A Review and Holistic Examination of Sustainable Urban Water Management

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ABSTRACT

Sustainable urban water management consists of multiple interacting systems. This paper analyzes three such systems: leak detection, grey water recycling and rain water harvesting, beginning with a review of the literature and interest in these three topics. A proper sustainable system will use a combination of all three, and grey water recycling and rain water harvesting systems in particular have many synergies. The connections between water management and other related systems, namely energy, food, and economics, are then detailed, and the importance of such a holistic review is heavily emphasized.

Introduction

Sustainable development in housing management and new construction requires a holistic approach encompassing environmental, social, and economic dimensions to address pressing challenges such as climate change, affordability, and social equity. This is especially relevant considering that larger and larger portions of the world population live in urban areas (from 30% in the 1950s to a projected 68% in 2050), areas that account for more than two-thirds of the planet's greenhouse gas (GHG) emissions (Chen et al., 2024). While sustainable practices in the buildings sector typically consist of minimizing the use of non-renewable energy involved in constructing, heating, cooling, and lighting homes as well as powering their appliances, the development of sustainable water management is just as critical. This research focuses on sustainable water management within urban settings, looking at them in isolation and, more importantly, their interactions with other systems: water management as a part of the water-food-energy nexus. All these systems are interconnected, and many papers and real-world policies on these areas may miss this fact, focusing only on one system. For example, water is critical for irrigation, a system that has a major impact on agriculture, and a sudden power outage could cause water systems, such as wastewater treatment, to fail. That being said, water scarcity is a pressing global issue and in 2021 it was estimated that 2.3 billion people lived in water-stressed countries, 733 million of which were in critically water-stressed countries (*Water scarcity*). This is an issue made more unpredictable by climate change as terrestrial water storage (soil, snow, ice) decreases. In addition, some 42% of global household wastewater is not treated properly, which can be harmful to both ecosystems and human health, especially in poorer urban areas. Only around 11% of wastewater worldwide is being reused, a statistic that must increase in the future (*Water quality and wastewater*).

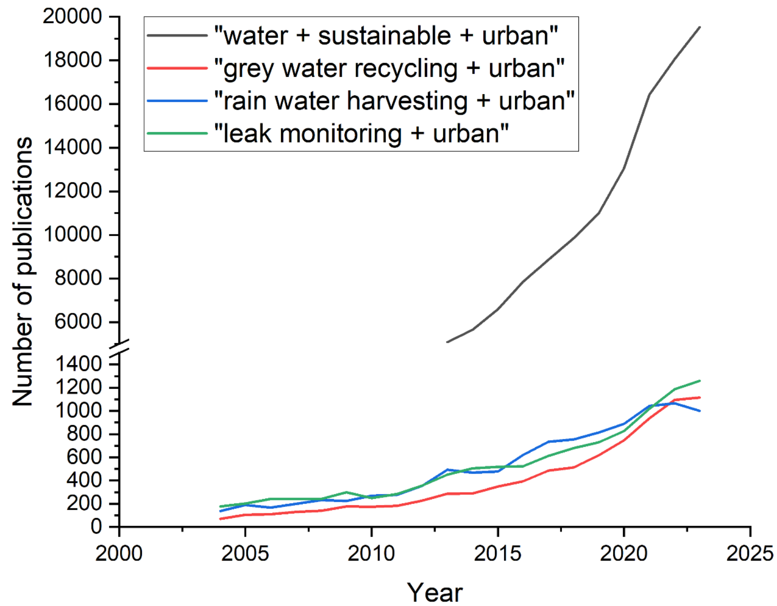

Figure 1. The number of publications for four different search queries, one broad and three about specific systems. All show an increase in publications and interest in recent years.

