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Review

Water, Ecosystem Services, and Urban Green Spaces in the Anthropocene

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Abstract: As urban centers worldwide face the escalating impacts of climate change, rapid urbanization, and increasing water scarcity, the need for sustainable water management practices to enhance urban resilience in the Anthropocene has become critical. This study explores how ancient water management practices—including Roman aqueducts, Maya rainwater harvesting systems, and ancient Chinese flood control techniques—can be adapted to address contemporary water challenges in modern cities. We evaluate these historical practices through a lens of contemporary environmental pressures, including climate change, urbanization, and resource scarcity. By integrating ancient methods with modern technologies, we propose adaptive solutions to enhance urban water resilience. Case studies from five cities (Singapore, Copenhagen, Mexico City, Los Angeles, and Philadelphia) illustrate how modern green infrastructure, inspired by ancient techniques, is being successfully implemented to manage stormwater, mitigate urban flooding, and improve water conservation. By integrating historical practices with modern technologies—such as advanced filtration systems and water recycling—these cities are enhancing their water resilience and sustainability. The findings suggest that urban planners can draw valuable lessons from historical systems to design adaptive, climate-resilient cities that balance human needs with ecological sustainability. This paper concludes with actionable recommendations for future urban planning, emphasizing the importance of decentralized water systems, nature-based solutions, and community engagement to ensure sustainable urban water management in the Anthropocene.

Keywords: water systems; nature-based solutions; ancient wisdom; Anthropocene; ecological sustainability; human needs

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1. Introduction

Urban areas are facing unprecedented environmental challenges due to rapid urbanization, climate change, and the degradation of natural resources. In the Anthropocene, cities must develop climate resilience by adopting sustainable water management practices that can withstand increasing pressures from extreme weather events, rising temperatures, and water scarcity [1]. One of the most promising approaches to addressing these challenges lies in the development and integration of urban green spaces, which play a pivotal role in enhancing ecosystem services (i.e., the benefits that people derive from ecosystems, including flood regulation, water purification, and groundwater recharge) [2]. These spaces, including parks, wetlands, green roofs, and gardens, not only contribute to urban biodiversity but also offer critical functions for water management in cities. Green spaces provide a wide range of ecosystem services that are particularly crucial for managing urban water cycles. For instance, they can reduce the risk of flooding by allowing rainwater to infiltrate the ground rather than overwhelming drainage systems, thereby mitigating stormwater runoff [3]. Moreover, vegetation in urban green spaces improves water quality by filtering pollutants before they enter rivers and lakes, contributing to cleaner waterways and healthier ecosystems [4]. As cities worldwide experience the impacts of climate change, including more intense storms and prolonged droughts, urban green spaces have emerged as essential components of climate-resilient cities, promoting both ecological health and human wellbeing [5].

Water management in urban areas has traditionally relied on gray infrastructure, such as drains, pipes, and water treatment plants, which often fail to account for natural water cycles and ecosystem dynamics. However, the integration of nature-based solutions—including green infrastructure and urban green spaces—offers a more sustainable and adaptive approach to managing urban water challenges [6]. These solutions not only address immediate concerns such as stormwater control and water quality improvement but also contribute to long-term urban sustainability by enhancing ecosystem services.

The goal of this study is to explore how ancient water management techniques and urban green spaces can together contribute to building climate resilience in modern urban environments. As cities face increasing challenges brought on by the Anthropocene, there is a growing interest in revisiting traditional methods for managing water resources. Ancient techniques, developed long before the industrial era, offer valuable insights into how humans in the past worked harmoniously with natural ecosystems to manage water sustainably.

This study has two primary objectives: (1) to critically assess the applicability of ancient water management techniques in modern cities, and (2) to evaluate their potential to address contemporary environmental challenges, particularly in relation to water resource management and climate adaptation. These ancient systems, such as aqueducts, terracing, and rainwater harvesting, have demonstrated resilience over centuries and can provide effective strategies for enhancing urban water systems today.

Additionally, this study explores the critical role of urban green spaces in supporting water management and ecosystem services in cities aiming to enhance their climate resilience. Green spaces are essential for improving water infiltration, reducing flooding risks, enhancing water quality, and promoting urban cooling amidst rising global temperatures. By integrating these spaces with ancient water management practices, cities can develop sustainable, nature-based solutions that address both immediate environmental needs and long-term resilience goals.

To illustrate the potential of these approaches, this paper examines case studies in which urban green spaces have been successfully integrated with ancient water management techniques. The purpose of these examples is to highlight the importance of combining historical knowledge with modern urban planning to create cities that are more adaptable, sustainable, and resilient in the face of ongoing climate challenges.

2. Methods

This study employed a combination of a literature review, a case study analysis, and a comparative framework evaluation to explore how historical water management systems can inform contemporary green infrastructure solutions in modern cities. The literature review followed a systematic approach to ensure the relevance and quality of the selected sources. The following steps were taken during the screening process:

Inclusion Criteria: We included studies that focused on ancient water management practices in civilizations such as ancient Rome, Maya, Mesopotamia, ancient China, and India, as well as studies on modern urban water management techniques that utilize nature-based solutions (NBSs). The selected publications were peer-reviewed articles, book chapters, or government reports that provide empirical data, historical analysis, or case studies.

Databases Used: The literature was retrieved from major academic databases such as Google Scholar, JSTOR, Scopus, and Web of Science, using key words such as "ancient water management", "Roman aqueducts", "Mayan rainwater systems", "nature-based solutions", "urban water resilience", and "green infrastructure".

Timeframe: We focused primarily on the literature published between 2000 and 2024, although foundational texts that are critical to the field (e.g., studies from the 1960s or 1970s on Roman aqueducts or Mesopotamian irrigation systems) were also included to provide historical context.

Screening Process: Our initial searches yielded over 300 articles. These were screened based on their titles and abstracts, reducing the pool to 200 articles. The remaining articles were assessed in detail for relevance, resulting in a final selection of 118 studies that were directly related to the research question.

Exclusion Criteria: Studies that lacked empirical evidence, focused solely on modern urban planning without considering ancient practices, or were not available in English, French, or Italian were excluded.

The literature review focused on ancient practices from civilizations such as the Romans, Maya, and ancient China (among others), with an emphasis on rainwater harvesting, flood control mechanisms, and decentralized water systems. This review provided the foundation for understanding how these historical practices could be adapted to address contemporary challenges related to water scarcity, urbanization, and climate change.

Five cities—Singapore, Copenhagen, Mexico City, Los Angeles, and Philadelphia—were selected for an in-depth case study analysis based on their implementation of green infrastructure solutions inspired by ancient water management techniques. These cities were chosen because of their innovative approaches to water management, integrating nature-based solutions into urban planning while drawing inspiration from historical systems. The selection was also influenced by the cities' varying climates, geographic conditions, and socioeconomic factors, providing a diverse perspective on the adaptation of ancient practices.

Each case study was analyzed using a structured comparative framework that examined the following elements:

- Challenges: Identifying the specific water-related challenges faced by each city, such as flooding, water scarcity, or urban heat islands.
- Ancient Practices: Analyzing which ancient water management practices were used as inspiration for modern solutions.
- Modern Adaptations: Assessing how these ancient techniques were adapted using contemporary technologies and materials.
- Outcomes: Evaluating the effectiveness of these adaptations in terms of water management, environmental sustainability, and urban resilience.
- Evaluation Criteria: The comparative framework focused on four key criteria to evaluate the similarities and differences between ancient practices and their modern adaptations:
    - Water Resource Management: The efficiency of water capture, storage, and distribution in both ancient and modern systems.
    - Sustainability: The long-term environmental impact and sustainability of the water management practices.
    - Scalability: The potential for these systems to be scaled to different city sizes or regions.
    - Resilience: The capacity of these systems to withstand climate change impacts and other external shocks, such as extreme weather events.

Although this study offers an analysis of how ancient water management practices can inform modern urban water systems, it presents some limitations: (1) limited geographic scope—the focus on five cities restricts the global generalizability of the findings. To gain a more comprehensive understanding, future research should expand the geographic diversity of case studies to include regions such as sub-Saharan Africa, the Middle East, and South Asia. (2) Incomplete historical knowledge—some historical water management systems, particularly those that have been lost or poorly documented, may not be fully understood, limiting their direct applicability to modern contexts [7,8]. Further archeological and historical research is needed to uncover the full potential of these ancient systems. We also examined the limitations of these ancient systems, particularly how overuse or environmental mismanagement contributed to the eventual collapse of civilizations such as the Maya and Mesopotamians. This critical evaluation informs our recommendations for applying ancient wisdom in ways that avoid repeating past failures.

3. Evolving Concepts of Sustainability and Resilience: Lessons from Ancient Water Systems for Modern Climate Challenges

As the world confronts the escalating pressures of global environmental change, including climate variability, resource depletion, and increasing demands from rapid urbanization, it has become increasingly critical to revisit and clarify the evolving concepts of sustainability and resilience [9,10]. These challenges are further compounded by population growth and the expanding need for equitable access to water, particularly in urban areas where water scarcity is becoming more pronounced [11,12]. The impacts of these environmental pressures are often disproportionately borne by marginalized communities, highlighting the growing importance of environmental justice in the discourse on water management [13–15]. Sustainability and resilience, once focused solely on the availability of resources, now encompass the need for equitable solutions that address social justice and ensure that vulnerable populations are not left behind.

