Policymakers can offer incentives to encourage the adoption of water-efficient technologies, both for utilities and consumers. These may include:

- Tax credits or subsidies for water utilities that invest in smart water meters, pressure management systems, and leak detection technologies.
- Incentives for developers to incorporate water-efficient designs in new buildings, reducing strain on the water system and preventing future leaks.

o Public Awareness Campaigns:

Engaging the public in leak prevention and reporting is essential. Policy frameworks should include public awareness campaigns that educate citizens on the importance of conserving water and the economic and environmental costs of water leaks. Utility companies can speed up response times and repairs by encouraging people to report visible leaks and providing clear channels.

4.3 FLOODING

4.3.1 Introduction

In a changing climate, increasing urbanisation, population growth, and economic development in cities and urban areas have increased flood risk, placing immense pressure on municipal flood control systems. Currently, more than half of the world's population lives in cities. With this population expected to grow to 68% by 2050, flooding is projected to be one of the most prevalent natural hazards in the next decade, with particularly disastrous impacts in low-income countries. By June 2022, 1.81 billion people, 23% of the world population, were directly exposed to 1-in-100-year floods (Rentschler et al, 2022). Depending on severity, flooding can lead to displacement of communities, destruction of essential services, including drainage infrastructure and disruption of local economies, leading to social instability and financial losses.

Disruption of economic activities by floods, Kakuma Refugee Camp, Kenya (© Eric Muchunku)

4.3.1 Effects of Climate Change on Flooding

Climate change has exacerbated flood risk by disrupting weather patterns and increasing river flows, making flood events more frequent, severe, and unpredictable. Climate change has intensified various flood-inducing factors, including extreme rainfall, storm surges, elevated river runoff, rising sea levels, and astronomical tides. The concurrence of two or more of these drivers leads to compound floods, aggravated by urbanisation-related issues such as land subsidence, the proliferation of impervious surfaces, and ageing drainage infrastructure, significantly heightening the risk of severe flood-related disasters. For instance, rising sea levels, intense tropical cyclones and typhoons and heavy monsoonal rainfall place an increasing number of East and Southeast Asia regions at heightened risk of compound flooding, likely to further strain and exceed the capacity of existing flood control infrastructure (Ruan et al, 2024).

In recent years, infrastructure systems have become increasingly vulnerable to climate change, which is defined as the degree to which a system is susceptible to and unable to cope with adverse effects, including climate variability and extremes (The Economist Intelligence Unit, 2021).

While infrastructure's vulnerability is influenced by its sensitivity and exposure to specific climate hazards in its geographical region, any degree of vulnerability results in diminished performance and shortened service life of critical infrastructure.

Climate change has rendered many existing design frameworks increasingly unreliable, leading to ineffective infrastructure designs. For instance, traditional design return periods, commonly used to size infrastructure, are no longer viable due to extreme weather events, heightened variability and unpredictability. Previous studies indicate that urban flood volumes exhibit a non-linear increase with rising rainfall intensity under climate change. Similarly, the maximum flood-affected area expands unproportionately, showing heightened sensitivity to smaller rainfall events (Sun et al., 2021).

Consequently, it is becoming ever more critical for cities to assess climate change-related flood drivers, develop tools to predict and design for compound floods and develop roadmaps to deal with the associated flood risks, including preventing flood events from causing further damage to infrastructure. Additionally, to mitigate the residual risk posed by floods, cities should thoroughly analyse infrastructure vulnerabilities to identify, evaluate and implement adaptation measures that enhance infrastructure resilience to climate change.

4.3.2 Inadequacies of Traditional and Ageing Flood Control Infrastructure

Most developed countries built their current infrastructure in the mid to late 90s with a service life of 50 years. Such ageing infrastructure installations, including flood management systems, present significant challenges as repairing or replacing them is both complex and costly. However, the cost of ignoring or delaying investments in maintenance and modernisation is far greater over time. This neglect results in cities grappling with the severe financial, public health, and safety impacts of flood disasters, arising from compromised systems, including overwhelmed drainage networks, ruptured pipelines, and inundated treatment plants.

Ageing infrastructure, including flood control structures, was designed based on historical climate data and is not equipped to handle the increased frequency and intensity of floods exacerbated by climate change. For instance, reservoirs, drainage channels, and treatment plants in older cities may no longer be large enough to manage the volume of water from extreme rainfall events or rising sea levels. Additionally, ageing levees, dams, and drainage systems often suffer from wear and tear, corrosion, or cracks, reducing their ability to function effectively.

4.3.3 Flooding mitigation for smart cities

Climate change is the long-term change of average weather patterns that has, over the years, defined the earth's local, regional and global climates (NASA, n.d.). The emission of heat-trapping greenhouse gases from human activities, especially burning fossil fuels, contributes to climate change. Human activity's interference with natural processes like internal variability (e.g. cyclical ocean patterns) and external forces (e.g. volcanic activity) can also contribute to climate change (National Geographic Education, n.d.). The heat-trapping greenhouse gases raise the Earth's average temperature, leading to global warming and climate change. Severe weather events such as forest fires, hurricanes, droughts, heat waves, floods, and storms are effects of climate change experienced globally (McSweeney, 2024). Scientific attribution studies attribute climate change to 71% of weather events and trends (Dharmarathne, 2024).

Cities have a vast network of infrastructure that is critical in providing services to residents. Critical infrastructure encompasses the physical assets, functions, and systems that ensure the population's health, safety, security, and prosperity. Critical infrastructure includes transportation systems (roads, railway lines, airports, ports), energy generation plants, industries, water supply networks, education and health infrastructure (Science Direct). Climate change affects critical infrastructure in diverse ways depending on the geographical location and its interaction with climate change effects. Although the transportation industry contributes to climate change, it is also vulnerable. Floods affect transportation networks constructed at grade and sited in flood zones. Flooded roads and railway lines cut off the transportation network, curtailing the movement of goods and services. Flooding events affect tunnels and subways, often constructed below grade, affecting transportation. Extreme heat and weather increase the weather variability. Transport and water supply systems designed under a particular climate range may fail before the end of their design life because of weather variability. Climate change has aggravated hailstorms, floods and damaging winds, exposing airports–often built near water bodies and coastal areas with favourable wind conditions–to disruptions because of the extreme weather events.

Increased precipitation leads to an increased volume of water passing through water supply systems, overwhelming the capacity of the water supply network. Increased precipitation may also increase soil runoff, further reducing the capacity of the water supply systems, ultimately leading to damage or redundancy. However, decreased precipitation can lead to increased water pollution because of reduced water flow. Increased air and water temperatures affect water supply systems' evaporation rate and asset corrosion. All these effects associated with climate change affect the maintenance and restoration costs of critical infrastructure in cities.

4.3.4 Flooding

Climate change, rising global temperatures, extreme weather events, and changes in rainfall patterns have contributed to increased flooding events. The causes of flooding are shifting, and their impacts are increasing against the backdrop of demographic growth and urbanisation trends (IPCC, 2021). The rapid urban growth and changes in land use have affected natural hydrological processes and reduced permeable surfaces, making cities of the 21st century susceptible to flooding. Flooding occurs because of various sources of flood risk, including fluvial, tidal, and coastal flooding, as well as pluvial. Sustained rain or heavy rainfall that is not easily absorbed overwhelms over-saturated ground and/or drainage structures, causing pluvial flooding. Climate change contributes to the frequency and severity of flooding through a complex interaction with other factors such as rapid urbanisation, change in land use, insufficient stormwater infrastructure and ageing infrastructure.

4.3.5 Climate change impact on urban drainage

Drainage structures contribute to safely removing and controlling surface runoff from the upstream and adjacent catchment areas to the downstream water course or drainage outfall (Jemberie et al., 2023). Cities often rely on integrated cross (bridges and culverts) and longitudinal (stormwater channels, inlets, access holes and sewers) drainage structures to control surface runoff.

Rapid urbanisation of cities because of population growth affects land use dynamics across the globe, characterised by a change in the structure and form of cities. As cities' populations increase, expansion becomes unavoidable, significantly changing land use. This affects the original natural connectivity of surface water bodies and the transformation path of surface and underground water. The development of cities replaces the natural drainage channels with urban drainage networks composed of many hydraulic structures. Implementing an extensive and integrated drainage system is expensive, compounded by the scarcity of resources experienced by most countries, making it difficult to implement, expand, maintain and modernise drainage systems. Land use changes in the urban environment reduce the permeability of soils, leading to increased surface runoff and vulnerability to flooding. This ultimately overwhelms the existing drainage infrastructure, damaging utilities and industrial and residential assets and posing a risk to the infrastructure and livelihoods of city residents. Inadequate urban drainage systems may lead to the inundation of sewage treatment plants and the overflow of combined sewers, compromising the integrity of sewer infrastructure (Forzieri et al., 2018). This increases the risk of contamination of water bodies with untreated sewage, causing a public health hazard to urban dwellers.

4.3.6 Flood mitigation for smart cities

Smart cities require adaptive measures to insulate existing and new infrastructure from the vulnerabilities of extreme weather events induced by climate change. A holistic approach is needed to address the vulnerabilities posed by the challenge of flooding. Smart cities must invest in resilient infrastructure, improved drainage and sewer systems, and integrated urban planning incorporating long-term water sustainability and community awareness. In addition, using technologies that provide data and information on flooding will go a long way in making cities resilient to this phenomenon.

Urban infrastructure will benefit from strategic design modifications that will future-proof it from extreme weather events. Design modifications, like raising building foundation levels beyond calculated flood levels, will ensure continuous operations during flooding events. Adapting dynamic building materials that are easily configured, strengthened, or replaced on a need basis will make buildings adaptive to changing conditions. Integrating green infrastructure in the urban planning of cities provides an avenue for mitigating flooding. Using green roofs on buildings increases the surface area of natural water absorbers. The design and construction of energy-efficient buildings that minimise energy consumption for heating and cooling contribute to lowering greenhouse gas emissions and overall urban resilience. Increasing the area of permeable surfaces in the urban planning process, such as using permeable pavements and permeable non-motorised transport facilities, enables water absorption, reducing the risk of flooding. Incorporating green spaces at strategic city locations will act as buffers that minimise the risk of flooding.

