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Resilient Water Management in Smart Buildings: Insights from the COVID-19 Pandemic

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Abstract. The COVID-19 pandemic presented unprecedented challenges for water management systems worldwide, amplifying the demand for resilience, adaptability, and sustainability. This study investigates the multifaceted impacts of the pandemic on water consumption patterns and resource management strategies, focusing on a case study of a residential complex in Larnaca, Cyprus. Data spanning pre-pandemic, lockdown, and post-lockdown periods revealed a 40% surge in daily water consumption during the lockdown, driven by heightened hygiene practices, increased domestic activities, and prolonged home confinement.

The findings underscore the critical role of smart technologies, such as IoT-enabled sensors and predictive analytics, in optimizing water use and ensuring resource sustainability. Furthermore, the study highlights the socio-economic disparities in access to clean water, exacerbated by the pandemic, and the need for equitable and inclusive governance frameworks. Strategies such as real-time monitoring, water recycling, and community engagement emerged as essential tools for navigating crises.

The research emphasizes the importance of integrating water management with broader sustainability goals, including renewable energy systems and urban planning. By combining innovative technologies with sustainable practices, this study provides actionable insights for policymakers, water utilities, and stakeholders, offering a roadmap toward robust and adaptive water management systems in an evolving global landscape.

Keywords: Water Management, COVID-19 Pandemic, Buildings, Smart Technologies, Resilience



1. Introduction

Water is a cornerstone of life and a critical resource for sustainable development. In the 21st century, the dual pressures of urbanization and climate change have significantly altered water availability and demand, creating a complex landscape for water resource management [1]. Cities, as hubs of economic and social activity, account for the majority of global water consumption, necessitating innovative approaches to address the associated challenges [2]. The intensifying impacts of climate change, including prolonged droughts and unpredictable precipitation patterns, further strain water resources, amplifying the need for resilient infrastructure and adaptive strategies [3][4].

Urban centers, where water demand is projected to grow by 30% over the next two decades, face an urgent need to balance rising consumption with sustainable practices [5]. The existing water infrastructure in many cities struggles to meet this demand due to inefficiencies in conveyance systems, aging infrastructure, and governance gaps [6]. Moreover, the global daily per capita water consumption has surged from an average of 150 liters to approximately 250 liters in the wake of the COVID-19 pandemic [7]. This increase underscores the intricate relationship between societal behaviors, public health crises, and water management systems.

The COVID-19 pandemic served as a catalyst, revealing vulnerabilities in water management systems and accelerating the adoption of smart technologies. Lockdown measures necessitated rapid adaptations in water usage, particularly within urban residential areas, where demand spiked up to 50%. This unprecedented shift underscored the critical importance of integrating Internet of Things (IoT) technologies, data analytics, and predictive maintenance in smart buildings to optimize resource utilization and ensure resilience [8]. At the same time, the pandemic magnified stark socio-economic disparities in access to clean water, with underserved communities disproportionately affected by heightened hygiene requirements and increased domestic water use. Today, 2.2 billion people—one in four—lack access to safe water, and 3.5 billion people—two in five—lack access to a safe toilet [9].

In many regions, limited infrastructure and unequal resource distribution exacerbated these challenges, demonstrating how systemic inequalities are intensified during crises. Communities with inconsistent water supplies faced significant barriers in meeting hygiene standards, further amplifying public health risks [10]. For example, urban areas with strained water systems struggled to meet surging residential demand, highlighting the urgent need for robust and inclusive governance frameworks.

The interplay between water management and public health became particularly evident during the pandemic, as water utilities worldwide faced challenges in meeting the dual objectives of maintaining hygiene standards and ensuring equitable distribution. Technological innovations emerged as key enablers of resilience during this period. IoT-enabled smart meters, real-time data monitoring, and predictive analytics played a crucial role in identifying consumption patterns and optimizing resource allocation. These technologies not only mitigated immediate disruptions but also demonstrated their potential as foundational tools for long-term water resilience. Their integration aligns with global sustainability goals, such as the United Nations' Sustainable Development Goal 6 (SDG 6), which advocates for equitable access to clean water and sanitation [11]. Similarly, the European Union's Water Framework Directive emphasizes the need for integrated water management strategies to promote sustainability across all levels of public administration [12].