In the context of water management, this evolution is particularly significant, as the balance between human demands and ecological health has never been more fragile. The principles of environmental justice call for water management systems that are not only sustainable and resilient but also ensure equitable access to clean water for all, regardless of socioeconomic status or geographic location.

In both ancient and modern contexts, the concepts of sustainability and resilience are critical for understanding the long-term viability and adaptability of water management systems. However, the application of these terms differs significantly across historical and contemporary settings. In ancient times, sustainability primarily referred to the capacity of water systems to provide reliable, long-term access to water for drinking, agriculture, and sanitation. For example, the Roman aqueducts, which supplied cities with water for centuries [16], and the chinampa system of the Aztecs, which created a sustainable agricultural and water management cycle [17], were exemplary of long-lasting water systems. These systems operated with minimal technological intervention, often relying on natural processes or human labor.

However, sustainability in ancient contexts was often viewed through a narrower lens. Long-term environmental impacts, such as soil salinization from Mesopotamian irrigation or deforestation in the Maya civilization, were not always accounted for [18]. Over time, these effects contributed to environmental degradation, reducing agricultural productivity and, ultimately, leading to societal collapse [19]. This phenomenon illustrates that, while ancient water systems may have been sustainable in the short term, their inability to prevent environmental harm underscores the limitations of their sustainability.

In the modern context, sustainability has taken on a broader and more complex definition, particularly within the framework of the Anthropocene and climate change [9]. Today, sustainability requires water management systems not only to provide reliable access to water but also to conserve resources, minimize environmental impacts, and support ecosystems. For instance, wetland restoration in cities such as Copenhagen and Singapore integrates biodiversity enhancement, carbon sequestration, and water filtration into urban water management strategies, demonstrating a more comprehensive understanding of sustainability today [20]. Furthermore, modern systems are increasingly expected to contribute to climate mitigation by reducing carbon emissions, conserving energy, and protecting ecosystems—an imperative that was absent in ancient practices [10].

The meaning of resilience has also evolved. In ancient civilizations, resilience referred to the ability of a water system to recover from or adapt to environmental stresses such as droughts, floods, or seasonal variations [7]. For instance, the Roman aqueduct system was designed to ensure a consistent water supply even during periods of low rainfall, and the flood control systems of ancient China (e.g., Dujiangyan) prevented destructive flooding while supporting agricultural productivity [21]. In these cases, decentralized structures, such as multiple cisterns and terraced fields, distributed water resources across various locations, thereby preventing the collapse of the entire system if one part failed [22].

However, many ancient societies ultimately lacked sufficient resilience, particularly when faced with prolonged environmental stresses. The Maya civilization, for instance, was unable to adapt to long-term droughts exacerbated by deforestation and the overuse of water resources, leading to its collapse [19]. This highlights the fact that resilience, while present, had its limits in ancient times, especially when combined with poor resource management and environmental degradation.

In the modern era, resilience has become a cornerstone of urban water management, particularly in response to climate change. A modern resilient system is not only one that can recover from disruptions, such as floods or droughts, but also one that can adapt to new challenges [23]. For example, Los Angeles is developing decentralized water systems that reduce reliance on a single source by incorporating a mix of groundwater, rainwater harvesting, and recycled water, creating a more resilient system in the face of increasing climate variability [24]. Furthermore, cities are building green infrastructure—such as bioswales, permeable pavements, and rain gardens—that can absorb excess water during storms and mitigate flood risk, helping urban environments adapt to more frequent extreme weather events [25]. These modern solutions emphasize adaptability and flexibility, allowing cities to better prepare for and respond to future climate challenges.

Sustainability and resilience in the Anthropocene now demand systems that actively contribute to both climate mitigation and climate adaptation. Rising global temperatures, shifting precipitation patterns, and more frequent extreme weather events mean that water systems must be designed not only to sustain water resources but also to withstand increasingly severe disruptions [10]. For example, modern adaptations of ancient techniques, such as rainwater harvesting and decentralized cisterns, can improve sustainability by reducing reliance on energy-intensive centralized water systems [26]. These ancient systems offer valuable lessons in redundancy and resource management, but modern applications must go beyond the practices of the past by integrating advanced technologies, energy efficiency, and climate-resilient designs [27].

Moreover, resilience in the face of climate change requires that modern systems be adaptive, not only to current conditions but also to future uncertainties. This adaptivity includes designing infrastructure that can accommodate future changes, such as water scarcity, extreme rainfall, or rising sea levels [28]. Ancient systems provide important insights into the decentralization and diversification of resources, but modern systems must incorporate predictive modeling and flexible technologies in order to remain viable in rapidly changing environments [29]. These technologies, combined with long-term planning and climate foresight, allow cities to anticipate and respond to challenges those ancient civilizations could not have foreseen, such as urban sprawl and global environmental changes.

In both the ancient and modern contexts, sustainability and resilience are essential for the long-term success of water management systems. Ancient systems, such as the Roman aqueducts or Aztec chinampas, were often sustainable and resilient in the environments for which they were designed. However, the challenges of the Anthropocene—including climate change, population growth, and urbanization—require a more expansive understanding of these concepts today. While modern cities can draw inspiration from ancient techniques, they must also incorporate new technologies, climate adaptation strategies, and ecological principles in order to ensure that their water systems remain sustainable and resilient in an uncertain future [9]. Thus, ancient wisdom provides a foundation, but modern challenges demand innovative, forward-thinking solutions.

4. Defining the Anthropocene: Human Impacts on Earth's Ecological Systems

The term Anthropocene has emerged as a crucial concept across various disciplines, emphasizing the unprecedented influence of human activity on Earth's ecological and geological systems. Originally proposed by biologist Eugene Stoermer in the early 1980s and popularized by atmospheric chemist Paul Crutzen in 2000, the Anthropocene suggests that humanity's impact—through industrialization, urbanization, deforestation, and climate change—has initiated a new geological epoch. Crutzen's work emphasized that these anthropogenic forces have fundamentally altered planetary processes, with effects that will be detectable in the Earth's stratigraphic record for millennia [30]. This shift is evidenced by key indicators such as rising carbon dioxide levels, widespread microplastic pollution, and significant biodiversity loss, all of which signal the transition from the stable Holocene epoch [31].

Despite its widespread usage, the formal recognition of the Anthropocene as a distinct geological epoch is still debated within the geology community. The Anthropocene Working Group (AWG), part of the International Commission on Stratigraphy (ICS), continues to investigate whether human-induced changes, such as the proliferation of radioactive isotopes after 1945, are sufficient to mark the beginning of a new geological era [32]. While scholars debate the specific criteria for defining this epoch, the Anthropocene has already become a powerful conceptual tool for understanding the intricate relationship between human societies and natural systems.

This concept is particularly relevant to the critical issues of sustainable urban development, water resource management, and ecosystem services, all of which are profoundly affected by human activity. Human interventions in the water cycle, the degradation of ecosystem services, and rapid urbanization have transformed the interactions between people and the environment, necessitating a new approach to urban planning [33]. In the context of the Anthropocene, cities must adopt resilient designs, including the integration of green infrastructure, to mitigate the consequences of environmental degradation and climate change.

The Anthropocene provides a framework for addressing these interconnected systems, offering insights into managing water scarcity and floods, protecting biodiversity, and leveraging green infrastructure to improve the sustainability of urban environments. As urbanization accelerates, the role of natural elements such as urban green spaces and water management systems is becoming essential in maintaining ecological balance and enhancing the quality of urban life [34]. Responding to the environmental realities of the Anthropocene will require innovative solutions that bridge the gap between human activity and environmental stewardship.

5. Modern Challenges: Climate Change, Urbanization, and Water Scarcity in the Anthropocene

As we enter the Anthropocene, cities are confronted with mounting challenges related to climate change, urbanization, and water scarcity. Rapid urban growth has placed unprecedented pressure on water resources, while the increasing frequency and severity of extreme weather events further exacerbate these challenges [1]. In this context, ancient water management practices, which were often highly efficient and adaptive to environmental conditions, offer valuable insights for modern urban sustainability. Climate change is one of the most significant challenges facing modern cities. As global temperatures rise, cities are experiencing more extreme weather events, which disrupt water supply systems, strain infrastructure, and increase the risk of water scarcity and flooding. In many regions, shifting rainfall patterns and prolonged droughts are reducing the availability of freshwater resources, leading to significant water stress in urban areas [35]. In other regions, increased precipitation and rising sea levels have caused more frequent and severe urban flooding, damaging infrastructure and displacing communities [36,37]. Ancient water management systems, such as rainwater harvesting and flood control mechanisms, offer solutions that are highly relevant to modern climate challenges. For instance, the Maya civilization relied on reservoirs and cisterns to capture and store rainwater, ensuring a stable water supply during periods of drought [38]. Modern cities facing water scarcity, such as Cape Town or São Paulo, could adapt these ancient techniques by incorporating urban rainwater harvesting systems to capture and store stormwater for future use [39]. Singapore, for example, has already adopted advanced rainwater harvesting practices, significantly improving its water security in the face of unpredictable rainfall patterns [40,41].