Design modifications of urban infrastructure and the urban planning process do not work in isolation to make cities resilient to flooding. Improvement of drainage and sewer infrastructure is required to supplement the design approaches expounded above. Cities should prioritise designs of stormwater infrastructure with a high capacity to sustain increased runoff. Implementing a maintenance culture for stormwater and sewer infrastructure will ensure their efficiency at full capacity, reducing the risk of flooding. Sustainable urban drainage systems (SUDS) will complement or provide an alternative to stormwater drainage infrastructure. SUDS allow direct and quick drainage of surface runoff. Incorporating sustainable urban drainage systems in urban planning supports urban areas in coping with severe rainfall by delivering quality urban drainage and improving the quality of life. Urban developments and spaces become more vibrant, visually attractive, sustainable and resilient to climate change. Incorporating SUDS in urban planning improves the urban air quality, regulates building temperatures, reduces noise and delivers recreation and education opportunities. Filter strips and drains, swales, permeable surfaces, basins and ponds, underground storage, wetlands, green roofs, and rainwater harvesting are types of SUDS to incorporate in urban planning. SUDS enhance stormwater drainage, including the capacity of the system to handle heavy rainfall, mitigating the risk of flooding.

The application of modern technologies like Artificial Intelligence (AI), Machine Learning (ML) and Remote Sensing in real-time monitoring and flood prediction enhances the management of urban flooding. Machine learning, a subset of AI, enables the development of robust models that provide a better understanding of precipitation trends and precise prediction of extreme weather events. In addition, the use of hydrological modelling to expound on river behaviour and watershed dynamics for cities becomes paramount. The models incorporate real-time data, such as rainfall intensity and soil moisture content, to predict river discharge and potential flooding. AI enables the integration of diverse datasets to develop comprehensive risk assessment and vulnerability mapping. ML algorithms analyse land use, topography, infrastructure, and historical data to identify vulnerable areas. Remote sensing technologies like satellites provide information on changing environmental conditions. This information is crucial in enabling urban planners and engineers to design resilient infrastructure and develop evacuation plans and policies that prioritise flood mitigation measures.

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5.0 INFRASTRUCTURE FOR THE FUTURE

5.1 RESILIENCE

Over the years, natural events have caused significant economic, material, and human losses. However, in recent years, the increase in frequency and intensity of extreme hydrometeorological events, including tropical cyclones, extreme rainfall, floods, storms, intense droughts, and tornadoes, among others, has become evident. These events, sometimes catastrophic, are a consequence of climate change, caused mainly by human activity and the burning of fossil fuels, which generate gases that prevent heat dissipation from the atmosphere.

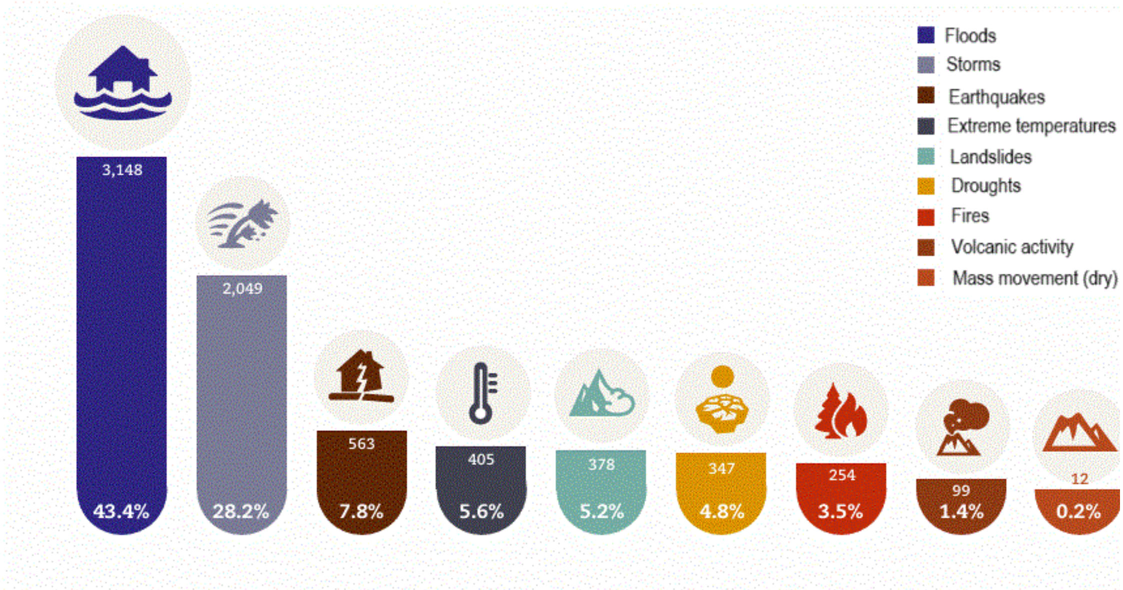
According to National Geographic, the worst natural disasters to devastate the planet in recent years include the 2011 earthquake in Japan, which was accompanied by a tsunami that caused significant damage, the 2015 earthquake in Nepal, the 2017 earthquake in Mexico, and the 2023 earthquake in Turkey and Syria, all of which left a large number of people dead and significant material damage. National Geographic also includes Hurricane Sandy in 2012 and Hurricane Irma in 2017, Typhoon Haiyan in the Philippines in 2013, the fires in California and Australia in 2017 and 2019-2020, respectively, and Cyclone Idai in Mozambique in 2019 (Roig, 2023).

On the other hand, other phenomena such as the worst drought in Somalia in 2017, the earthquake in Ecuador in 2016, the floods in the Philippines in 2012, the earthquake in Haiti in 2010, Cyclone Nargis in Burma in 2008, the earthquake in Sichuan in China in 2008, Hurricane Katrina in 2005, the earthquake in Kashmir in India in 2005, and the Southeast Asian tsunami in 2004 have been described as among the most significant natural disasters of the 21st century (ONU-Habitat, 2024).

Concerning this topic, UN-Habitat states that "Half of the human and economic damage caused by disasters in the last fifty years is related to water and climate. Water-related disasters have caused nearly 1.3 million deaths, accounting for 50% of all disasters" (UNHCR ACNUR, 2017).

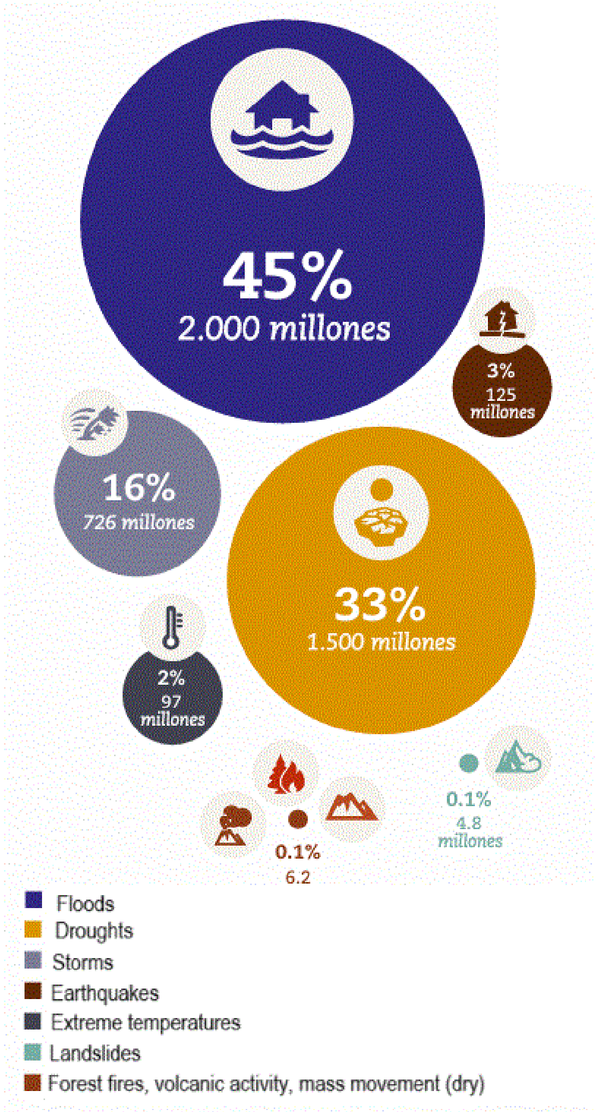
Among the 10 principal calamities recorded during the last fifty years, those that have caused the most significant number of victims have been droughts, with 650,000 deaths, followed by storms, with 577,232; floods, with 58,700; and extreme temperatures, with 55,736, according to the Atlas on mortality and economic losses due to extreme meteorological, climatic and hydrological phenomena between 1970-2019 (ONU Habitat).

The figure shows the disasters by type between 1998 and 2017, compiled by the United Nations Office for Disaster Risk Reduction (UNDRR).