This paper aims to explore the interplay between smart technologies, water management, and crisis response, with a focus on the COVID-19 pandemic. By analyzing key challenges and

opportunities, the study seeks to provide actionable insights for enhancing water resilience in urban settings. Through an in-depth literature review and a case study on a residential complex in Larnaca, Cyprus, the research highlights innovative strategies and solutions that can shape the future of sustainable urban living.

The paper is structured as follows: Section 2 examines the impacts of the COVID-19 pandemic on water consumption and management. Section 3 presents the case study analysis, while Section 4 discusses implications and recommendations for future research and practice.

2. COVID-19 and Water Management

The COVID-19 pandemic significantly disrupted global water management systems, reshaping consumption patterns and exposing systemic vulnerabilities. Lockdown measures resulted in a dual impact: a surge in residential water demand and a decline in non-residential sectors. These shifts highlighted the urgent need for adaptive water management strategies capable of responding to rapid and unexpected changes [13]. The pandemic also exposed inequalities in water access, particularly in underserved regions, further emphasizing the importance of resilience in water infrastructure and governance [14].

2.1 Changes in Water Consumption Patterns

During the lockdown, residential water consumption increased significantly due to heightened hygiene practices such as frequent handwashing, as recommended by the World Health Organization (WHO), and prolonged home confinement. In England, household water demand rose by 46%, driven by increased cooking, cleaning, and personal care activities [7]. Similar trends were observed in Germany, where residential water use increased by 14.3%, particularly during peak morning and evening hours [15].

Conversely, commercial and industrial water demand declined sharply. In some regions, non-residential sectors experienced reductions of up to 50%, reflecting reduced operations in offices, factories, and public spaces [16]. This imbalance between rising domestic demand and declining non-domestic use presented challenges for water utilities, which had to adjust distribution systems and operational priorities accordingly.

Regional variations in water consumption patterns were also evident. In Qatar, residential water consumption increased by at least 9%, with villas consuming more water than apartments due to their larger size and more extensive landscaping needs [8]. In rural areas of developing countries, the increased demand for hygiene-related water exacerbated pre-existing shortages, leaving many households unable to comply with WHO guidelines on handwashing and sanitation [17]. Additionally, the pandemic provided insights into the resilience of water management systems. Real-time data monitoring and predictive modeling became vital tools in addressing anomalies in consumption patterns. These tools not only ensured operational continuity but also offered valuable lessons for enhancing system resilience in future crises [18].

2.2 Operational Challenges

The operational challenges faced by water utilities during the pandemic were significant. Supply chain disruptions delayed the procurement of essential supplies such as treatment chemicals, spare parts, and equipment. These delays were particularly acute in regions heavily reliant on imports, creating additional pressure on water treatment facilities. Staffing shortages, driven by illness and social distancing requirements, further disrupted routine maintenance and operational activities [16].

Maintaining water quality emerged as another critical challenge. Reduced occupancy in commercial and institutional buildings led to stagnant water in plumbing systems, creating an environment conducive to the growth of bacteria such as *Legionella*. Addressing these risks required enhanced monitoring and testing protocols, alongside the deployment of innovative solutions like IoT-enabled remote sensing technologies [19].

The outbreak of the COVID-19 pandemic also highlighted vulnerabilities in other critical infrastructure systems, such as energy supply chains. Similar to water management, the energy sector experienced significant disruptions in demand, production, and investment planning due to the pandemic's cascading effects. This turbulence exposed weaknesses in supply chains and raised concerns about the security of essential resources. While energy geopolitics has historically been a critical issue, the green energy transition has introduced new dimensions to this geopolitical importance, emphasizing the interconnectedness of global challenges like climate change and resource security [20]. The integration of renewable energy systems into buildings further complements these efforts by enhancing resilience and reducing dependency on external networks. By coupling renewable energy technologies with effective water management strategies, buildings can optimize resource use and mitigate vulnerabilities during crises [21]. While operational challenges underscored the need for resilient infrastructure, the pandemic also exposed stark socio-economic disparities in access to clean water, further compounding the crisis.