Similarly, cities can learn from ancient Chinese flood control methods, such as the Dujiangyan Irrigation System, which used natural river dynamics to prevent flooding without causing environmental damage [42]. Modern urban planners could integrate nature-based solutions, such as constructed wetlands and floodplains, to manage excess water during heavy rains, reduce urban flooding, and restore natural hydrological cycles.

Urbanization is placing immense stress on modern water infrastructure. As cities expand, impermeable surfaces—such as roads, buildings, and parking lots—replace natural landscapes, reducing the ground's ability to absorb rainfall and increasing stormwater runoff [43]. This not only heightens the risk of flooding but also contributes to the degradation of water quality, as runoff collects pollutants from urban surfaces and deposits them into rivers and lakes [44]. Moreover, rapid urban growth often outpaces the development of water infrastructure, leaving many cities vulnerable to water shortages and inadequate stormwater management.

Ancient cities developed innovative ways to manage water within densely populated environments. The Romans, for example, constructed complex aqueduct systems that transported water from distant sources into urban centers while simultaneously managing waste and stormwater through underground drainage systems [16]. This type of decentralized water infrastructure—where water is collected, stored, and distributed across a network of systems—could inform modern strategies for urban water resilience. Modern cities such as Los Angeles are already adopting decentralized water systems, including the use of green infrastructure such as rain gardens and bioswales, to manage stormwater, reduce runoff, and enhance water's infiltration into the ground [45].

Additionally, Rome's cisterns and water storage systems could inspire modern approaches to managing water demand in rapidly urbanizing areas. By integrating rainwater harvesting systems and greywater recycling into urban infrastructure, cities can reduce their dependence on external water sources and build more resilient water systems that can cope with population growth and climate variability [46]. Water scarcity is an escalating problem in many regions around the world, particularly in arid and semi-arid climates. According to the United Nations, more than 2 billion people are living in countries experiencing high levels of water stress [47]. As populations grow, so does the demand for water, further straining already limited resources. The overextraction of groundwater, inefficient agricultural practices, and climate change-induced droughts are depleting freshwater supplies faster than they can be replenished [48]. Ancient civilizations, such as those in Mesopotamia and India, faced similar challenges but developed irrigation and water management systems that maximized water efficiency.

The qanat system—an ancient method used in Persia and the Middle East to transport groundwater to arid regions—is a prime example of a sustainable technique that conserved water while meeting the needs of growing populations [49]. Modern cities in water-scarce regions, such as the Middle East and North Africa (MENA), could adapt these practices by incorporating groundwater recharge systems and efficient irrigation techniques to sustainably manage limited water resources. In addition, the use of stepwells in ancient India, which allowed for the collection and storage of rainwater during the monsoon season for use in dry periods, could be adapted in modern water-scarce cities through the implementation of urban water storage systems and reservoirs that increase resilience to drought [50]. These systems provide valuable lessons in how cities can reduce water waste and improve water security by utilizing locally available water resources more effectively [51].

The challenges posed by climate change, urbanization, and water scarcity are reshaping the way in which cities approach water management in the Anthropocene. While modern technology has made significant advancements in infrastructure, ancient water management practices—developed by civilizations that faced similar environmental pressures—offer time-tested solutions that can be adapted to meet contemporary needs. By integrating ancient practices such as rainwater harvesting, flood control, and water conservation with modern green infrastructure and nature-based solutions, cities can enhance their resilience to climate impacts and ensure sustainable water management for future generations [52].

6. Adapting Ancient Water Management Techniques to Modern Climate Challenges

Sustainable water management practices have long been important. Ancient civilizations developed sophisticated techniques for controlling and distributing water, which were essential for both urban sustainability and the survival of growing populations. These early systems reflect an inherent understanding of the delicate balance between human needs and the natural environment, as well as the long-term consequences of water scarcity, flooding, and resource depletion [53]. By studying these ancient water management practices, modern cities can glean valuable insights for managing urban water challenges in the Anthropocene, where climate change and rapid urbanization demand innovative and sustainable approaches. One of the earliest examples of urban water management comes from Mesopotamia, where irrigation systems were central to the region's agricultural success. The Tigris and Euphrates rivers provided water, but their annual flooding could bring either life or destruction. To harness these water resources effectively, ancient Mesopotamians developed an intricate network of canals, dikes, and levees to control the flow of water for agricultural irrigation and flood protection [54]. These systems were crucial for the sustainability of large urban centers such as Babylon, which relied on agricultural productivity to support growing populations. However, the overuse of these irrigation systems led to long-term soil salinization due to the high evaporation rates in the arid climate, insufficient drainage systems, and the continued use of river water containing dissolved salts [43,55]. Despite these problems, Mesopotamian practices offer lessons in how water systems can be integrated into urban planning, balancing human water needs with environmental considerations. Similarly, the Romans are renowned for their extensive and efficient urban water management systems, particularly their aqueducts, which supplied water to cities across the Empire [56]. These aqueducts, built from the 4th century B.C. onwards, were monumental in scale, capable of transporting vast quantities of water over long distances to meet the needs of urban populations. Rome itself had 11 aqueducts that provided water for drinking, public baths, fountains, and irrigation [16]. The Roman approach to water management was highly advanced, emphasizing sustainability and reliability. Roman engineers built cisterns and reservoirs to store excess water for times of drought, and they integrated drainage systems to manage stormwater and prevent flooding [57]. The fact that some Roman aqueducts, such as the *Aqua Virgo*, are still functioning today speaks to the durability and long-term vision behind their design [58]. These ancient techniques remain relevant as modern cities grapple with urban water scarcity and the need for robust infrastructure.

In ancient India, rainwater harvesting and stepwells were critical methods of water management, particularly in regions prone to seasonal rainfall variability. The Indus Valley Civilization (c. 2500 B.C.) built advanced drainage systems and water storage tanks that allowed urban centers such as Mohenjo-Daro to thrive in an otherwise arid environment [50]. These cities were designed with an intricate network of sewers and wells, which ensured that water was conserved, reused, and directed where needed most. Additionally, the use of stepwells—elaborate structures that allowed access to underground water sources—was common in India, especially in areas with scarce rainfall. These systems enabled sustainable water to be used by storing water during the monsoon season for use during drier periods [59]. The principles of water conservation and resource efficiency seen in ancient India are increasingly being revisited today as cities face similar challenges of water scarcity and the need for rainwater harvesting solutions [60]. Ancient China also developed advanced water management techniques to control seasonal flooding and irrigate agricultural fields. The Dujiangyan Irrigation System, built around 256 B.C. in Sichuan Province, is one of the most remarkable examples of ancient hydraulic engineering [61,62]. This system was designed to manage the Min River's flow without the need for dams, using a series of channels and levees to divert excess water during floods while maintaining a stable water supply for agriculture. The Dujiangyan system is still in use today and stands as a testament to sustainable water management. Its design minimized environmental disruption while providing uninterrupted water to surrounding farmlands, contributing to the long-term sustainability of the region [63]. The balance between flood control, irrigation, and environmental preservation seen in this system offers a valuable model for modern urban water management, particularly in flood-prone areas.

The Maya civilization in Mesoamerica (around 2000 B.C.—1500 A.D.) faced significant challenges with water availability due to the seasonal nature of rainfall in the region. In response, the Maya developed a range of water management techniques, including the construction of reservoirs, cisterns, and channels to capture and store rainwater [64]. These systems were critical for supporting large urban populations in regions that lacked permanent rivers. The Maya's use of water storage technologies reflects an early understanding of climate variability and the need for resilient infrastructure. As cities around the world face growing concerns of water scarcity and climate change, ancient Mayan techniques provide a model for contemporary water storage solutions in urban areas [38].

Ancient civilizations developed a wide array of water management practices to ensure the sustainability of their urban centers, from the complex irrigation networks of Mesopotamia to the monumental aqueducts of Rome and the innovative rainwater harvesting techniques of the Maya. These systems not only supported the day-to-day needs of their populations but also reflect a sophisticated understanding of environmental constraints and the long-term consequences of unsustainable practices. By revisiting these ancient approaches, modern urban planners and policymakers may find valuable strategies for addressing the water-related challenges of the Anthropocene [39].

7. Examples of Cities Integrating Ancient Practices and Green Infrastructure for Urban Water Resilience

As cities confront the growing impacts of climate change, water scarcity, and urbanization, some are turning to ancient water management practices and green infrastructure to enhance their water resilience [65]. These cities have successfully adapted historical techniques or implemented nature-based solutions to address their modern water challenges, promoting sustainability and climate resilience [51]. This study examines five cities—Singapore, Copenhagen, Mexico City, Los Angeles, and Philadelphia—to analyze the modern adaptation of ancient water management techniques through green infrastructure. These cities were selected because their unique water challenges and urban contexts closely correspond to the historical methods developed by ancient civilizations.