Just as interest in climate science and the climate crisis has been increasing in recent years, so has interest in sustainable water management. Searching in ScienceDirect, the keywords “water”, “sustainable” and “urban” show a marked increase in interest in this topic over the past two decades, evidenced by Figure 1. The search had a time parameter starting in 2004 and ending in 2023. During this 19-year period, there was a nearly 13-fold increase in publications using these keywords. Compared to the keywords “water” and “sustainable”, “urban” restricts the number of publications the most. This paper will focus on sustainable urban water management with respect to three specific systems: grey water recycling, rain water harvesting, and leak monitoring, and the different possible synergies between them.

Searching in ScienceDirect using combinations of “urban” and either “grey water recycling”, “rain water harvesting” or “leak monitoring” gives similar results. For “grey water recycling” and “urban”, there was a nearly 16-fold increase. Grey water is non-potable water that does not contain feces, and it makes up about 30-50% of all wastewater discharged into sewers. Recycled grey water could immensely help decrease water usage and utility bills, and it can be treated through methods like UV light. For “rain water harvesting” and “urban”, there was around a 7-fold increase. Rain water harvesting can be used to supplement other water sources such as surface water and groundwater. Rain water can be collected from rooftops and is typically used for irrigation, fountains, and toilets. If it is filtered properly, rain water can be used as potable water. For “leak monitoring” and “urban”, there was also around a 7-fold increase. Leak detection technology is vital in stopping this waste, and typically works using a turbine or ultrasonic waves. Some are able to block the flow of water to prevent leaks and water damage. In the US, 6 billion gallons of potable water are lost every day due to leaks, the equivalent of more than 9,000 swimming pools (*Drinking water*). While there is not an overwhelming number of articles in these research areas, interest has certainly been increasing in each just as it has in the broader area of sustainable urban water management as shown in Figure 1. Compared to the other two topics, “rain water harvesting” increases at a more erratic rate, stagnating between 2013 and 2015 and then decreasing from 2022 to 2023.

Leak Monitoring, Grey Water Recycling And Rain Water Harvesting Systems

Leaks can result in financial losses, cause public health risks and create environmental impacts. The utilization of sensors is among the most effective preventative measures to find abnormalities within pipe systems and monitor where potential leaks may occur. Various sensing technologies include listening rods, geophones, ground penetrating radars, hydrophones, and even resistive paper-based sensors (Goodman et al., 2021; Sitaropoulos et al., 2023). Leak detection is doubly important when it comes to the implementation of other systems, like grey water recycling and rain water harvesting, ensuring as little water as possible is wasted. As already established, water leakage from pipes is a serious issue. In the US and Canada, there was a 27% increase in the rate of water main breaks from 2012 to 2018, which excludes unreported leaks. Being about water mains, this statistic doesn't capture all the water that is lost through smaller, unreported leaks. Some 85% of water main pipes in the US and Canada are smaller than 300 mm (12 inches) in diameter, and leaks that occur in these smaller pipes happen through smaller cracks, joints and pipe fittings (Shabangu et al, 2020; Sitaropoulos et al., 2023). One study focuses on the advantages of hydrophones as leak detection, listing advantages such as lower sensitivity to ambient noise, an ability to detect at longer distances, and the ability to detect a wider range of leaks. Most leak detection systems used currently are localized and portable. That means they are only deployed to an area if a leak is suspected instead of continuously running, possibly letting smaller, unreported leaks go undetected. A continuous monitoring system would find leaks, especially smaller ones, earlier, minimizing the damage they could do and improving the speed and quality of repairs. The characteristics of a pipe system, including diameter, thickness, material, bend, branches, pressure, flow rate, and the soil around it all have an effect on the effectiveness of leak-detecting sensors. It has been postulated by many papers that machine-learning artificial intelligence can be used to help monitor for leaks, but there are many complications to that, and most approaches will require some sort of manual monitoring. It will be difficult to create a comprehensive training dataset, as data collection will be time-intensive, resource-intensive, and lab-based data does not represent reality effectively (Liu et al, 2024).