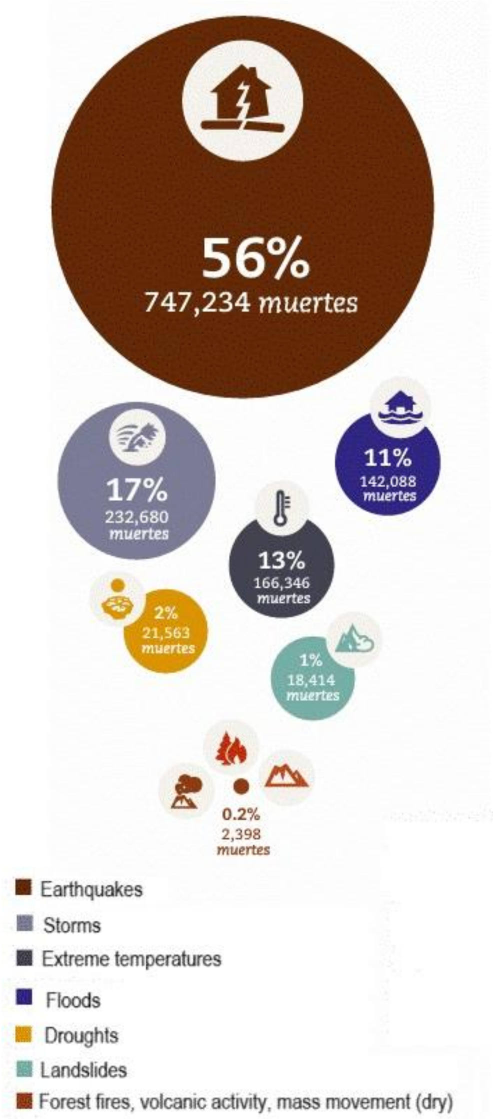


Number of disasters by type during the period 1998 – 2017. Adapted from UNDRR (2021)

The figure shows that the largest number of disasters have been caused by floods, followed by storms, both related to the significant increase in the effects of climate change. However, despite the prevalence of hydrological, meteorological and climatic threats affecting many people, the largest number of deaths continues to be caused by earthquakes, mainly due to their sudden and unpredictable nature and the high pre-existing vulnerability in the affected areas, as shown in the following figure.



a)



b)

Human impacts by type of disaster between 1998 and 2017. a) Number of people affected. b) Number of deaths. Source: Modified from UNDRR (2021).

The figure shows a high level of vulnerability on a global scale. To successfully face extreme events, measures to improve resilience models and increase the safety of infrastructure and communities are needed.

5.1.1 Vulnerability of water infrastructure. Realities about universal access to safe drinking water and sanitation

Water infrastructure is not exempt from presenting significant levels of vulnerability under the action of extreme natural events and the effects of climate change. The following figure shows the Shih-Kang Dam in Taiwan, damaged by the 7.6 magnitude Chi-Chi earthquake on 21 September 1999.

Shih-Kang Dam. Taiwan. Damaged by the magnitude 7.6 Chi-Chi earthquake on 21 September 1999 (Wieland, 2014)

On the other hand, in September 2017, Hurricane Maria directly hit Puerto Rico, causing considerable damage. Among the damaged structures was the Guajataca reservoir, the most important water storage northwest of the island. According to the US Army Corps of Engineers, "the erosion caused by the continuous overflow of the spillway and the force of the water, partially destroyed the concrete structure, the main pipe that supplied water from the reservoir to the drinking water treatment plant and caused significant damage to the dam gates" (USACE, 2019).

In July 2023, in an interview with the newspaper *elDiario.es*, engineer Asier Pérez, director of operations of the seven dams managed by the Gipuzkoa Water Consortium, stated that among the harmful effects on dams and reservoirs are extreme rainfall on the one hand, and rising temperatures and soil desertification on the other, which can cause slope instability, sediment accumulation, an increase in the volume of floods, the accumulation of materials in drainage organs and structural damage (Ferreira, 2023). Likewise, rising temperatures cause evaporation and a significant increase in water loss.

Hurricane Maria damaged the Guajataca Dam in September 2017 (Photo by Airman 1st Class Nicholas Dutton, 1st Combat Camera Squadron)

On 28 July 2010, the United Nations General Assembly recognised the human right to access water through resolution 64/292. However, it is now documented that more than 2 billion people worldwide still lack access to safe drinking water, and 4.2 billion lack adequate sanitation services (CEPAL, 2024).

According to UN-Water, climate change is primarily a water crisis. We feel its impacts through worsening floods, rising sea levels, shrinking ice fields, wildfires and droughts (UN-Water, 2024).

The current scenario confirms that hydraulic infrastructure must be able to face the increasingly aggressive effects of climate change. The evidence highlights the need to implement sustainable measures to ensure everyone's access to water. Therefore, increasing resilience standards is absolutely necessary in the present and future scenarios.

5.1.2 Sustainable and Resilient Infrastructure. Challenges and perspectives

Sustainable infrastructure refers to projects planned, designed, built, operated, and dismantled according to economic, financial, social, environmental, and institutional sustainability criteria throughout their life cycle (UNPD, 2023).

This concept implies that sustainability must be resilient; therefore, to ensure the infrastructure's functionality over time, it is essential to guarantee its capacity to remain intact and respond satisfactorily to the effects of climate change and the impact of extreme natural events.

Resilience is nothing more than the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management. The United Nations Office for Disaster Risk Reduction (UNDRR, 2024) states that:

"Infrastructure resilience is the timely and effective prevention, assumption, recovery, adaptation and transformation of essential structures and functions of national infrastructure that have been exposed to current and potential future threats. Implementing resilience at all phases of disruption should be done through collaborative risk and uncertainty management, multi-hazard assessment and methods that encompass the systemic nature of national infrastructure".

According to the UNDRR, the delivery of resilient infrastructure needs both the creation of capacity for each of the phases of disruption management, as well as recognising:

1. The changing nature of risks and uncertainties;
2. The increasingly challenging nature of multi-hazards;
3. The need to use trans-disciplinary, systemic methods that consider the life-cycle of national infrastructure and its interdependent, multi-sectoral nature.

Some of the measures aimed at increasing resilience standards are:

- Projecting climate scenarios to anticipate the effects of change.
- Introducing new sustainability requirements related to climate change adaptation in the planning, projection, construction, maintenance and operation phases of new infrastructures.
- Increasing the application of artificial intelligence in monitoring threats and early warning systems.
- Conducting comprehensive vulnerability and risk studies of built infrastructure. Implementing renovation, maintenance and adaptation actions to climate change.
- Using local materials and mitigating the negative impacts generated by engineering works and their operation on the environment.
- Training communities and decision-makers at the local level on issues of climate change adaptation, sustainability and community resilience.
- Incorporating environmental solutions to provide the best combination of grey, green and blue infrastructure.
- Proactively maintaining the natural environment around infrastructure locations to reduce vulnerability exposure.

- Select solutions based on available skills and resources, as well as the solution's suitability for the changing environment.

The fight against the effects of climate change requires a global effort. Reducing greenhouse gas emissions, transitioning to clean and renewable energy sources (such as solar, wind, wave, tidal, and geothermal), conserving electricity, walking, using public transportation, and cycling are essential to human survival.

Building resilient and sustainable infrastructure is essential to guarantee universal access to safe drinking water and sanitation. Of course, considerable economic effort is required, as the necessary investments are substantial. However, the existence of vulnerable engineering works to the impacts of climate change and extreme natural events implies significant economic and material losses, as well as potential human casualties.

5.2 TECHNOLOGY DEPENDENCY

The smart world is technology-driven. Taking advantage of technological advances is necessary to achieve most smart cities' goals. Which are these technologies?

In the modern era, the concept of smart cities has emerged as a beacon of innovation and efficiency. These urban areas leverage cutting-edge technologies to enhance the quality of life for their residents, optimise resource usage, and ensure sustainable development. The dependency on technology in smart cities is not just a trend but a necessity to meet the growing demands of urbanisation and environmental sustainability.

5.2.1 Internet of Things (IoT)

The Internet of Things (IoT) is the backbone of smart cities. IoT involves the interconnection of everyday objects via the Internet, allowing them to send and receive data. In smart cities, IoT devices monitor and manage various aspects, including traffic flow, energy consumption, waste management, and public safety. For instance, smart traffic lights can adjust their timing based on real-time traffic conditions, reducing congestion and emissions.

5.2.1 Big Data and Analytics

Big data and analytics play a crucial role in the functioning of smart cities. The vast amount of data generated by IoT devices and other sources is analysed to gain insights and make informed decisions. This data-driven approach helps city planners and administrators optimise services, predict future trends, and respond to emergencies more effectively. For example, analysing data from weather sensors can help predict and mitigate the impact of natural disasters.

How IoT-based devices are helping cities grow smarter - (buzzmuzz.com)

5.2.2 Artificial Intelligence (AI)

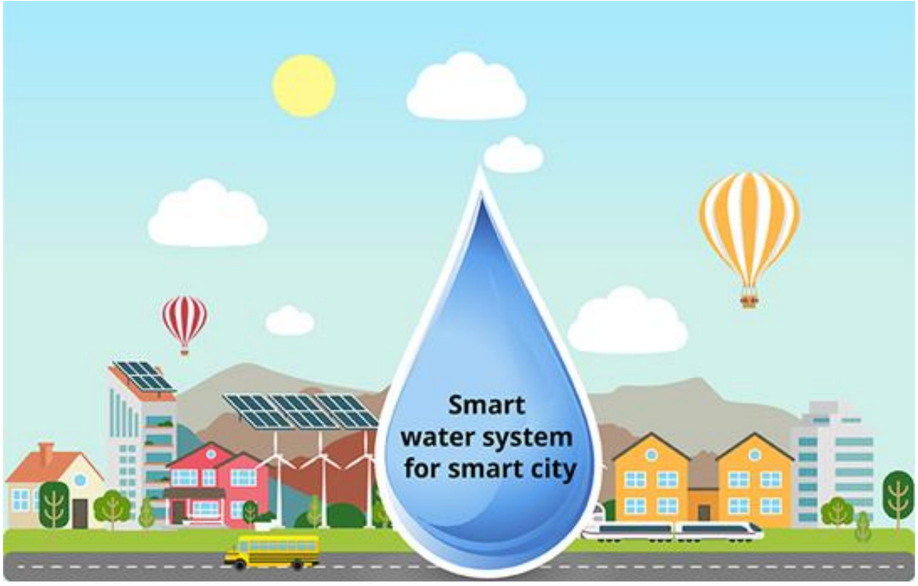
Artificial Intelligence (AI) is another cornerstone of smart cities. AI algorithms can process large datasets to identify patterns and make predictions. In smart cities, AI is utilised for various applications, including predictive infrastructure maintenance, personalised public services, and enhanced security systems. AI-powered chatbots can provide residents with instant information and assistance, improving the overall efficiency of city services.

5.2.3 Renewable Energy Technologies

Sustainability is a key goal of smart cities, and renewable energy technologies are crucial to achieving this goal. Solar panels, wind turbines, and other renewable energy sources reduce the dependency on fossil fuels and lower greenhouse gas emissions. Smart grids, which use digital technology to manage the production and distribution of electricity, ensure that energy is used efficiently and sustainably.