7.1. Singapore: Water Scarcity and Mayan Rainwater Harvesting

Singapore, despite its dense urban environment and limited freshwater resources, has emerged as a global leader in water resilience by integrating modern technology with traditional rainwater harvesting practices. Given its small land area and lack of natural freshwater resources, Singapore relies heavily on rainwater harvesting as a central component of its urban water strategy. The city collects stormwater through an extensive network of drains, canals, and reservoirs that capture rainwater for reuse [66]. This approach echoes ancient techniques used by civilizations such as the Maya, who also relied on reservoirs and cisterns to store rainwater during periods of drought [64].

Singapore's flagship initiative, PUB's Four National Taps, includes rainwater as a critical water source, complemented by desalination, imported water, and the city's highly successful NEWater program, which recycles treated wastewater [67]. Marina Barrage, one of Singapore's major urban water management projects, serves as both a dam and a recreational space, capturing rainwater while preventing flooding in the city [68]. This approach to urban rainwater harvesting is highly efficient and can be replicated in other water-scarce cities facing similar challenges of limited resources and climate variability.

- Challenges: Singapore faces significant water scarcity due to its limited natural freshwater resources and high population density. The city-state has implemented extensive rainwater harvesting and water recycling systems to address these challenges.
- Ancient Technique Correspondence: Singapore's rainwater collection and decentralized water storage systems are reminiscent of the Maya civilization's sophisticated rainwater harvesting techniques. The Maya built reservoirs and cisterns to store water during the rainy season for use during long dry spells. Singapore has similarly adopted decentralized water systems that collect rainwater through a network of drains and canals, reducing reliance on external water sources.
- Modern Adaptation: Singapore's innovative "ABC Waters Program" (Active, Beautiful, Clean Waters) integrates nature-based solutions such as bioretention systems, green roofs, and stormwater harvesting, which echo the ancient Mayan principles of resource management through natural systems.

7.2. Copenhagen: Urban Flooding and the Dujiangyan Flood Control System

Copenhagen has become a model of urban water resilience through the use of green infrastructure to address extreme rainfall events and urban flooding [69]. Climate change has increased the frequency of cloudbursts—intense rainfall events that overwhelm traditional drainage systems, leading to severe flooding. In response, the city developed the Copenhagen Cloudburst Management Plan, which integrates green and blue infrastructure (open spaces and water bodies) to manage stormwater [70]. The plan includes a network of green streets, rain gardens, bioswales, and water retention areas that slow down and absorb stormwater before it can flood urban areas. By incorporating permeable pavements and water-absorbing green spaces into its urban landscape, Copenhagen can control stormwater runoff and reduce the urban heat island effect, enhancing the city's overall climate resilience. These approaches draw from the principles of nature-based solutions used in ancient flood control systems, such as the Dujiangyan Irrigation System in China, which also worked with natural water flows to prevent flooding while maintaining water supplies [71].

- Challenges: Copenhagen is increasingly vulnerable to flooding due to rising sea levels and increased rainfall caused by climate change. The city has adopted green infrastructure strategies to manage excess stormwater and reduce flood risks.
- Ancient Technique Correspondence: Copenhagen's flood management systems are similar to those of ancient Chinese civilizations, particularly the Dujiangyan irrigation and flood control system, which diverted water from rivers to prevent floods while ensuring a steady supply of water for agriculture. This ancient system used natural principles to manage water flow without relying on dams.
- Modern Adaptation: Copenhagen's "Cloudburst Management Plan" includes green infrastructure such as permeable pavements, bioswales, and rain gardens, which help absorb excess rainwater and manage floods naturally. This approach draws on the principles of ancient Chinese flood control by working with natural water flows to mitigate risks.

7.3. Mexico City: Water Scarcity and Pollution: The Aztec Chinampa System

Mexico City has drawn inspiration from the chinampa system, a traditional form of agricultural water management used by the Aztecs to sustain large populations. Chinampas are artificial islands built in shallow lakebeds that allow for the efficient use of water in farming [72]. These islands were historically fed by a network of canals that controlled water levels and supplied moisture directly to crops, offering a model of sustainable, self-sufficient agriculture [73]. Today, Mexico City is revitalizing this ancient system to address its water scarcity and food security challenges. The Chinampa Project focuses on restoring the remaining chinampas in the Xochimilco area, combining traditional water management practices with modern techniques to support sustainable urban agriculture [74]. This initiative not only improves local food production but also enhances water retention and filtration in a city that faces significant challenges related to water supply and flooding.

By reintroducing the chinampa system, Mexico City is promoting eco-friendly water management and urban biodiversity [75].

- Challenges: Mexico City faces severe water scarcity and is prone to both floods and droughts. The city's over-reliance on groundwater extraction has also caused significant land subsidence.
- Ancient Technique Correspondence: The city's green infrastructure projects are inspired by the Aztec civilization's chinampa system, which involved creating floating gardens in wetland areas to manage water for both agriculture and flood control. Chinampas were an effective water management system that reduced flooding while increasing agricultural productivity.
- Modern Adaptation: In recent years, Mexico City has revived parts of the chinampa system in the Xochimilco area to restore wetland ecosystems and improve urban water management. Additionally, the city has introduced green roofs, urban parks, and constructed wetlands to address water shortages and manage stormwater, reflecting the Aztec approach of using natural ecosystems to solve urban water challenges.

7.4. Los Angeles: Drought and the Roman Aqueducts

Los Angeles has increasingly turned to rainwater harvesting to enhance its water security in response to chronic droughts and water scarcity exacerbated by climate change [76]. As part of its Sustainable City pLAn, Los Angeles has implemented a wide range of green infrastructure projects, including rain gardens, green streets, and bioswales, to capture stormwater and reduce runoff [77,78]. These projects not only reduce flood risks but also replenish groundwater supplies, making the city more resilient to drought. Los Angeles' use of rainwater harvesting echoes the practices of ancient civilizations such as the Maya, who developed systems of reservoirs and cisterns to capture rainwater during periods of seasonal rainfall [64]. In modern Los Angeles, the use of permeable pavements, detention basins, and urban water gardens helps mitigate water scarcity while reducing the impact of urban runoff on local ecosystems. The Los Angeles River Revitalization Plan is another key initiative aimed at transforming the river into a natural flood control system that supports urban biodiversity, green spaces, and recreational areas, further integrating nature-based solutions into the city's water management strategy [79].

- **Challenges**: Los Angeles frequently suffers from droughts, and much of its water is imported from distant sources. The city has also struggled with managing stormwater runoff, which can lead to flooding and water contamination.
- **Ancient Technique Correspondence**: Los Angeles' approach to groundwater recharge and stormwater management mirrors the Roman Empire's aqueduct systems, which transported water across great distances to supply cities. The Romans also used cisterns to store water for times of scarcity, ensuring the availability of water in drought-prone regions.
- **Modern Adaptation**: Los Angeles has adopted decentralized stormwater capture systems, including green streets, rain gardens, and infiltration basins, which aim to recharge the city's groundwater. These methods reflect Roman principles of water transport and storage but with modern ecological enhancements, such as permeable surfaces and natural filtration systems.

7.5. Philadelphia: Combined Sewer Overflows and Roman Cisterns

Philadelphia's Green City, Clean Waters initiative is one of the most ambitious urban green infrastructure programs in the United States. Launched in 2011, this 25-year plan aims to manage stormwater, improve water quality, and reduce combined sewer overflows through the implementation of green infrastructure [80]. By establishing a network of green roofs, permeable pavements, rain gardens, and tree trenches, Philadelphia captures stormwater where it falls. This approach allows water to infiltrate the ground and reduces the burden on the city's aging sewer systems. This initiative mirrors ancient water management principles, such as those seen in Roman aqueducts and cisterns, which efficiently transported and stored water while mitigating flood risks [81]. By decentralizing its stormwater management through green infrastructure, Philadelphia is not only reducing urban flooding but also enhancing biodiversity and public green spaces, improving both environmental and social outcomes [82,83].

- **Challenges**: Philadelphia faces issues related to stormwater runoff, which overwhelms its combined sewer systems, leading to flooding and water pollution.
- **Ancient Technique Correspondence**: The city's green stormwater infrastructure is reminiscent of the Minoan civilization's early wastewater management systems, which included drainage networks and natural filtration systems to manage both floodwaters and sewage. The Minoans were pioneers in separating stormwater and wastewater to prevent contamination.
- **Modern Adaptation**: Philadelphia's "Green City, Clean Waters" initiative incorporates rain gardens, green roofs, and permeable pavements to manage stormwater. These nature-based solutions align with the ancient Minoan approach of using natural filtration and drainage to prevent flooding and water contamination. By mimicking natural hydrological processes, Philadelphia's modern systems reduce the strain on its sewage infrastructure and improve water quality.

These five cities were selected based on their diverse but pressing water management challenges, their significant investments in green infrastructure, and their use of ancient water management principles adapted to modern urban settings. Each city offers unique insights into how historical techniques can be reimagined to address contemporary issues such as water scarcity, flooding, and urban resilience in the face of climate change. By examining these cities, this study provides a comprehensive understanding of how ancient knowledge can be integrated into modern water management strategies.

These examples demonstrate how cities worldwide are successfully integrating ancient practices and green infrastructure to enhance urban water resilience. Whether through rainwater harvesting in Singapore, flood control in Copenhagen, or the revitalization of traditional farming systems in Mexico City, these strategies offer valuable lessons for managing water sustainably in the Anthropocene. By combining modern innovations with time-tested techniques from ancient civilizations, cities can build more resilient, climate-adaptive systems that address both immediate water challenges and long-term environmental sustainability.