2.3 Socioeconomic Inequalities

The COVID-19 pandemic exposed and exacerbated existing socio-economic disparities in access to clean water, with underserved urban and rural areas bearing the brunt of these inequities. In Sub-Saharan Africa, inadequate access to clean water severely hindered compliance with hygiene recommendations, leaving vulnerable populations disproportionately exposed to the virus and its consequences [14]. Similar challenges were evident in parts of South Asia, where communal water sources, often overcrowded and poorly maintained, significantly increased the risk of virus transmission due to inadequate sanitation infrastructure [22].

These disparities underscored the urgent need for equitable water distribution policies and targeted infrastructure investments. In arid regions such as the Gulf Cooperation Council (GCC) member states, the pandemic intensified these issues, as household water consumption surged significantly due to heightened hygiene practices and prolonged home confinement. While these increases were essential for public health, they placed unsustainable pressure on already scarce water resources, raising critical concerns about water security in these regions [23]. Such scenarios highlight the fundamental challenge for policymakers and water utilities: ensuring consistent access to sufficient and safe water supplies for all populations, especially during public health emergencies.

Achieving this goal requires not only immediate measures to address disparities but also long-term strategies that promote resilience, sustainability, and equity in water management systems. These efforts must account for the compounded effects of health crises, climate change, and socio-economic inequalities, emphasizing the need for proactive planning and international collaboration.

2.4 Global Insights and Research Findings

Research conducted during the pandemic yielded valuable insights into its impact on water systems across diverse regions. In Belgium and Thailand, studies using cascade models identified significant shifts in water usage in tourist-centric areas due to reduced tourism activity [22][24].

In Italy (Puglia), lifestyle changes during lockdowns altered peak water demand patterns, reflecting how behavioral factors influence consumption [19]. Similarly, in Joinville, Brazil, water use dropped below pre-pandemic levels, attributed to economic constraints and modified habits [13].

In Nepal, a nationwide study revealed a dual trend of increased residential consumption and decreased commercial water use, underscoring the need to tailor water management strategies to regional and cultural contexts [15]. Beyond consumption, environmental improvements were observed: the Sebou River in Morocco and the Tawi River in India showed enhanced water quality during lockdowns due to reduced industrial activity and wastewater discharge. Physicochemical parameters such as pH, alkalinity, and conductivity improved, making some stretches fit for bathing [25][26]. These findings highlight not only the adaptive challenges of crisis-driven demand shifts but also the unintended environmental benefits, suggesting a potential for long-term sustainable practices post-crisis.

3. Case study

After an extensive review of the literature and the challenges that arose during the COVID-19 lockdown, a practical component was developed to further explore these issues through a case study. This study focuses on a residential complex in Larnaca, Cyprus, chosen for its representativeness and the availability of detailed data from the lockdown period. The aim was to capture and analyze measurable data on water consumption before and during the pandemic lockdowns to identify key patterns and actionable insights. Figure 1 shows the examined complex of buildings, which served as the primary site for this study.



Figure 1. Examined Complex of Buildings

3.1 Methodology

Considering the unique conditions of the lockdown period, it was essential to select a data collection period that would provide a comprehensive view of the changes in water usage. Considering that the outbreak of the pandemic in Cyprus began in March 2020, it was deemed appropriate to select the data at least one year before and one year after the lockdown in order to have a complete picture of the changes that occurred. Thus, data from January 2019 to January 2021 were analyzed to encompass the pre-pandemic, lockdown, and post-lockdown phases. The water consumption data was collected, visualized and analyzed for a period of two years. Real-time water consumption data were obtained through IoT-enabled smart meters installed across

the complex, and visualizations were generated using iModel technology to enhance the analysis. Figure 2 presents the water consumption data, highlighting key trends and variations during the study period.