5.2.4 Smart Water Management

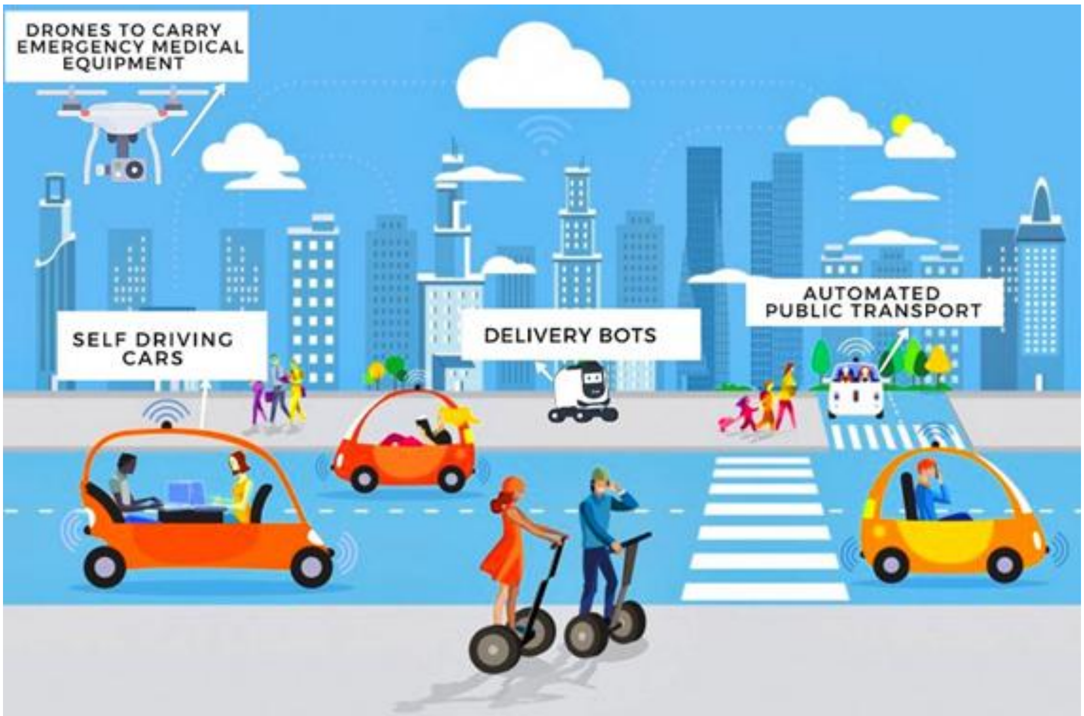
Water is a critical resource, and smart water management technologies help ensure efficient use and distribution. Sensors and IoT devices can monitor water quality, detect leaks, and manage irrigation systems. These technologies help reduce water waste, ensure a reliable supply, and protect water resources from contamination.



How to manage water efficiency using Smart Water Management (softwebsolutions.com)

5.2.5 Autonomous Vehicles

Autonomous vehicles, including self-driving cars and drones, are transforming urban mobility. These vehicles can reduce traffic congestion, lower emissions, and improve road safety. In smart cities, autonomous public transportation systems can offer efficient and accessible transportation options for residents, thereby reducing the need for private car ownership.



Autonomous Vehicles in Smart Cities (Technology-innovators.com)

5.2.6 Blockchain Technology

Blockchain technology provides secure and transparent methods for managing data and transactions in smart cities. It can be utilised for various applications, including secure voting systems, transparent supply chains, and efficient property management. Blockchain ensures that data is tamper-proof and transactions are verifiable, enhancing trust and security in smart city operations.

5.2.7 Conclusion

The dependency on technology in smart cities is undeniable. By harnessing the power of IoT, big data, AI, renewable energy, smart water management, autonomous vehicles, and blockchain, cities can become more efficient, sustainable, and livable. These technologies address the challenges of urbanisation and pave the way for a smarter, more connected future.

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6.0 SMART SANITATION FOR RESILIENT SMART CITIES

6.1 INTRODUCTION

Urbanisation is accelerating globally, with projections indicating that by 2050, nearly 70% of the world's population will live in cities (UN DESA, 2022). This urban growth, while bringing economic opportunities, presents immense challenges for infrastructure, particularly sanitation. Sanitation, often under-prioritised in smart city discourse, is vital for public health, environmental sustainability, and urban resilience (United Nations, 2016). According to WHO (2024), 57% of the global population (4.6 billion people) used a safely managed sanitation service as of 2022, and over 1.5 billion people still do not have basic sanitation services, such as private toilets or latrines. Of these, 419 million still defecate in the open, for example, in street gutters, behind bushes or into open bodies of water. These pointers show that the world is not faring well concerning sanitation. Poor sanitation reduces human well-being, social and economic development due to impacts such as anxiety, risk of sexual assault, and lost opportunities for education and work (Eguvbe et al., 2024). Poor sanitation is linked to transmission of diarrhoeal diseases such as cholera and dysentery, as well as typhoid, intestinal worm infections and polio (WHO/UNICEF, 2023). It exacerbates stunting and contributes to the spread of antimicrobial resistance. Sanitation is a fundamental determinant of human health, dignity, and sustainable development. Despite its centrality, billions of people globally continue to lack access to safe sanitation. In response to this crisis, the concept of Total Sanitation emerged as a transformative framework—one that goes beyond mere infrastructure provision to encompass behavioural change, community participation, environmental health, and inclusive development. Total Sanitation is a comprehensive, community-based approach aimed at achieving complete sanitation coverage and behavioural change at the household and community levels (Kar and Chambers, 2008). It seeks to eliminate open defecation and ensure that everyone uses a safe, hygienic toilet and engages in appropriate hygiene behaviours. Key features of total sanitation include: Elimination of open defecation; Universal access to functional toilets; Proper management of solid and liquid waste; Promotion of handwashing with soap; Clean and safe public spaces; Community ownership and sustained behaviour change (UNICEF, 2009). Unlike earlier models that emphasised subsidised toilet construction, Total Sanitation promotes self-mobilisation and collective responsibility for a clean environment. As cities confront the dual pressures of climate change and demographic shifts, traditional centralised sanitation systems are proving insufficient. At the same time, cities are becoming smarter, integrating digital technologies into governance, mobility, energy, and infrastructure management. Smart sanitation emerges as a crucial but often overlooked dimension in this transformation. It represents the fusion of sanitation service delivery with smart technologies such as the use of sensors, GIS mapping, AI-driven analytics, and citizen feedback systems, aimed at ensuring efficient, equitable, and sustainable sanitation in urban ecosystems. By definition, Smart sanitation refers to the integration of information and communication technologies (ICT), sensor networks, and data analytics into sanitation systems to optimise performance, accessibility, and sustainability (TBC, 2018; Adams and Carnovale, 2023). Unlike conventional infrastructure-heavy systems, smart sanitation emphasises:

- Real-time monitoring and feedback
- Decentralised and modular solutions
- Data-informed governance
- User-centred design and inclusivity

The core characteristics of smart sanitation includes the use of real-time monitoring, remote sensing, and cloud-based analytics (Data-Centric); tailored to meet the needs of diverse urban populations (User-Centered); designed to withstand climate shocks, disease outbreaks, and population surges (Resilience-Oriented); focused on resource recovery and zero waste models (Circular) and accessible for all, including vulnerable and marginalized populations (Inclusive).

6.2 SMART CITIES AND URBAN RESILIENCE

6.2.1 The Smart City Paradigm

A smart city is an urban system that uses ICT to enhance the quality of life, improve operational efficiency, and ensure sustainability. Essentially, smart cities use technology to collect data and optimise the delivery of city services. These data can come from various sources like citizens, devices, buildings, or cameras. By analysing these datasets, cities can improve efficiency, reduce costs, and enhance the overall quality of life for residents. Key Components of a Smart City include:

Smart Infrastructure:

Smart Infrastructure is the result of combining physical infrastructure with digital infrastructure, providing improved information to enable better decision making, faster and cheaper deployment of assets. It refers to everything that has to do with the key themes associated with developing a smart city; it provides for good quality, good economy, good living, good governance, and good atmosphere, which are essential for human survival (Padmavathi and Aruna, 2022). This includes intelligent transportation systems, smart grids for energy management, water and wastewater management, telecommunications and public safety systems. Digital infrastructure is comprised of three basic layers, namely data management, sense making and decision making, which are in turn connected by communication, with data as the key. It is the overlay of this model onto physical infrastructure that makes it “smart.”

Data Collection and Analysis:

Smart cities rely on sensors, IoT devices, and other technologies to collect data on various aspects of city life, which is then analysed to identify trends and areas for improvement and thereby help in making smart decisions on appropriate cost-saving, efficiency-promoting options for various livelihoods in the city.

Citizen Engagement:

Smart cities involve citizens in the decision-making process through online platforms and digital tools, fostering a sense of community and collaboration. Engaging the people ensures acceptance and adoption of new technologies that aim to improve livelihoods.

Sustainable Practices:

Smart cities aim to reduce their environmental footprint through initiatives like smart grids, efficient waste management, and green transportation options. Sustainable practices are actions and strategies designed to meet present needs without compromising the ability of future generations to meet their own needs. These practices encompass various aspects of life, from individual choices to business operations, and aim to minimise negative impacts on the environment, society, and the economy. They promote long-term well-being by encouraging responsible resource management, waste reduction, and the adoption of eco-friendly solutions.

6.2.2 Examples of Smart City Initiatives

As stated above, a number of initiatives can be deployed to achieve a smart city. Cities across the world are presently transforming their systems, which are further outlined below:

Intelligent Transportation Systems:

These are advanced applications that utilise information and communication technologies to manage transportation networks and enhance safety, efficiency, and sustainability. These systems employ sensors, communication networks, and data analytics to optimise traffic flow, reduce congestion, and improve the overall transportation experience.