Table 1 provides a comparative summary of the water management strategies and outcomes for each city, demonstrating how ancient techniques have been adapted to address modern challenges.

Table 1. Comparison of water management approaches in selected cities.

City	Water Challenge	Ancient Technique Applied	Modern Adaptation	Outcome
Singapore	Water scarcity	Mayan rainwater harvesting systems	Rainwater harvesting infrastructure	Improved water security and recycling
Copenhagen	Urban flooding	Dujiangyan flood control system	Green infrastructure (rain gardens, bioswales)	Reduced flood risk and stormwater management
Mexico City	Water scarcity and pollution	Aztec chinampa system	Restored chinampas for farming	Increased water retention and urban sustainability
Los Angeles	Drought	Roman aqueducts	Decentralized water systems	Enhanced groundwater recharge and reduced reliance on external sources
Philadelphia	Combined sewer overflows	Roman cisterns	Green roofs and permeable pavements	Reduced stormwater runoff and improved water quality

8. Ancient Water Management Systems and Modern Green Infrastructure: Building Resilience in the Anthropocene

Climate change has significantly impacted the applicability and effectiveness of ancient water management methods, while simultaneously presenting new opportunities for adaptation. Ancient techniques—such as Roman aqueducts, Mayan rainwater harvesting systems, and Mesopotamian irrigation—were highly effective at addressing the water needs of their time. However, modern climate conditions, characterized by increased variability in precipitation, more frequent droughts, and intense storms, introduce challenges that these systems were not designed to handle [84]. Ancient water management systems relied on predictable seasonal rains or consistent river flows, but the erratic weather conditions caused by climate change—such as prolonged droughts or sudden, intense rainfall—have been straining these historical systems [85].

Despite these challenges, modern technologies offer ways to enhance the resilience of ancient techniques. For example, Mayan rainwater harvesting systems and Roman aqueducts, which were designed for more stable climates, can be adapted with water level sensors and sophisticated storage solutions that address the extremes of contemporary weather patterns [86]. In addition, drought resilience can be improved by decentralizing water storage, as demonstrated by Los Angeles' groundwater recharge projects, which mimic ancient decentralized systems by spreading out water management and reducing the risk of total system failure [87]. Singapore's success in adapting water recycling technologies—such as its NEWater program—illustrates how ancient storage methods can be adapted to modern contexts, ensuring water security during extended droughts and shortages [67].

Similarly, flooding and sea-level rise present substantial challenges, particularly in coastal regions, where ancient water management systems such as canals and cisterns face the threat of inundation. Ancient flood management systems, such as those in the Indus Valley or ancient Mesopotamia, were designed primarily for riverine flooding. However, they are not as effective in handling the unprecedented sea-level rise and storm surges caused by climate change [88]. Modern flood management strategies, such as the Netherlands' Room for the River initiative, were inspired by ancient methods but were adapted to manage higher sea levels and more extreme flooding [89]. Furthermore, the revival of ancient techniques such as the Aztec chinampa system in Mexico City showcases how traditional methods of wetland restoration can improve flood protection and water storage in urban areas [17].

A related climate challenge is the increase in temperatures and evaporation rates, which affect the functionality of open-air canals and reservoirs commonly used in ancient systems. In arid regions such as Mesopotamia and parts of the Roman Empire, large open water storage systems were once feasible, but higher evaporation rates under modern temperatures render these systems less viable [90]. Cities today are responding by adapting these systems with closed or covered water reservoirs and using underground pipelines that reduce evaporation while conserving water. These adaptations can be further enhanced with renewable energy technologies that improve sustainability [91]. By incorporating evaporation control technologies and automated systems to regulate water release based on weather patterns, ancient water management systems can continue to be effective even in hotter climate [92,93].

Another pressing issue for modern cities is the challenge of increased water demand due to population growth. Ancient water systems were typically designed for much smaller populations, and, while they were innovative for their time, such as the Roman aqueducts, they are not sufficient for today's megacities [16]. Nonetheless, ancient methods offer scalable solutions when integrated with modern technologies. For example, cities such as Singapore have expanded on ancient rainwater harvesting techniques, incorporating smart water management tools to efficiently manage water resources in densely populated areas [94]. By combining ancient techniques with modern water efficiency technologies such as precision irrigation and water monitoring sensors, cities can scale these systems to meet the growing demands of urban populations [16].

Resilience to extreme weather events is another area where ancient water management systems can provide valuable lessons. Floods, droughts, and heatwaves are becoming more frequent and severe due to climate change, and ancient systems—when adapted to modern conditions—can help cities create more resilient water management infrastructures [95]. Enhancing water storage capacities, decentralizing water systems, and integrating modern technology with ancient practices offer pathways to sustainable water management in the Anthropocene [9].

The exploration of both ancient water management systems and modern green infrastructure initiatives highlights how cities can build resilience in the face of climate change. Ancient civilizations such as the Romans, Maya, Mesopotamians, and ancient Chinese developed highly effective water management systems that ensured urban resilience by aligning with natural hydrological cycles. These systems maximized water efficiency, allowing large urban populations to access water resources without depleting their environments. Roman aqueducts, for example, transported water over long distances while incorporating decentralized storage and redistribution, demonstrating the foresight of managing water resources in a way that accommodated urban growth [16].

At the moment, these historical lessons are more relevant than ever as cities face growing vulnerability to climate change. Practices such as decentralized water collection and natural flood control—which were intrinsic to ancient systems—are being adapted to meet modern challenges. The resilience embedded in these ancient methods, which align with natural hydrological cycles, is central to modern nature-based solutions [96]. For example, modern green infrastructure solutions such as rain gardens, bioswales, green roofs, and permeable pavements have been successfully implemented in cities such as Copenhagen, Singapore, Mexico City, Los Angeles, and Philadelphia. These systems mimic the ecological functions of ancient water management practices, helping to manage stormwater, reduce urban flooding, and improve water quality (Table 1) [17].

In addition to water management, these green infrastructure solutions enhance urban livability by mitigating the urban heat island effect, improving biodiversity, and providing recreational spaces. The multifunctionality of green spaces creates sustainable urban ecosystems that benefit both human populations and the natural environment [97]. This dual functionality is essential for urban resilience, as these spaces reduce the physical impacts of climate change, such as flooding and heat, while simultaneously improving the wellbeing of residents.

Moreover, green infrastructure offers cost-effective and scalable solutions. Studies show that the long-term benefits of bioswales, rain gardens, and permeable pavements—such as flood reduction and pollution control—outweigh their initial investment costs [12]. By integrating these systems into the broader urban landscape, cities can reduce their dependence on centralized water infrastructure, minimize their vulnerability to extreme weather, and promote water conservation [41]. The use of decentralized water systems—such as neighborhood-level rainwater harvesting or localized water recycling plants—ensures the availability of water even during infrastructure disruptions caused by climate-induced challenges. Singapore's NEWater program exemplifies how decentralized systems can address both water scarcity and environmental concerns by efficiently reusing water, offering a model for modern cities [94].

In conclusion, while climate change presents significant challenges to ancient water management techniques, it also provides opportunities for innovation and adaptation. By integrating these time-tested methods with modern technologies and urban planning strategies, cities can harness the potential of these ancient practices to build more resilient, sustainable, and climate-adaptive water management systems that address the realities of the Anthropocene. The lessons learned from both ancient and modern approaches can help shape the future of urban water management, ensuring that cities are equipped to meet the demands of a changing world.

Figure 1 illustrates the locations of ancient civilizations and modern cities that integrate ancient water management practices.