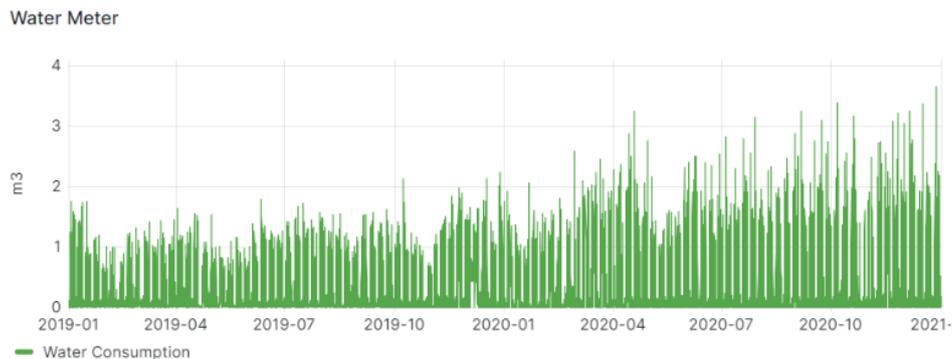


Figure 2. Water consumption

The study focused on:

1. Baseline Analysis: Establishing pre-pandemic consumption norms.
2. Lockdown Impact Analysis: Identifying changes in water consumption patterns during the lockdown.
3. Post-Lockdown Recovery: Analyzing the reversion or persistence of patterns after restrictions were lifted.

3.2 Results and Analysis

The analysis of the water consumption data revealed several significant findings. From March 2020, coinciding with the onset of lockdowns in Cyprus, there was a sharp increase in water consumption. Average daily usage rose by 40% compared to pre-pandemic levels. The increase was attributed to prolonged home confinement, frequent handwashing, food sanitization, and increased cooking and cleaning activities, as per WHO guidelines. Peak usage times shifted from early mornings and evenings to mid-mornings and afternoons, reflecting the new rhythms of remote work and schooling.

Observing the data, a clear correlation emerged between the implementation of restrictive measures and the spike in water consumption. Domestic cleaning and personal hygiene routines, such as showering more frequently and sanitizing household surfaces, contributed significantly to the increased demand [27]. Additionally, the rapid rise in household cooking needs further drove water usage. These behavioral changes were consistent with WHO recommendations for frequent handwashing and heightened cleanliness.

The surge in water demand strained local water resources, raising concerns about long-term sustainability. While the lockdown temporarily reduced pressure on shared water systems, the increased domestic use highlighted vulnerabilities in resource management. Water utilities had to adapt quickly to accommodate the new consumption patterns. Adjustments included rebalancing water supply systems and implementing measures to prevent disruptions. These actions ensured that residents had consistent access to water despite the challenges posed by the pandemic. As restrictions eased, water consumption began to normalize. However, certain

behaviors, such as increased handwashing, persisted beyond the lockdown period, indicating a potential long-term shift in water use habits.

These findings highlight the complex interplay between public health directives, behavioral changes, and resource management during crises. The data emphasizes the importance of developing resilient water management strategies that balance immediate public health needs with long-term sustainability goals [28].

The results of the case study reinforce the need for resilient water management systems capable of adapting to crises. The lockdown underscored the importance of integrating advanced technologies in building management to ensure water efficiency and safety during emergencies.

Key strategies identified for optimizing water management include:

1. **Real-Time Monitoring and Control:** Employing IoT-enabled sensors for continuous water monitoring and remote adjustments.
2. **Predictive Maintenance:** Using data analytics to identify inefficiencies and address potential leaks before they escalate.
3. **Automated Leak Detection and Response:** Implementing systems that automatically shut off water in case of leaks to minimize waste.
4. **Water Recycling and Reuse:** Adopting greywater recycling systems for non-potable uses, such as irrigation and flushing.
5. **User Engagement:** Educating occupants on water conservation through building automation systems and encouraging the adoption of low-flow fixtures.
6. **Touchless Fixtures:** Upgrading to sensor-activated faucets and flush systems to reduce disease transmission.
7. **Remote Management:** Facilitating remote control of water systems to maintain efficiency during lockdowns.
8. **Emergency Preparedness Plans:** Developing comprehensive plans to ensure uninterrupted water services during crises.