Many studies have been conducted in regard to the implementation of grey water and rain water systems. One of them looked at a hypothetical mixed-use building based on Library at The Dock in Melbourne, Australia (Naserisafavi et al., 2022). The systems studied were a rain water harvesting system, greywater treatment systems, and greywater subsurface irrigation, both in terms of their efficiency and their economic effect. The study found that, annually, rain water harvesting systems supplied 684 kL to the building, greywater subsurface irrigation supplied 1853 kL, and local grey water treatment systems supplied 2686 kL. In addition, grey water treatment systems decreased wastewater discharge by 42%, and rain water harvesting systems reduced stormwater runoff by 26.2%. A hybrid system using both rain water and grey water systems was the most efficient in regard to mains water consumption and stormwater reduction (Naserisafavi et al., 2022). Of course, this determination will be affected by the location and climate of a building where a water system will be installed. For example, a RWHS may not make as much sense in a region with very low precipitation. In addition, grey water recycling systems are typically more resilient to climate change than rain water systems, making a hybrid system even more appealing, incurring the benefits of both systems (Wanjiru & Xia, 2018). The paper detailed above also ultimately concluded that some sort of hybrid system was probably the best solution for larger spaces and buildings, both to meet sustainability targets and economically. However, it also concluded that various safety regulations about reclaimed water usage and close human contact could preclude conventional alternative water solutions from hitting water-saving targets (Naserisafavi et al., 2022).

Economic Impact of Water Management and Connections with Energy and Food Systems

It is crucial to examine all these systems in context, parsing through their effects and impacts on other systems holistically. When leaks happen more power is needed to maintain the desired service level, and it is estimated that some

10 billion kWh of power is used purely to maintain those levels (Shabangu et al., 2020). A decrease in leaks also means energy and cost savings, making water systems more sustainable not only environmentally, but also financially, as depicted in Figure 2. So too could a hybrid grey water and rain water system incur financial benefits through conserving water. It is important to note, however, that not all financial impacts may be positive. The financial savings from energy and water savings are also heavily dependent on location and climate. Economically, a hybrid system may have higher initial, operational and maintenance costs, and a longer analysis period increases these costs. In contrast, a longer analysis period generally decreases levelized costs (Naserisafavi et al., 2022). Grey water recycling systems and rain water harvesting systems also can have a very high payback period of more than 20 years (Wanjiru & Xia, 2018). As a result, their effectiveness should be determined on a case-by-case basis, studying all possible factors of a particular locale, including climate, location, local policy, and economic impact.