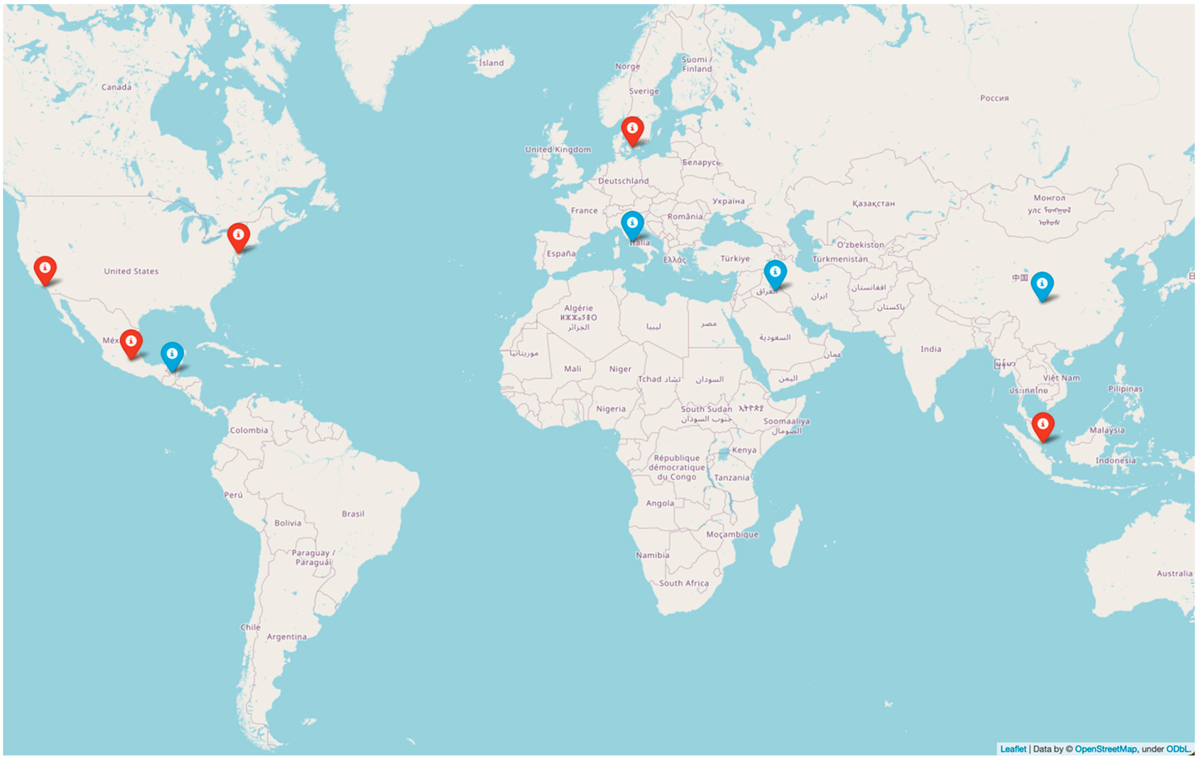

Figure 1. Locations of both ancient civilizations (blue marker) and modern cities (red marker) interconnected by water management practices.

9. Cultural and Social Dimensions of Ancient Water Management: Lessons for Modern Sustainability and Governance

While the technical aspects of water management, such as engineering and hydrology, are critical to understanding how ancient systems operated, the role of cultural and social factors is equally significant. Water management in ancient civilizations was far more than a practical necessity—it was deeply embedded in the religious rituals, social hierarchies, and political power structures of those societies. This integration of cultural and social dynamics shaped the design, implementation, and long-term maintenance of water systems across various ancient civilizations, offering valuable insights for modern water management strategies.

In Mesopotamia, water played a pivotal role not only as a resource but also as a powerful symbol of religious and political life. The Tigris and Euphrates rivers were seen as divine gifts, and the success of agriculture was tied to the favor of the gods. Temples, which were the centers of both religious and political authority, directly controlled the management of the vast irrigation systems. The construction of canals and levees was often organized by the temple complexes, and rituals were performed to ensure favorable water flows. Kings, such as Hammurabi of Babylon, codified laws regulating water use, further demonstrating the centrality of water in both governance and social order [98]. This intertwining of water management with religious and political life illustrates how control over water resources was synonymous with power in Mesopotamian society. The management of water was not merely a functional task but a demonstration of divine and royal authority, reinforcing the political structure of the city-states.

In ancient Rome, aqueducts served as symbols of both engineering prowess and political power. The construction of public water systems was a means for Roman emperors and officials to display their wealth and authority, while also providing essential services to citizens. The Roman aqueducts, baths, gardens, and fountains were designed to reinforce the ideals of Roman civilization—public health, civic responsibility, and social order [16]. Access to water in Roman society was not only a necessity but also a reflection of the state's ability to provide for its people, demonstrating the strength and organization of the empire. The public baths, for example, were spaces where people of all social classes gathered, thereby promoting social cohesion and the health of the empire. This Roman approach shows that water infrastructure was not only about providing resources but also about promoting social harmony and the legitimacy of the state.

Similarly, in the Maya civilization, water was intimately tied to religious practices. The Maya believed that water, particularly rain, was controlled by gods such as Chaac, the rain god. Rituals and offerings were performed to ensure adequate rainfall—especially during the dry season when stored water from reservoirs and cisterns was essential for survival [64]. The cenotes, natural sinkholes found throughout the Maya region, were considered to be sacred gateways to the underworld and played a dual role as both water sources and spiritual sites. The construction of water management systems, such as reservoirs and canals, was often overseen by the priestly class, who acted as intermediaries between the people and the gods. This integration of water management with spiritual beliefs reinforced the social cohesion of Maya communities and ensured that the maintenance of these systems was seen not just as a technical task, but as a moral and religious obligation. The connection between water and religion in Maya culture illustrates how closely water management is tied to cultural identity.

In ancient China, water management was considered a moral duty of the emperor, whose ability to control water, particularly in flood-prone regions such as the Yellow River Basin, was tied to the "Mandate of Heaven" [21]. The emperor's legitimacy was believed to depend on his ability to manage natural resources effectively, ensuring prosperity and social harmony. Large-scale projects such as the Dujiangyan irrigation system were seen as demonstrations of the emperor's divine right to rule. The failure to control water resources, such as during catastrophic floods, was often interpreted as a sign that the emperor had lost the Mandate of Heaven, leading to social unrest and rebellion. This connection between water management and political legitimacy underscores the importance of governance and public accountability in water infrastructure projects—a lesson that remains relevant today as modern governments grapple with providing reliable water services in the face of environmental challenges.

In the Incan Empire, water was managed communally, with distribution carefully regulated by local leaders based on social hierarchies and agricultural needs [99]. The terracing and irrigation systems in the Andean highlands were designed to ensure equitable water distribution among the agricultural communities, and local leaders allocated resources according to the agricultural calendar. Water was also viewed as a sacred resource, with many rivers and springs believed to be inhabited by spiritual beings, known as "apu". These beliefs influenced water usage, ensuring that it was respected and managed sustainably within the community. The communal approach to water management helped to maintain social cohesion and ensured the long-term sustainability of water resources in the challenging Andean environment.

These examples from ancient civilizations demonstrate that water management was never solely a technical issue—it was deeply intertwined with the cultural, social, and political fabric of society. Water systems were often symbols of power, tools of governance, and reflections of the values and beliefs of the communities that they served. The lessons from these ancient societies remain relevant today. In modern cities, water management is not only a matter of providing adequate resources but also involves addressing issues of social equity, governance, and environmental justice. Engaging local communities in water management decisions, especially those with cultural or spiritual connections to water, can lead to more sustainable and resilient water systems. Additionally, the symbolic power of water infrastructure can be harnessed to promote social cohesion, as seen in modern eco-friendly infrastructure projects that prioritize access to clean water and green spaces as a reflection of civic responsibility and sustainability.

The success of these ancient systems illustrates that water management is not simply a technical challenge but a cultural and social one as well. Water systems that ignore the cultural significance of water or fail to engage with the social dynamics of the communities they serve are likely to be unsustainable in the long run. For example, modern attempts to build large, centralized water management systems in developing regions have often failed due to a lack of consideration for the local customs and governance structures that have traditionally managed water resources [41]. By understanding the cultural and social dimensions of water management in ancient societies, modern planners can better appreciate the need for solutions that engage communities, respect cultural practices, and promote social equity in water access.

In today's context, social equity in water management is becoming increasingly critical, especially as climate change exacerbates water scarcity and increases the frequency of extreme weather events. As water becomes more scarce, marginalized communities are often the first to suffer from inadequate water access, highlighting the importance of environmental justice in modern water management [13]. Lessons from ancient water systems show that water management strategies must be inclusive, considering the cultural and social context of the communities that they serve. For instance, engaging indigenous communities in water management decisions—especially those with deep cultural ties to water—can improve the sustainability and acceptance of water projects, as seen in various regions where indigenous knowledge has informed environmental stewardship [29].

Cultural appropriateness and social equity are therefore essential for sustainable water management. Ancient civilizations, through their deeply rooted connections between water, culture, and society, demonstrate that water management systems must serve more than just the physical need for water—they must also address the social and cultural needs of communities. Modern urban planners can draw from these ancient lessons to design systems that are both technically sound and culturally resonant, ensuring that water management not only provides resources but also unifies communities and promotes social wellbeing. Figure 2 provides a visual summary of the evolution of water management practices, showing how early water systems, initially developed for stability and community needs, have transformed to address contemporary challenges like urban resilience and climate adaptation.