These strategies, when integrated into smart building systems, enhance resilience, improve efficiency, and ensure sustainability [29]. The findings from Larnaca demonstrate the critical role of technology and proactive planning in navigating the challenges posed by public health emergencies like COVID-19. Integrating strategic tech innovations, smart buildings can not only overcome crises like the COVID-19 lockdown but also become stronger and more resilient. Using advanced smart building technologies enhances water management, increases efficiency, reduces waste, and ensures occupant safety [30]. By combining these technologies with proven water management and emergency preparedness practices, a robust foundation is established to navigate future crises [31].

4. Discussion

The findings of this study underscore the critical need for resilience and strategic planning in water management during crises such as the COVID-19 pandemic. The Larnaca case study revealed a 40% increase in daily water consumption during lockdown, driven by heightened hygiene and domestic activity, emphasizing the urgency for adaptive supply systems capable of responding to rapid shifts in demand. Water utilities had to act swiftly, using data-driven insights to allocate resources effectively and maintain service continuity.

This surge also exposed vulnerabilities in shared water infrastructure, reinforcing the importance of sustainable management practices that address both short-term surges and long-term system resilience. Technologies like IoT-enabled sensors and predictive analytics proved

vital in identifying inefficiencies and minimizing waste, enabling proactive responses to emerging needs.

Equally important is community engagement. Raising awareness on water conservation and promoting efficient technologies—such as low-flow and touchless fixtures—can significantly reduce consumption while cultivating a culture of sustainability. Community acceptance is also key to the successful deployment of smart solutions.

Looking forward, the integration of predictive models and advanced tools like machine learning can help forecast demand and optimize resource use in future emergencies. Research should also focus on how these technologies can be adapted across diverse socio-economic and infrastructural contexts, ensuring effectiveness and cultural appropriateness.

Finally, water management must be understood within a broader systems perspective. Integrating water, energy, and waste management under a unified framework could provide holistic solutions to urban sustainability challenges. These interdisciplinary approaches are essential for building urban ecosystems capable of withstanding complex crises—including pandemics, climate change, and economic shocks [32][33].

Overall, this study advocates for a technology-enabled, community-focused, and cross-sectoral approach to ensure sustainable and resilient water systems capable of meeting both current and future challenges.

5. Conclusion

The COVID-19 pandemic served as an unprecedented stress test for global water management systems, exposing both vulnerabilities and opportunities for innovation. The increase in residential water consumption, driven by hygiene and domestic activities, highlighted the critical importance of adaptive and resilient infrastructure. At the same time, socio-economic disparities in access to clean water underscored the urgency of addressing systemic inequalities through inclusive governance and targeted investments.

This study, through an in-depth analysis of a residential complex in Larnaca, demonstrated the significant role of smart technologies, such as IoT-enabled sensors and predictive analytics, in optimizing water use and ensuring resource sustainability during crises. These technologies not only mitigated immediate disruptions but also provided a foundation for long-term resilience. Strategies like real-time monitoring, greywater recycling, and touchless fixtures emerged as effective tools to enhance water efficiency and occupant safety.

The findings also revealed that crises like the COVID-19 pandemic offer valuable lessons for future resource management. Integrating water management strategies with renewable energy systems and urban planning initiatives can address broader sustainability challenges, such as climate change and resource scarcity. Policymakers, water utilities, and stakeholders must collaborate to develop robust frameworks that balance public health needs with environmental sustainability.

Looking ahead, the development of predictive models and community-driven approaches will be critical in navigating future crises. By fostering innovation, encouraging behavioral change, and building inclusive systems, societies can transform water management from a reactive to a proactive discipline. This transformation will not only enhance resilience but also ensure equitable access to essential resources for all, aligning with global sustainability goals.

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