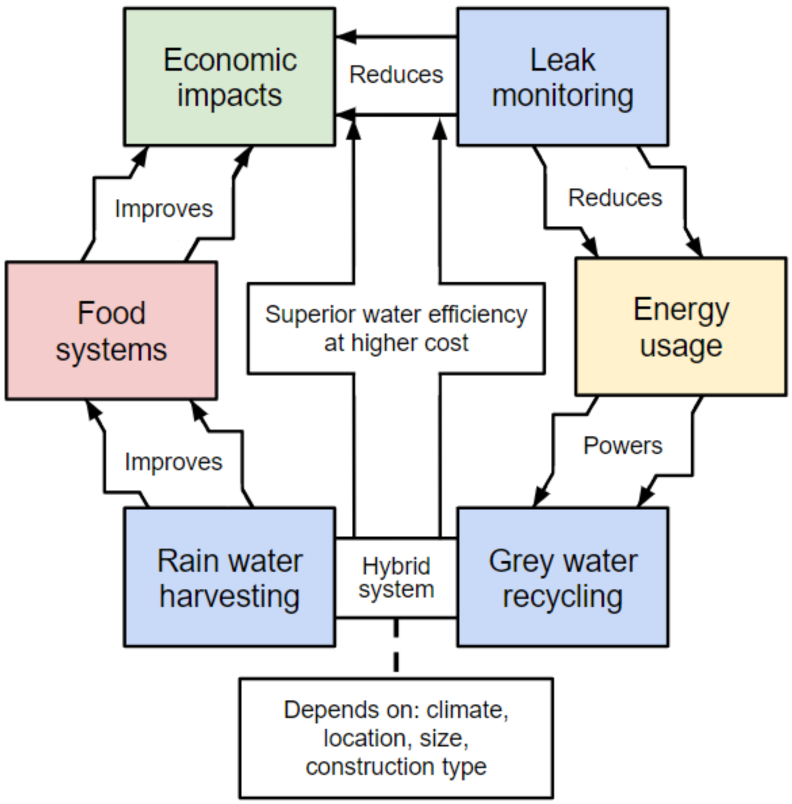

Figure 2. A visual representation of the various synergies and interactions in a sustainable system.

The effectiveness of water management systems also depends heavily on the type of building. For example, in dense urban settings, the installation of large water tanks and water systems may be infeasible. In less dense, suburban areas with single-family homes, water systems will be less efficient since they do not share walls with other homes, have utilities that take up more energy, and are typically less compact. Many other aspects can affect a building's footprint, such as the construction process, maintenance and operation, as well as the end-of-life of certain appliances and systems. In addition, the integration of water systems in new construction and existing buildings has differences. There is generally more flexibility when integrating systems into new buildings, and additional land-use and biodiversity loss analysis can happen (Arceo et al., 2024).

Incorporating green infrastructure into urban environments can also have positive synergistic impacts (Wanjiru & Xia, 2018). This can be done by planting water-efficient vegetation, which gives various benefits, producing fresh vegetables, fruits and meat products, fostering both social inclusion and entrepreneurship, and generally improving human health (Figure 2). There are also benefits to water management, air and water cleanliness, natural pest control, service provisioning, natural pollination, and extreme weather mitigation. Assessing the effectiveness of green infrastructure requires a holistic viewpoint as well, looking at ecological, human, and socio-economic parameters, as well as using spatial analysis. Remote sensing mapping tools can be useful to gather data to assess the impact of green infrastructure (Korkou et al., 2023). They may also be beneficial for gathering data for machine-learning models.

Conclusion

An all-encompassing sustainable system for the future will involve the interactions of multiple systems, among them water, energy and food. This requires a holistic assessment of their impacts, both negative and positive. Continuous leak detection systems will be crucial to stem the vast quantities of water lost to small, unreported leaks. This lays the groundwork for more sustainable water management, namely one that combines rain water and grey water systems to accrue the advantages of both and increase the resilience and effectiveness of the resulting system. However, the final determination of what sort of system to use must be decided on a case-by-case basis, factoring in a building's climate, location, size and construction type among other concerns. This paper also reviewed some other impacts of these systems, specifically financial and economic impacts, as well as the benefits of incorporating green infrastructure into urban environments.

There are many uncertainties when it comes to the future of housing that may affect the future of sustainable water management. Population, household sizes and work patterns, demographics, economic circumstances and societal norms are subject to change and demand robust planning. Future government policy will also have an outsized effect on the types of buildings and systems that may exist in the future (Arceo et al., 2024). Inequity still exists, despite recent legislation to change that fact. As an example, in the US, the American Rescue Plan Act of 2021 and the Infrastructure Investment and Jobs Acts (Bipartisan Infrastructure Law) were passed, and include provisions to help expand wastewater treatment to more communities. There is evidence that despite the conventional wisdom that high-income countries such as the US have near-universal basic sanitation, there are still gaps in access. Specifically, these gaps may include limited access to sewers and onsite treatment systems, regions where systems may be less effective due to environmental factors (impermeable clay, seasonally high water table), and limited access to water systems due to high cost. While the above legislation unlocked federal funding to help fix these issues, access to that funding is not necessarily fair to all communities. As well as general flaws in existing funding mechanisms, people may have limited knowledge of what systems are best for their communities, and federal funding is typically biased towards larger municipalities and projects, as well as more conventional technologies, limiting its impact on underserved communities (Elliott et al., 2023). A sustainable future must be an equitable future as well, and more must be done to expand services.

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