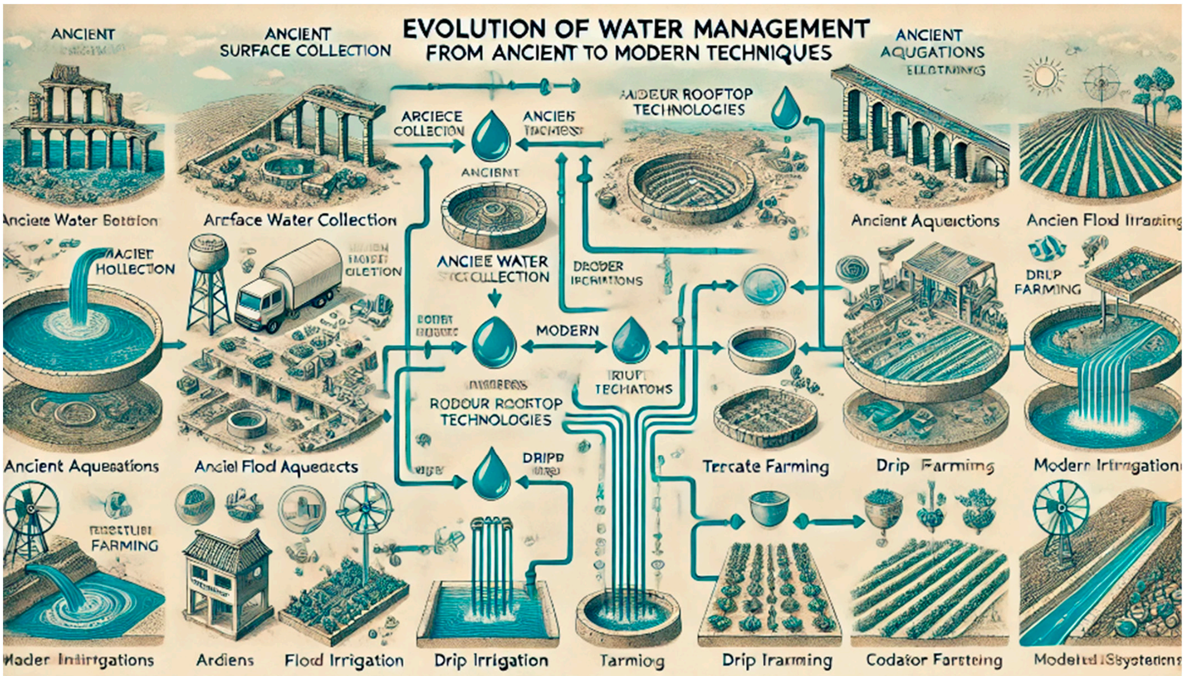

Figure 2. Evolution of water management from ancient to modern techniques.

10. Adapting Ancient Water Management Systems for the Anthropocene: Insights, Challenges, and Modern Applications

Ancient water management systems were often highly effective in meeting the needs of their time, but many ultimately failed due to environmental degradation, over-irrigation, and climate variability. These failures offer crucial lessons for modern water management, particularly as the world grapples with the unprecedented challenges of the Anthropocene—marked by extreme weather, rising temperatures, and rapid urbanization [9]. For example, the collapse of the Maya civilization is partially attributed to the overexploitation of water resources and an inability to adapt to prolonged droughts [19]. Similarly, Mesopotamian irrigation systems sustained agricultural productivity for centuries, but, over time, they contributed to soil salinization, reducing crop yields and leading to a decline in agricultural output [55]. These historical failures underscore the limitations of ancient systems that failed to balance human needs with environmental sustainability. However, by critically analyzing these failures, valuable insights can be derived for implementing resilient water management strategies in modern contexts. Ancient systems, such as the Roman aqueducts and Mayan rainwater harvesting, offer time-tested solutions that can be adapted to modern conditions. For instance, decentralized systems—by reducing reliance on centralized infrastructure—are inherently flexible and scalable, enhancing urban resilience to climate-related disruptions. A contemporary example is the restoration of the chinampa system in Mexico City, where ancient practices support sustainable urban agriculture, improving water retention and mitigating water scarcity [17]. However, the adaptation of ancient techniques to modern contexts requires careful consideration of climate resilience and technological augmentation. Modern cities face new challenges, such as unpredictable climate patterns, megadroughts, and extreme flooding, which were less common in ancient times [1]. While this study provides insights into the adaptation of ancient water management systems in modern urban settings, several limitations must be acknowledged, particularly concerning the geographical scope of this study, data availability, and the broader applicability of the findings, as shown below.

10.1. Geographical Scope

This study focuses on a selected number of cities—Singapore, Copenhagen, Mexico City, Los Angeles, and Philadelphia—that have integrated green infrastructure into their water management inspired by ancient techniques. As these cities represent a diverse range of climate, urban challenges, and water management strategies, the geographical scope of this study is inherently limited. The analysis may not fully capture the unique water challenges or solutions in other regions, particularly areas facing extreme water stress, such as sub-Saharan Africa and the Middle East, where water scarcity, desertification, and glacier melt present urgent challenges [11,20]. Future research should expand the geographical focus to include more regions and cities in order to offer a broader, more comprehensive global perspective on water management.

10.2. Data Availability and Quality

The availability and quality of historical data on ancient water management systems are often incomplete, as much of the evidence relies on archeological reconstructions, historical texts, or theoretical models [7]. This incomplete nature of historical data creates challenges in directly comparing the efficiency, scalability, and sustainability of ancient systems with those of modern practices. The lack of uniform and reliable empirical data from ancient systems makes it difficult to draw precise conclusions about their long-term impacts on water security and sustainability. In contrast, modern cities often benefit from advanced monitoring technologies, such as sensors and satellite imagery, which provide real-time data on water usage and climate impacts, further complicating comparisons between ancient and modern systems [100].

10.3. Technological and Environmental Differences

The technological context in which ancient systems were developed differs significantly from the advanced engineering and technological solutions available today. While ancient systems, such as Roman aqueducts or Mayan rainwater harvesting, were highly effective in their time, they operated without the technological support of modern tools, such as predictive climate modeling or real-time water monitoring [88]. Today, modern applications of these ancient systems often require significant technological augmentations, including sensor networks, automated water regulation, and advanced filtration technologies. These augmentations deviate considerably from the original principles and techniques, raising the question of whether they can still be considered "ancient" systems or whether they represent entirely new approaches inspired by historical precedents [26]. Moreover, environmental conditions have changed dramatically since ancient times due to urbanization, industrialization, and climate change, complicating the direct application of ancient methods in modern settings [9].

10.4. Cultural and Political Factors

Water management systems in ancient civilizations were often deeply embedded in cultural, religious, and political practices. In societies such as the Mayan and Mesopotamian, water management was guided by religious rituals and social hierarchies, influencing how these systems were designed and maintained [64]. In contrast, modern cities may lack the same cultural or religious values that historically guided this water management practices, potentially hindering the success of decentralized or community-driven systems inspired by ancient models [93]. Political resistance to decentralization in many modern cities, where centralized governance structures dominate, further complicates the adoption of these systems, despite their proven efficacy in historical contexts [13].

10.5. Scalability of Ancient Techniques

Ancient water management systems were often designed for smaller, less densely populated communities. For instance, Roman aqueducts and Mayan cisterns served cities much smaller than today's megacities. Consequently, the scalability of ancient techniques in modern urban environments presents significant challenges. While decentralized systems, such as those inspired by Roman aqueducts or Mayan cisterns, may work well in localized areas, their ability to meet the demands of modern cities with millions of inhabitants is uncertain [101]. Additionally, ancient systems were often tailored to specific geographical and environmental conditions, which may not be easily transferable to different climate or urban structures.

10.6. Incomplete Historical Knowledge

Many ancient water management systems have been lost over time, and what remains are often fragmented or incomplete records. This incomplete historical knowledge limits our ability to fully understand the operational efficiency, maintenance needs, and long-term sustainability of these systems. The decline of civilizations such as the Maya or the Mesopotamians due to environmental degradation, such as deforestation and soil salinization, underscores the potential risks associated with over-reliance on ancient systems [19,55]. This incomplete historical knowledge presents significant limitations in applying ancient models to modern contexts without fully understanding their historical weaknesses.

10.7. Climate Change Uncertainty

While this study draws connections between ancient water systems and modern climate challenges, it is important to recognize that the scale and pace of contemporary climate change are unprecedented. Although ancient civilizations dealt with seasonal variability or regional climate shifts, they did not face the global environmental changes that modern cities must confront, such as rising sea levels, increasing temperatures, and more frequent extreme weather events [1]. Thus, while ancient techniques offer valuable insights, their capacity to address the scale of contemporary climate risks remains uncertain. Modern cities will likely need to combine ancient practices with advanced technologies and policy innovations to meet the demands of a rapidly changing climate [102].

In conclusion, while ancient water management systems offer valuable lessons for addressing contemporary urban water challenges, several limitations must be considered when adapting these methods to modern contexts. These constraints include an incomplete historical record, differences in environmental and technological conditions, and the unique cultural and political landscapes of modern cities. Nevertheless, the adaptation of ancient methods—enhanced by modern technologies—provides promising pathways for creating sustainable and resilient water management systems that can help cities cope with the challenges of the Anthropocene. Future research should focus on expanding the geographical scope of studies, improving the data collection from historical systems, and examining the long-term effectiveness of modern adaptations.

11. A Holistic Approach to Urban Water Resilience

The challenges of the Anthropocene—particularly those related to water security, ecosystem services, and urban green spaces—cannot be addressed in isolation. The interconnected nature of these issues demands holistic, integrative approaches that involve multiple stakeholders and disciplines. Cities must adopt nature-based solutions and innovative water management practices to enhance urban resilience.

In the Anthropocene, human activities are having unprecedented impacts on ecosystems, making it crucial to integrate water security with ecosystem services and urban green spaces. Water security is not only about ensuring access to clean water but also about protecting the ecosystems that provide, regulate, and purify water. Ecosystem services—such as water filtration, flood regulation, and habitat provision—are closely linked to the health of both urban and rural water systems. The degradation of these ecosystems directly undermines efforts to secure reliable water supplies, particularly in urban areas where green spaces can enhance water management [103].