Smart Waste Management:

Smart waste management utilises technology and data to optimise the waste management process, leading to increased efficiency, cost-effectiveness, and environmental sustainability. This approach involves using tools such as sensors, GPS, and data analytics to monitor waste levels, optimise collection routes, and improve resource allocation. Sensors on trash bins can indicate when they need to be emptied, thereby optimising waste collection routes and reducing fuel consumption.

Energy Efficiency:

Energy efficiency means using less energy to perform the same task or achieve the same result. It's about optimising energy consumption without sacrificing productivity or performance. This can involve adopting more efficient technologies, optimising processes, or changing behaviours to reduce energy waste. Smart cities leverage technology to enhance energy efficiency and sustainability. By integrating advanced technologies like the Internet of Things (IoT), 5G, and cloud computing, smart cities can optimise energy consumption across various sectors, including transportation, buildings, and utilities. This leads to reduced energy consumption, lower costs, and a smaller environmental footprint. Smart grids and smart lighting systems can help reduce energy consumption and lower carbon emissions.

Public Safety:

Smart city technologies offer significant potential to enhance public safety through improved situational awareness, faster emergency response, and crime prevention. By leveraging data, connectivity, and automation, cities can become safer and more efficient. However, it's crucial to address concerns about data privacy, cybersecurity, and the potential for misuse of these technologies. Smart surveillance systems and emergency response technologies can help improve public safety and reduce crime rates.

6.2.3 Benefits of Smart Cities

Improved Quality of Life:

Smart cities utilise technology to enhance various aspects of urban life, leading to a higher quality of life for residents. This includes improved transportation, safety, environmental sustainability, and access to information and services. By connecting data, machines, and people, smart cities aim to make daily life easier, safer, and more efficient. Smart cities offer residents better access to services, improved public safety, and a more sustainable environment.

Economic Growth:

Economic growth in smart cities is driven by the strategic integration of technology, data, and infrastructure to create efficient, inclusive, and sustainable urban environments. These cities become engines of growth by optimising resources, enhancing productivity, and stimulating innovation. Smart city initiatives can attract investment, create new jobs, and boost local economies. It is essential to note that smart cities develop digital infrastructures and innovations which enable business innovation, digital entrepreneurship, and the development of new industries. Furthermore, it leads to an improved business environment and promotes E-governance platforms, which in turn reduce bureaucratic delays, making it easier to start and operate businesses. Smart regulatory frameworks and real-time data will improve market transparency and investor confidence.

Increased Efficiency:

Efficiency is a core pillar of smart city development. By leveraging digital technologies, data analytics, and intelligent infrastructure, smart cities streamline urban operations, reduce resource wastage, and enhance service delivery. This not only improves the quality of life for residents but also drives economic and environmental sustainability. By optimising city operations, smart cities can reduce costs and improve the overall efficiency of city services.

Enhanced Sustainability:

Smart cities can reduce their environmental footprint through sustainable practices and resource management. They are designed to address urban challenges through sustainable solutions that balance environmental, economic, and social needs. By integrating digital technologies with sustainable planning practices, smart cities enhance sustainability across sectors such as energy, transportation, water, and waste management.

6.3 URBAN RESILIENCE AND SMART CITIES

Urban resilience and smart cities are closely linked concepts, with smart city initiatives often playing a crucial role in enhancing a city's ability to withstand and recover from various challenges. Urban resilience refers to a city's capacity to absorb, adapt to, and recover from shocks and stresses, encompassing social, economic, and environmental systems (Almulhim, 2025). Smart cities, leveraging technologies like the Internet of Things, big data, and cloud computing, can significantly improve urban resilience by enabling better monitoring, faster response times, and more efficient resource management. Some of the shocks and stresses include Climate-induced flooding and droughts, Public health emergencies (e.g., COVID-19), Infrastructure failures, and Social inequity. Smart cities can enhance urban resilience in several ways; firstly, it brings about improved monitoring and data collection, smart city technologies, like IoT sensors, can provide real-time data on various urban systems (e.g., traffic, air quality, energy consumption), allowing for proactive identification of potential issues and faster response times; secondly, efficient resource management is made possible and even enhanced via smart grids, intelligent transportation systems, and optimized waste management systems which can improve resource utilization and reduce the impact of disruptions; fourthly, it makes communication and collaboration more robust and more enhanced due to the deployment of platforms that can facilitate better communication and coordination between different stakeholders (e.g., citizens, government agencies, emergency services) during crises. It is pertinent to point out that sanitation plays a pivotal role in each of these domains. Resilient sanitation ensures continuity of services, reduces vulnerability, and safeguards human dignity during crises.

6.3.1 Role of Sanitation in Promoting Urban Resilience

Sanitation plays a crucial role in both urban resilience and the development of smart cities. It is fundamental to public health, environmental protection, and the overall sustainability of urban environments. In the context of smart cities, sanitation technologies can be integrated to improve efficiency, reduce environmental impact, and enhance the quality of life for citizens. Adequate sanitation, including proper wastewater and faecal sludge management, is essential for preventing the spread of diseases like cholera, typhoid, and diarrhoea, which are particularly harmful in densely populated urban areas. Good sanitation practices reduce pollution of water sources (rivers, lakes, groundwater) and soil, contributing to a healthier environment. Furthermore, effective sanitation systems can help mitigate the impacts of climate change, such as flooding, by managing stormwater runoff and reducing the risk of water contamination during extreme weather events. Improved sanitation access can reduce inequalities, as vulnerable populations often bear the brunt of inadequate sanitation services. Through investments in resilient sanitation systems, we can safeguard public health and, further, create a sustainable economy around sanitation services, as well as foster innovation as a pivotal component of combating climate change on a global scale.

6.3.2 Challenges of Urban Resilience in Smart Cities

While smart technologies offer powerful tools for building urban resilience, they also introduce new vulnerabilities. A resilient smart city must go beyond digital infrastructure to include inclusive planning, robust governance, and climate-adaptive systems. Addressing these challenges requires a balanced approach that combines innovation with equity, sustainability, and institutional strength. Increasing reliance on digital infrastructure exposes cities to cyberattacks, data breaches, and system failures. A single point of failure in smart systems (e.g., power grid or traffic control) can have widespread disruptive effects. It is necessary to point out that Digital divides persist across income, age, and geographic lines, leaving vulnerable populations underserved. Unequal access to smart services can exacerbate social inequality and undermine community resilience.

6.4 THE SMART SANITATION VALUE CHAIN

The Smart Sanitation Value Chain refers to the end-to-end process of managing human waste and wastewater using digital technologies, data systems, and intelligent infrastructure to improve efficiency, hygiene, sustainability, and public health outcomes in urban settings. It integrates each stage of the sanitation lifecycle—from containment to resource recovery—with smart innovations. Some of the identified and already deployed components of the smart sanitation value chain are outlined below:

6.4.1 Smart Toilets and Infrastructure

Smart toilets and supporting infrastructure are critical components of the smart sanitation ecosystem in smart cities. These systems use sensors, connectivity, automation, and data analytics to improve hygiene, user experience, resource efficiency, and maintenance across public and private sanitation facilities. Smart toilets are equipped with features that support touchless flushing, automated seat cleaning, and UV sterilization; in advanced applications, toilets can collect data on users' health via urine/feces analysis; they can track usage patterns, detect blockages, and monitor water levels or tank fill status; and possess features such as heated seats, air dryers, and odor control systems etc. Smart toilets find applications in urban slums and low-income areas and are deployed in forms such as mobile or modular smart toilets to improve access to safe sanitation; in high footfall public areas such as airports, malls, railway stations, and parks where sensor-based, self-cleaning toilets are installed; it also finds applications in tourist destinations and social events which require high-standard, hygienic facilities that enhance user experience.

6.4.2 Faecal Sludge and Wastewater Management

In smart cities, effective faecal sludge management (FSM) and wastewater management are essential for public health, environmental sustainability, and resource recovery. Smart technologies enable real-time monitoring, predictive maintenance, data-driven planning, and automation across the sanitation value chain—from collection to treatment and reuse. Smart Solutions will include smart containment and collection systems, which will enable IoT-enabled septic tanks to monitor fill levels and alert operators when emptying is needed, the use of mobile apps which allow households to request desludging services on demand, and GPS tracking of desludging trucks, which improves routing, prevents illegal dumping, and ensures accountability. In the area of digital transport and logistics, fleet management platforms will optimise fuel consumption and travel time. At the same time, real-time dashboards show the movement of waste from households to treatment facilities. Additionally, blockchain systems will track the origin and treatment status of collected waste, enhancing transparency. In the treatment of these wastes, treatment facilities are fitted with automated sensors which monitor key parameters such as pH, biochemical oxygen demand (BOD), chemical levels, and microbial content; supervisory control and data acquisition (SCADA) systems provide centralized monitoring and control of treatment plants while AI-powered predictive maintenance reduces downtime and extends equipment life. In a circular sense, reuse and resource recovery are made possible as biogas digesters convert sludge into energy while using smart meters to track energy output, and reclaimed water is used for agriculture, landscaping, or industrial cooling, with quality monitored via smart sensors.

6.4.3 Behaviour and User Engagement

Behavioural change and active user engagement are critical success factors in the development and functioning of smart cities. While technology and infrastructure form the foundation, it is people's actions, choices, and feedback that determine how effectively these systems work. Engaging citizens ensures adoption, trust, and long-term sustainability. It is essential to note that user engagement is critical to the development of smart cities due to the need to ensure a human-centred design, which makes services usable and accessible to all. Furthermore, citizen participation fosters ownership and accountability in public services, while behavioural insights help shape policies that promote sustainability, efficiency, and resilience.

6.4.4 Monitoring and Governance

Effective sanitation governance and real-time monitoring are foundational pillars of smart city development. As cities grow and sanitation needs become more complex, integrating digital technologies enables data-driven decision-making, transparent operations, and accountable service delivery. This ensures that sanitation systems are not only efficient but also equitable and resilient. Governance involves the frameworks, institutions, policies, and stakeholder coordination required to plan, regulate, finance, and manage urban sanitation systems. Effective monitoring, on the other hand, ensures that infrastructure is maintained, services are delivered equitably, and future planning is based on objective evidence, driving cities closer to universal, safe, and sustainable sanitation.