Nature-based solutions (NBSs) are among the most promising integrative approaches to environmental management in the Anthropocene [104]. These solutions use natural processes to address societal challenges, providing both environmental and social benefits. For instance, reforestation, wetland restoration, and floodplain reconnection can regulate water flows, improve water quality, and mitigate the impacts of climate change [105]. In Melbourne, Australia, the "10,000 Raingardens Program" has been a successful initiative, encouraging the community to install rain gardens in urban areas to address stormwater management and water scarcity [106,107]. Another notable example is the "Room for the River" program in the Netherlands, where natural river dynamics have been restored to address flood risks while enhancing biodiversity and recreational spaces [108]. These programs demonstrate how nature-based solutions can offer resilience against extreme weather events, provide ecological services, and enrich urban living.

Environmental education is a key tool for promoting sustainable water practices and fostering a deeper understanding of the interconnectedness between water, ecosystems, and human activities. Educational initiatives that emphasize water conservation, ecosystem services, and sustainable urban planning empower individuals and communities to take proactive steps toward protecting water resources. Programs that incorporate experiential learning—such as community-based rainwater harvesting projects or wetland restoration—can enhance public awareness and encourage long-term sustainable behavior [109].

In Cape Town, South Africa, the Day Zero initiative provided a strong example of public education on water conservation. With the city was facing severe drought, widespread education campaigns about water-saving techniques—such as rainwater harvesting and reducing daily consumption—helped the city avert a major crisis. Such campaigns illustrate how educational outreach can drive behavioral change and support urban resilience [110].

Literature has historically shaped public perceptions of nature and can inspire action on environmental issues [111]. In the Anthropocene, literary works that address water crises—such as droughts, floods, and pollution—are powerful tools for raising awareness about the global water crisis. Authors such as Margaret Atwood (*The Year of the Flood*) [112], Barbara Kingsolver (*Flight Behavior*) [113], and Kim Stanley Robinson (*New York 2140*) [114] depict worlds where water scarcity and climate change reshape societies, offering readers both warnings and calls to action. These narratives help humanize the often-abstract data on environmental degradation, making them more relatable and urgent [115]. The impact of literature is evident in the case of Rachel Carson's *Silent Spring* (1962) [116], which catalyzed the environmental movement by exposing the dangers of chemical pollution in water systems. Carson's work contributed to the establishment of the U.S. Environmental Protection Agency (EPA), underscoring how literature can influence policy and environmental consciousness.

By combining ancient water management practices with modern green infrastructure solutions, cities can build resilient and sustainable water systems that address the demands of a changing climate [117]. The lessons learned from historical techniques offer valuable insights into decentralization, water efficiency, and working with natural systems. These strategies, when integrated into urban planning, supported by strong policy frameworks, and driven by community participation, will ensure that future cities are not only livable but also sustainable in the Anthropocene. Policymakers should incentivize the adoption of nature-based solutions through subsidies, regulations, and public–private partnerships.

12. Recommendations for Urban Water Resilience

Future urban planning must prioritize the integration of ancient water management practices with modern green infrastructure. Actionable recommendations, listed below, outline specific steps that urban planners can take to achieve this objective.

This study has tried to show that ancient water management systems offer valuable insights for addressing modern urban water challenges, particularly in the context of climate change and rapid urbanization. By examining the adaptation of historical techniques—such as rainwater harvesting, aqueducts, and flood control systems—modern cities can implement nature-based solutions to enhance their resilience. However, to fully realize the potential of these ancient systems in contemporary contexts, urban planners and policymakers must adopt a strategic and integrated approach. Below are key practical recommendations based on the findings of this research.

1. Integrate Decentralized Water Systems
    - Recommendation: Urban planners should prioritize the decentralization of water management infrastructure, drawing from ancient techniques such as Roman cisterns and Mayan rainwater harvesting systems. These decentralized systems reduce dependence on centralized water supply networks and increase resilience to droughts and water shortages. For instance, cities can implement community-level rainwater harvesting systems, green roofs, and localized stormwater capture methods to manage water resources more effectively.
    - Actionable Insight: Policymakers should incentivize the adoption of decentralized water systems through subsidies, regulatory frameworks, and community engagement programs. This action could include offering financial incentives for homeowners and businesses to install rainwater harvesting systems and green infrastructure that helps reduce urban runoff.
2. Promote Nature-Based Solutions (NBSs)
    - Recommendation: Cities should incorporate nature-based solutions into their water management strategies, taking inspiration from historical systems such as the Dujiangyan flood control project in ancient China or the chinampas of the Aztecs. NBSs such as wetland restoration, green corridors, and permeable surfaces provide dual benefits by enhancing water management and improving biodiversity and air quality in urban areas.

- Actionable Insight: Policymakers should update urban planning regulations to prioritize green infrastructure in new developments and retrofit existing neighborhoods with nature-based water solutions. Public–private partnerships can be leveraged to finance large-scale NBS projects, such as urban wetlands and floodplain reconnection programs, to reduce the impact of urban flooding and improve water quality.

3. Focus on Resilience to Climate Change
    - Recommendation: As climate change increases the frequency and severity of extreme weather events, cities must design water systems that are adaptable and resilient. Drawing lessons from the Romans' long-distance aqueducts and the Inca's terracing systems, urban planners should create multi-source water networks that incorporate both local and external water sources. These systems should be designed to function even during extreme droughts or floods.
    - Actionable Insight: City governments should integrate climate resilience into water management policies by mandating climate impact assessments for all new water infrastructure projects. This action could include designing water systems that can handle higher rainfall variability, rising sea levels, and heatwaves. Urban planners can collaborate with climate scientists to ensure that water systems are future-proof and capable of withstanding climate shocks.
4. Encourage Community Involvement and Cultural Sensitivity
    - Recommendation: Community involvement is crucial for the long-term sustainability of water management systems, particularly in decentralized models. Ancient water systems, such as the communal management of irrigation canals in Incan and Mesopotamian societies, highlight the importance of involving local communities in decision-making processes. Planners and policymakers should engage citizens in water conservation efforts and infrastructure projects to ensure public involvement and effective management.
    - Actionable Insight: Policymakers should establish community-driven water management programs, where local residents participate in the design, maintenance, and operation of water infrastructure. Educational initiatives could be launched to raise awareness of sustainable water practices, with a particular focus on water conservation, the use of recycled water, and green infrastructure. Additionally, respect for local, cultural, and spiritual values surrounding water should be incorporated into water management strategies in order to ensure that systems are culturally appropriate and socially sustainable.
5. Leverage Technology for Efficiency and Monitoring
    - Recommendation: While ancient techniques provide valuable foundational knowledge, modern technologies must be integrated to optimize these systems for today's urban environments. Technologies such as smart sensors, automated water management systems, and predictive modeling can enhance the efficiency of ancient techniques such as rainwater harvesting and aqueducts. These technologies enable the real-time monitoring of water usage and climate conditions, allowing for more precise management.
    - Actionable Insight: Urban planners should collaborate with technology providers to implement digital tools that can monitor water flows, detect leaks, and predict future water demand. Policymakers can support the deployment of smart water management systems by providing funding for pilot projects and encouraging innovation through research grants focused on water-efficient technologies.
6. Build Policy Frameworks for Sustainable Water Management
    - Recommendation: Sustainable water management requires strong policy frameworks that promote long-term resilience and resource efficiency. Drawing from historical lessons, such as the regulatory systems implemented by Mesopotamian

kings or the water laws of ancient Rome, modern cities need policies that prioritize water conservation, equitable distribution, and ecosystem protection.

- Actionable Insight: Policymakers should create comprehensive water management plans that align with national sustainability goals and international climate agreements. These plans should include clear targets for water-use reduction, the investment in green infrastructure, and the protection of natural water sources. Cities should also adopt water pricing strategies that encourage conservation and equitable access, ensuring that all residents, regardless of income level, have access to clean and affordable water.

In conclusion, the adaptation of ancient water management techniques through modern green infrastructure offers promising solutions for cities facing the dual challenges of climate change and urbanization. By integrating decentralized water systems, promoting nature-based solutions, enhancing climate resilience, involving communities, leveraging technology, and building robust policy frameworks, urban planners and policymakers can create water systems that are both sustainable and adaptable. The lessons from ancient civilizations provide a valuable foundation, but they must be combined with modern innovations to meet the demands of today's cities and future-proof urban water infrastructure.

Urban planners and policymakers must take proactive steps to ensure that water management systems are not only efficient and sustainable but also resilient in the face of ongoing climate challenges. By learning from ancient practices and applying modern technological and social innovations, cities can build water infrastructure that serves both current and future generations [118].

13. Conclusions

In conclusion, this study demonstrates that ancient water management practices offer valuable insights for creating sustainable and resilient urban water systems. By integrating nature-based solutions and decentralized water systems, modern cities can address the challenges posed by urbanization and environmental pressures. Moving forward, adopting these strategies offers a pathway to balancing human needs with ecological sustainability, thereby ensuring a more resilient urban future.

The modern cities considered as case studies remind us that integrating historical lessons with modern innovations can provide crucial blueprints for water security. As we face increasingly unpredictable climate, the examples of these urban centers show how technological advancement, public engagement, and a deep respect for ecological limits are essential in addressing contemporary water challenges in the Anthropocene.

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