6.5 Technologies Driving Smart Sanitation

Smart sanitation harnesses emerging technologies to create safe, efficient, inclusive, and sustainable sanitation systems in urban environments. These technologies enable real-time monitoring, data-driven decision-making, predictive maintenance, and citizen-centric service delivery across the entire sanitation value chain—from toilet usage to waste treatment and reuse. The integration of digital and physical technologies across the sanitation lifecycle transforms urban sanitation from a basic necessity into a smart, efficient, and sustainable system. When deployed with inclusive governance and human-centred design, these technologies can significantly improve public health, environmental protection, and service equity in smart cities. The table below shows the various technologies and their areas of application usable in driving smart sanitation in smart cities.

Technology	Application Area
IoT (Internet of Things)	Smart toilets, sludge trucks, sewage monitoring
Artificial Intelligence	Predictive analytics, leak detection, optimisation
GIS & Remote Sensing	Asset mapping, spatial planning, risk assessment
Blockchain	Smart contracts, financial accountability
Big Data	Decision support, service gap identification
Mobile Applications	Citizen reporting, toilet locators, and education

Smart Sanitation Drivers and areas of application

6.5.1 Internet of Things (IoT) Applications in Smart Cities

The Internet of Things (IoT) refers to a network of physical devices—embedded with sensors, software, and connectivity—that collect and exchange data in real time. In smart cities, IoT enables real-time monitoring, automation, and data-driven decision-making, transforming how urban services are delivered and managed. IoT is a backbone technology in smart cities, enabling a shift from reactive to predictive and proactive urban management. When combined with AI, cloud computing, and citizen participation, IoT enhances efficiency, resilience, and quality of life across city systems—from sanitation and mobility to energy and safety.

6.5.2 Artificial Intelligence (AI)

This is a transformative technology in smart cities, enabling machines and systems to simulate human intelligence, learn from data, and make decisions. By integrating AI across city functions, urban systems become more efficient, predictive, adaptive, and citizen-centric. AI enhances everything from traffic flow and waste management to health services and sanitation monitoring. It is a cornerstone of future-ready smart cities, enabling proactive, adaptive, and citizen-focused solutions. However, its success depends on responsible deployment, inclusive design, ethical oversight, and transparency. When combined with other technologies like IoT and big data, AI has the power to transform urban living at every level—from sanitation and mobility to planning and governance.

6.5.3 GIS & Remote Sensing

Geographic Information Systems (GIS) and Remote Sensing (RS) are foundational technologies that support spatial intelligence, urban planning, and real-time decision-making in smart cities. Together, they provide city administrators, planners, and service providers with the ability to visualise, analyse, and monitor urban environments effectively. They empower urban leaders to see the city as a dynamic, data-rich landscape and make evidence-based, location-specific decisions. When integrated with IoT, AI, and citizen engagement tools, GIS and RS create smarter, cleaner, and more responsive urban environments.

6.5.4 Blockchain

Blockchain is a decentralised, transparent, and secure digital ledger technology that enables trusted data exchange without intermediaries. In smart cities, blockchain is used to ensure data integrity, automated service execution, and trustworthy transactions across multiple sectors. It enhances transparency, reduces fraud, and promotes decentralised governance. Its ability to automate services, verify actions, and securely manage data makes it a powerful tool for urban governance, sanitation, infrastructure, and citizen empowerment. However, to be effective, blockchain must be integrated responsibly, with attention to privacy, regulation, and interoperability.

6.5.5 Big Data

Big Data refers to extremely large, complex, and diverse datasets generated from sensors, devices, social media, and transactional records, which are too massive for traditional data processing tools. In smart cities, big data analytics plays a pivotal role in transforming raw information into actionable insights for urban planning, service optimisation, and real-time governance. It is the backbone of smart city intelligence, enabling cities to become predictive, personalised, and proactive in their operations. By leveraging data across sectors—transport, sanitation, energy, health, governance—cities can improve quality of life, optimise resource use, and build urban environments that are resilient, inclusive, and sustainable.

6.5.6 Mobile Applications

Mobile applications (apps) are essential tools in the digital infrastructure of smart cities. They serve as the primary interface between citizens and urban services, offering real-time access, interaction, feedback, and participation. Mobile apps empower residents, improve governance transparency, and help city managers optimise urban services efficiently. Mobile applications are the digital front door of smart cities—connecting citizens with services, authorities with feedback, and systems with real-time data. When designed with inclusivity, security, and user-friendliness in mind, mobile apps help cities become more responsive, efficient, participatory, and resilient.

6.6 Policy and Governance Frameworks for Smart Sanitation

Smart sanitation systems are complex and involve multiple actors, including municipal authorities, private sector partners, tech companies, communities, and regulators. Without proper governance, there is a risk of:

- Technological misalignment with local needs
- Data misuse or privacy violations
- Exclusion of vulnerable populations
- Infrastructure fragmentation
- Regulatory bottlenecks

Effective policy frameworks act as enablers for investment, integration, and long-term sustainability. Key components of an innovative sanitation governance framework will include the following:

6.6.1 Institutional Coordination and Multi-Stakeholder Engagement

Smart sanitation systems operate at the intersection of technology, urban planning, public health, and environmental management. Consequently, institutional coordination and multi-stakeholder engagement are essential to prevent siloed decision-making and promote integrated service delivery. Effective collaboration and engagement with local communities, NGOs, and service providers ensures that sanitation policies are inclusive, contextually appropriate, and technologically feasible. Institutional coordination and multi-stakeholder engagement are foundational to the success of smart sanitation initiatives. Through integrated governance and inclusive participation, cities can unlock the full potential of digital sanitation technologies, ensuring they are accessible, sustainable, and aligned with broader urban development goals.

6.6.2 Legal and Regulatory Instruments

The successful implementation of smart sanitation systems requires a robust legal and regulatory environment that not only supports innovation and integration of technologies but also protects public interests, ensures service equity, and promotes sustainability. Traditional sanitation laws are often outdated, failing to account for the digital, decentralised, and data-driven nature of modern sanitation systems. Legal and regulatory instruments must evolve to reflect the complexities and opportunities of smart sanitation. Legal and regulatory instruments are the backbone of smart sanitation governance. They must strike a delicate balance—providing enough structure to protect the public while remaining agile enough to accommodate innovation. As smart cities evolve, so too must the laws that govern their sanitation systems—toward frameworks that are integrated, inclusive, and future-ready.

6.6.3 Policy Integration with Smart City and Sustainability Goals

The transformative potential of smart sanitation lies not just in deploying digital technologies but in embedding these systems within broader smart city policies and sustainable development agendas. Policy integration ensures that smart sanitation initiatives do not operate in isolation, but are strategically aligned with city-wide goals such as climate resilience, digital transformation, public health, and environmental sustainability. Policy integration is essential to unlock the full benefits of smart sanitation. It ensures that sanitation systems are not just technologically advanced but are also systemically embedded within broader urban and global frameworks for resilience, equity, and sustainability. Forward-looking cities must therefore embrace integrated policy models that reflect the interconnected nature of urban development in the 21st century.

The table below illustrates how smart city objectives align with SDGs, highlighting the areas of impact and demonstrating the wide-reaching nature of smart city initiatives.

Smart City Pillars	Aligned SDGs	Sustainability Focus
Smart Mobility	SDG 11, SDG 9, SDG 13	Low-carbon, inclusive transportation
Smart Energy & Efficiency	SDG 7, SDG 12, SDG 13	Renewable energy, demand-side management
Smart Sanitation & Health	SDG 6, SDG 3, SDG 11	Universal access, public health, clean environments
Smart Governance	SDG 16, SDG 17	Participatory, transparent governance

Smart Economy	SDG 8, SDG 9, SDG 10	Inclusive growth, innovation, decent jobs
Environmental Sustainability	SDG 13, SDG 14, SDG 15	Climate action, biodiversity, and pollution reduction

Relationship of Smart City initiatives with SDGs

6.6.4 Data Governance and Digital Rights

Smart cities rely heavily on data from sensors, mobile apps, social media, smart meters, and connected devices to optimise services and enhance urban life. However, the growing volume, variety, and sensitivity of data collected pose critical challenges around privacy, ethics, transparency, and accountability. Effective data governance and the protection of digital rights are essential for creating smart cities that are trustworthy, inclusive, and citizen-centric. As smart cities become more data-driven, the need for robust, transparent, and inclusive data governance becomes urgent. Respecting digital rights ensures that technological innovation does not come at the cost of privacy, equity, or democracy. A rights-based approach to smart urbanism is essential for building ethical, resilient, and human-centred cities.

Smart sanitation can transform urban resilience, public health, and environmental outcomes, but only when backed by coherent policy and governance frameworks. These frameworks must be agile, inclusive, and responsive to technological advances while safeguarding rights, ensuring equity, and promoting sustainability. As cities move toward digital transformation, rethinking sanitation policy is not optional; it is foundational to their success.

6.7 Conclusion

Smart sanitation offers an unparalleled opportunity to transform how cities deliver and manage essential services. By integrating technology with inclusive planning and climate resilience, cities can ensure dignified, safe, and sustainable sanitation for all. To succeed, smart sanitation must move beyond pilot projects and into the realm of systems thinking, institutional integration, and human-centred design.

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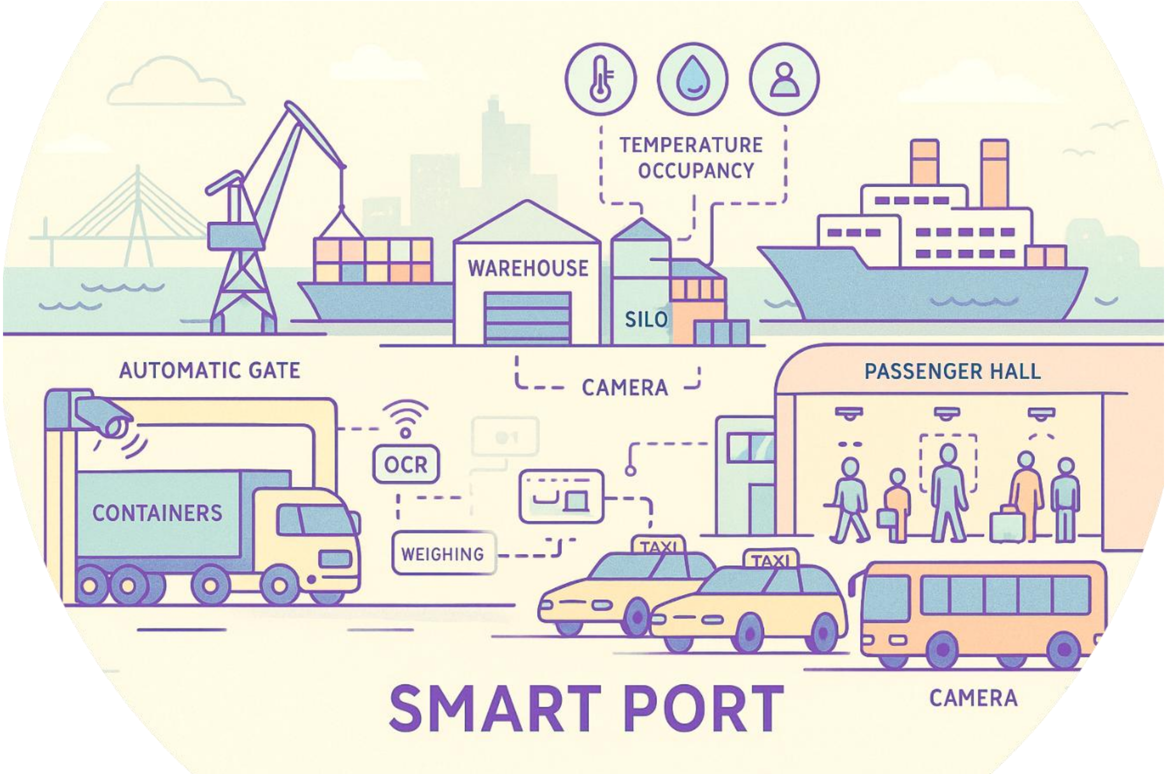


7.0 WATERFRONT SMART CITIES

7.1 PORTS, BRIDGES, WATER INTAKES, AND OUTFALLS

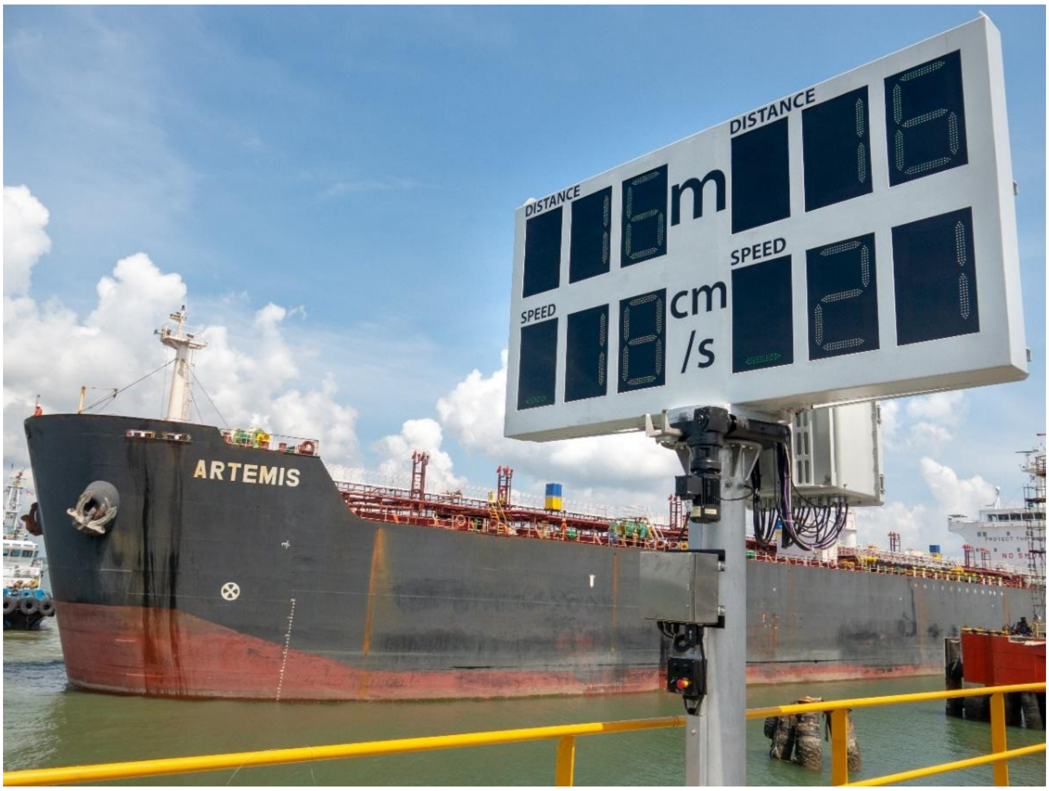
The ports of smart cities and the infrastructure related to shoreline cities, like bridges, water intakes, and sewage discharges, must also be smart. The world faces a historic era when there are more urban than rural dwellers (UN, 2026). In 2003, Liz Creel (2003) counted about three billion people living within 200 km of the shoreline and predicted that figure would double by 2025. She also pointed out that 14 of the world's 17 largest cities are along coasts. World Urbanisation Prospects 2018 (UN, 2018) counted 513 cities with more than 1 million inhabitants, 52,8% located less than 100 km from a coastline in 2015. These figures show the weight of the shoreline cities in the global context. However, there are not only seafront cities but also riverfront cities far inland featuring ports that are even more needed for technology-driven and efficient infrastructure to be competitive.

What is a smart port, and what other smart infrastructure is required? A modern city will require the integration of all its components: ports, water intakes and treatment, sewage collection and treatment, flood control, bridges that span from one bank to the next across a river or an inlet, and desalination plants. It's not just a network of construction pieces but also a network of data, decisions, and controls.

Innovative port technology started over 20 years ago and has become more sophisticated as the big data management system, communication speed, and processors have become more powerful. A Smart Port's neural part is software that integrates the ship's arrival with the incoming truck waiting in a parking lot before it crosses the port gates. It requires a lot of sensors and "eyes" to gather information. In the water, sensors collect water levels, current speeds, wave heights, directions, and periods. Smart buoys can compile this critical data, such as water and air temperature, wind data, and water quality. They can have cameras transmitting what they see online to the land control tower. On top of their traditional functions of marking channels and dangers, smart buoys mark their positions by sight, light, and unique radio signals.

For decades, ships have had to transmit their position through AIS (Automatic Identification System), repeated in every smart port control tower (and to websites that anyone could see worldwide). The AIS is checked against the images from the radars, which are scattered throughout the smart port periphery. AIS, radars, buoys, and software feed the Vessel Traffic Systems or River Traffic Systems, preventing collisions, avoiding ship delays, and minimising chances for grounding.

Laser-actuated sensors help pilots reduce and control the vessel's impact velocity and angle when berthing. The data is transmitted to the port operation control office, and captains can see the numbers on their screens or by visualising digital signs on the berth. These systems are economic and provide additional benefits: they discourage reckless behaviour from mariners and provide unquestionable records to pinpoint responsibilities in case of collisions or damage to the infrastructure.



LiDar sensors used to control approaching speed and angle (Thanks to Straatman and Seti Equipos Petroleros)

Sensors can also control the tension on the moorings, which they can adjust according to changes in the water level, wind direction and speed, and draft variations caused by the ship's loading and unloading process. This mechanism allows for efficient control of the moored ship's movements and prevents lines or bollards from being overloaded.

Cranes are operated remotely from comfortable control rooms. The crane operators manipulate them with joysticks, examine the cargo through video cameras, and measure distances with Lidar technology. They can also discuss situations with colleagues who share the same room.

The cargo is then stored in warehouses or yards. Some ports already use automated vehicles to distribute the cargo within the yards. For instance, in the case of containers, the slot is preassigned before the ship arrives, and the local vehicles are programmed to take the cargo and slide into the right spot, reducing time and maximising the capacity of the available surface.

Crane Remote Control Operation System (Siemens, https://xcelerator.siemens.com/global/en/industries/cranes/harbor-cranes/remote-control-system.html)

Smart Ports use smart warehouses, silos, and yards, with sensors to control temperature, humidity, available capacity and occupancy, and other parameters dependent on the handled cargo. The entrance/exit gates are also automatic. Tags, identification numbers of the cargo, license plates, and even driver’s data are read by OCR (optical character recognition cameras) and compared to the database to check authorisations and documentation. The trucks are weighed as they pass the gates, and all this data is registered with time stamps. In cruise terminals, cameras distributed in passenger halls can detect and tag the number of travellers and suitcases. At the same time, they tag the number of taxis and buses waiting for their arrival, thus triggering requests for an increased flow of transfer vehicles.

All this information is gathered in massive databases with backups on the cloud and integrated with invoicing and administrative software.

Smart ports must be resilient and energy efficient. With expected increased water levels and extreme flood events, designers must decide the delicate equilibrium between raising deck levels and costs. Efficient ports will tend to provide grid energy to the moored ships and have the means to supply power to their buildings and systems through alternative energy sources.

Electric autonomous container truck (Gaussin SA, https://www.gaussin.com/agv-p)

Many bridges in smart cities are fixed; however, there are also frequent mobile bridges in coastal areas or spanning rivers and channels. In both cases, authorities can use smart technologies to engineer more resilient and durable infrastructure. The key is adequate maintenance through continuous monitoring using IoT (Internet of Things) sensors, Big Data, and Machine Learning. Data to collect includes traffic, weather parameters, stresses of specific structural elements, corrosion, ship collision courses, vibrations, etc. Smart bridges combine sensors, actuators, and command-control processors (Giurgiutiu, 2001). Smart materials, such as optical fibres or composite materials like piezoelectric ceramics, can sense and create mechanical strains when incorporated into the structure. Lifting bridges may interact with land and waterborne traffic, controlling the opening as it senses congestion through cameras and connecting with the frequencies of the traffic lights.

7.2 SMART TOURISM INFRASTRUCTURE IN COASTAL CITIES

7.2.1 Introduction

As the global population becomes increasingly urbanised and climate change reshapes the vulnerabilities of coastal zones, smart cities have emerged as a holistic response to the interconnected challenges of sustainability, resilience, and technological innovation. Coastal tourism is a critical economic sector and a vector for cultural exchange. However, it also exerts significant pressure on fragile ecosystems and public infrastructure. In this context, developing smart tourism infrastructure —such as sea walks, fishing piers, beaches, and urban parks— offers a transformative pathway to achieving the United Nations Sustainable Development Goals (SDGs).

This way, smart tourism infrastructure in coastal cities can be aligned and multiple SDGs promoted, including SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 17 (Partnerships for the Goals).

7.2.2 Smart Sea Walks (Coastal Promenades): Walkability, Climate Resilience, and Innovation

Smart sea walks are modern promenades that blend functionality, aesthetic appeal, and ecological consciousness. Traditionally used for leisure and coastal access, today's sea walks are being reimagined with embedded technologies such as:

- Real-time data panels: Displaying weather, tide levels, air quality, and tourist information.
- Interactive lighting: Energy-efficient, motion-activated, and programmable for events or mood lighting.
- Solar-powered lighting systems that reduce carbon emissions,
- Smart benches with solar panels, USB charging, Wi-Fi, and occupancy sensors.
- Real-time information panels for tourists and emergency alerts.
- Resilient materials that adapt to tidal changes and reduce maintenance costs.
- Using recycled plastics or permeable surfaces to reduce runoff and maintenance.

Combined with natural infrastructure, these features encourage walkability, connect public spaces, and create a buffer against coastal erosion.

Smart technologies applied to the coastal zone contribute to achieving SDG 9 by promoting infrastructure innovation while enhancing SDG 11 by making cities more inclusive and accessible. Importantly, sea walls can also act as green infrastructure, integrating natural elements such as sand dunes or living shorelines to buffer storm surges and rising seas, directly supporting SDG 13: Climate Action.

7.2.3 Fishing Piers: Convergence of Recreation, Education, and Marine Conservation

Fishing piers in smart cities are no longer merely platforms for leisure; they are dynamic, data-rich environments. They may include:

- IoT sensors: Monitoring fish populations, water quality, and structural integrity.
- Augmented reality (AR) guides: Offering species identification, fishing tutorials, or historical context via smartphone.
- Adaptive lighting: Minimises disruption to marine ecosystems while enhancing safety.
- Booking systems: Smart platforms for space reservation, equipment rental, or educational tours.

In this case, the use of these technologies promotes recreational fishing while monitoring ecological impact, creates educational hubs for marine conservation, allows for tracking marine biodiversity and pollution levels (IoT sensors), provides guides that teach sustainable fishing practices (AR), and increases safety and inclusiveness.

These piers facilitate citizen science and provide valuable data for marine research, advancing SDG 14 (Life Below Water). Moreover, when fishing activities are managed through digital permits or quotas, sustainable resource use is ensured, consistent with SDG 12 (Responsible Consumption and Production). Smart piers can also serve educational purposes by hosting school groups and eco-tourists, helping to foster awareness of marine ecosystems, aligned with SDG 4 (Quality Education).

7.2.4 Smart Beaches: Technology for Sustainability and Visitor Experience

Smart beach design encompasses a suite of integrated systems that monitor environmental quality and enhance visitor safety and satisfaction. Key innovations include:

- Smart bins: Smart waste bins that alert municipal services when full,
- Sensor-based waste tracking, alerts for overflow, and gamified recycling.
- Beach quality monitoring: Sensors for water temperature, bacterial levels, and jellyfish alerts, all connected to mobile apps.
- Accessibility tech: Including beach wheelchairs, tactile paths, and voice-assist kiosks.

- Energy-efficient amenities: Solar showers, LED lighting, and modular lifeguard stations.
- Use dune-restoration technologies, smart irrigation for coastal vegetation, and erosion sensors.
- Water quality monitoring stations, which feed data to mobile apps in real-time,
- Climate sensors for UV, wind, and temperature alerts,
- Digital kiosks with accessibility features for people with disabilities.

These systems support SDG 3 (Good Health and Well-being) and SDG 14 by reducing pollution and improving safety. Moreover, beaches with inclusive design elements—such as wheelchair ramps, tactile paving, and multilingual digital signage —contribute to SDG 10 (Reduced Inequalities). In many cities, data-driven management systems allow crowd monitoring and coastal zoning during peak seasons, ensuring visitor safety and environmental protection.

7.2.5 Urban Parks: Multifunctional Public Spaces for Sustainability and Inclusion

Parks in smart cities are essential not only for local quality of life but also as tourism assets. Smart parks are equipped with:

- Intelligent irrigation systems that conserve water (SDG 6),
- Interactive learning stations focused on biodiversity (SDG 15),
- Air quality and noise sensors that inform urban planning,
- Wi-Fi-enabled rest areas that support digital inclusion.
- Digital wayfinding: App-guided trails, event alerts, and AR tours.
- Biodiversity sensors: Tracking flora/fauna health and visitor impacts.
- Smart irrigation and lighting: Reducing water and energy usage.
- Social fitness tech: Interactive workout stations with app integration, leaderboards, and health tracking.
- Real-time monitoring for crowd density and security.
- Smart lighting to reduce crime and increase usability after dusk.

Parks support SDG 11 by fostering inclusive, safe, green public spaces. Their ability to sequester carbon, mitigate urban heat, and provide habitat for native species aligns with SDG 13 and SDG 15 (Life on Land). They also offer venues for cultural activities, civic engagement, and physical fitness, enhancing social cohesion and public health.

7.2.6 Cross-Cutting Enablers: Governance, Data, and Partnerships

These innovations cannot be realised without strong institutional frameworks and multi-stakeholder collaboration—core tenets of SDG 17 (Partnerships for the Goals). Public-private partnerships (PPPs), open data policies, and citizen participation platforms are vital to planning and maintaining smart tourism infrastructure. For instance, governments must invest in resilient infrastructure and enforce environmental standards; private tech firms can provide digital solutions and data analytics platforms; and academia and civil society play roles in research, monitoring, and public education. Data interoperability across systems (e.g., linking marine sensors to public health databases or urban mobility apps) ensures more intelligent decision-making and accountability.

7.2.7 Conclusion: A Smart and Sustainable Future

Smart tourism infrastructure is more than an aesthetic or technological upgrade; it is a strategic investment in the future of coastal cities by aligning design, technology, and sustainability goals. Such infrastructure transforms how people experience nature, culture, and urban life, while actively contributing to achieving the Sustainable Development Goals. These technologies and approaches are not just chimaeras, as a couple of examples may testify. In Barcelona, Spain, a smart beach management system with real-time dashboards is in place to monitor cleanliness, occupancy, and safety. In Singapore, Marina Bay integrates sea walkways with smart lighting and sustainable landscaping. In Los Angeles (USA), Santa Monica’s "Pier of the Future" concept includes underwater ROVs for live marine viewing and educational displays.

As climate risks grow and tourist expectations evolve, smart cities must ensure that innovation is efficient, equitable, and ecological. With the right policies, partnerships, and priorities, the tourism infrastructure of the future can be a global model for how cities thrive in harmony with people and the planet.

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8.0 FINAL REMARKS

As this volume draws to a close, one conclusion stands clear: building smart cities is no longer a distant aspiration but an urgent necessity. The convergence of climate pressures, ageing infrastructure, rapid urbanisation, and resource constraints demands innovative, integrated, and sustainable approaches to urban water management. Moreover, the book clarifies that smart cities are not defined solely by the technologies they adopt but by the values they uphold: inclusivity, sustainability, resilience, and a commitment to human and environmental well-being. In this sense, the engineer's mission transcends technical mastery. It is about stewardship of water, infrastructure, and ultimately the future.

The transformation of urban areas into smart, resilient, and sustainable cities requires an integrated, technically grounded approach in which engineering plays a pivotal role. This publication has examined the multifaceted challenges and opportunities associated with water infrastructure and urban development, offering a structured framework supported by real-world applications and forward-looking strategies.

The transition toward smart water systems is not merely a technological upgrade but a systemic shift in planning, design, operation, and governance. As evidenced in this book, integrating digital technologies such as IoT, big data analytics, and artificial intelligence into water management allows for real-time monitoring, predictive maintenance, and efficient resource allocation. These capabilities enhance operational performance while improving resilience to climate variability, population growth, and ageing infrastructure.

A key insight from this compendium is that engineering solutions must be context-specific, scalable, and adaptable. Smart water systems must be designed with interoperability and modularity to ensure long-term sustainability and resilience. Investment in infrastructure alone is insufficient without concurrent development of regulatory frameworks, performance indicators, and capacity-building strategies to support implementation.

Moreover, the case studies and frameworks presented reinforce the importance of embedding resilience thinking into water systems, from design to operation. This involves anticipating and preparing for shocks and stresses, enabling systems to absorb disturbances and continue functioning with minimal disruption. Key enablers include data-driven decision-making, decentralised systems, robust asset management, and demand-side efficiency measures.

The future of urban water infrastructure lies in integrated, multidisciplinary action, where engineers collaborate with urban planners, environmental scientists, data analysts, and policymakers. Circular water economies, regenerative infrastructure, and adaptive governance must become standard components of all water-related projects and planning efforts.

This book underscores the engineering profession's responsibility and potential to drive transformative change. The methodologies, technologies, and policy recommendations presented here serve as reference points for practitioners, researchers, and institutions committed to advancing smart water management and sustainable urban development.

The solutions presented are not one-size-fits-all. Each city must adapt these ideas to its challenges, culture, resources, and geography. However, the guiding principles—systems thinking, circular water economies, data-informed decision-making, and collaborative governance—are universally applicable.

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