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*Perspective*

# Urban Water Supply: From Safe and Reliable to Green and Healthy

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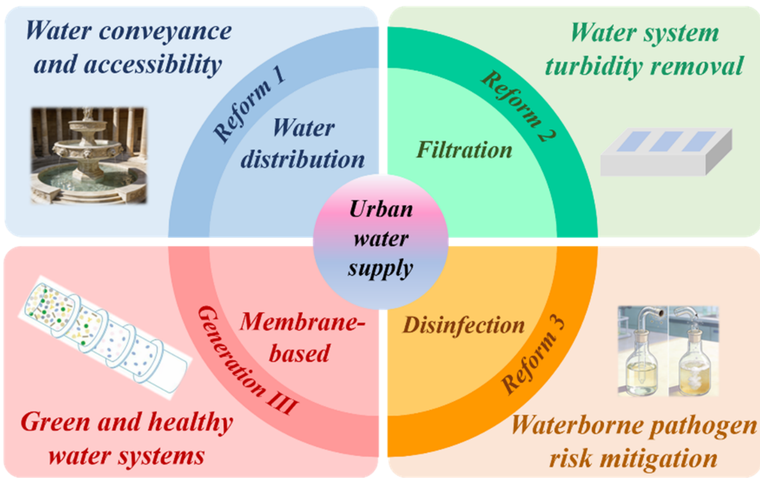
**Highlights**

- Urban water supply is shifting from a safety-oriented framework toward a green and health-oriented paradigm.
- Nature-based processes and membrane technologies play key roles in enabling this transition.
- Integrated and adaptive system design is essential for future resilient urban water management.

**Abstract:** Urban water supply systems have traditionally focused on ensuring safe and reliable water delivery to support public health and urban development. This paradigm, built on centralized treatment and disinfection, has effectively controlled microbial risks but is increasingly challenged by concerns over chemical exposure, ecological impacts, and long-term sustainability. Consequently, urban water supply is undergoing a transition from a safety-oriented framework toward a green and healthy paradigm that emphasizes reduced chemical dependence, preservation of natural water characteristics, and enhanced system resilience. This transformation calls for rethinking both technological pathways and system integration. Nature-based processes and membrane-based separations are emerging as key approaches to support this shift. Overall, the evolution toward green and healthy water supply reflects an advancing move toward adaptive, integrated, and sustainability-oriented urban water management.




## 1. The Connotation of Urban Water Supply

Clean water is a fundamental natural resource underpinning urban population growth, industrial operation, and public health, and it also constitutes a critical component of urban safety and resilience. According to the *United Nations World Water Development Report 2024* [1], global water consumption has increased sixfold over the past century due to population growth, economic development, and changes in consumption patterns, and is expected to continue rising. In contrast, China possesses only about 4% of the world's freshwater resources, with per capita availability approximately one quarter of the global average, and is therefore confronted with the dual pressures of water scarcity and water quality deterioration under rapid urbanization [2,3]. In this context, urban water supply is no longer merely an engineering task of delivering water to end users, but a systemic issue closely linked to resource security, public health, ecological sustainability, and high-quality development.

As Figure 1 illustrates, an urban water supply system primarily delivers surface and groundwater to consumers through integrated intake, conveyance, treatment, and distribution. In practice, raw water is transported to treatment facilities, purified through a series of treatment units, and subsequently delivered through distribution networks, with secondary supply systems employed when necessary to ensure adequate pressure and storage at the terminal level [4]. This process requires the system to simultaneously fulfill dual functions of conveyance and purification, ensuring both supply continuity and water quality safety through multiple protective barriers.

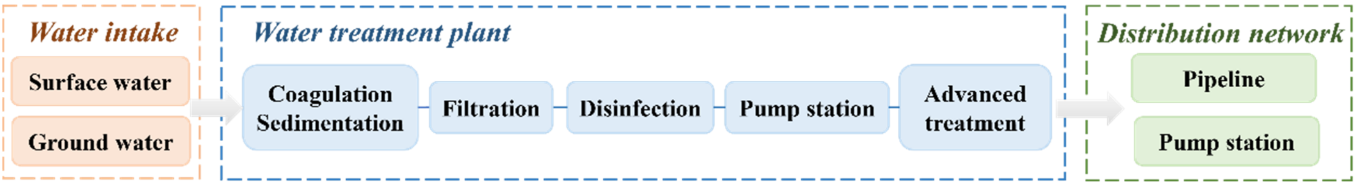



**Figure 1.** Formation of urban water supply system.

Urban water supply systems did not emerge in their current form at once but evolved through a series of paradigm shifts. Early development focused primarily on accessibility and conveyance, while subsequent public health crises drove the incorporation of filtration and disinfection as central components of centralized water treatment, thereby establishing the modern framework of urban water supply [5,6]. This historical trajectory also corresponds to the evolution of drinking water treatment technologies across successive generations. Alongside technological advancement, a growing understanding of natural systems has reshaped the conceptual foundations of urban water supply, shifting the emphasis from mere safety and reliability toward green and health-oriented objectives. This transition highlights the preservation of water's natural attributes and the mitigation of potential health risks, such as disinfection by-products, while stimulating continuous innovation across water abstraction, treatment, distribution, and system operation.

Overall, urban water supply has entered a new stage characterized by system-level integration, transformation-oriented development, and coordinated advancement across multiple scales. This manuscript therefore discusses the paradigm evolution of urban water supply systems, emerging requirements driven by green and health-oriented objectives, and the feasible pathways to achieve these goals.

## 2. Paradigm Shifts in Urban Water Supply Systems

The technological evolution of urban water supply systems can be broadly characterized by three major paradigm shifts, as shown in Figure 2, which together have shaped the modern framework of centralized water treatment and distribution networks [7,8]. The first paradigm focused on water conveyance and accessibility. In ancient Rome, long-distance gravity-driven water conveyance was achieved through aqueducts, lead pipes, and open channels, enabling spring water to be transported from outside the city to urban users. This period marked the emergence of rudimentary water supply infrastructure, accompanied by early forms of water allocation and prioritized distribution through diversion structures [9].

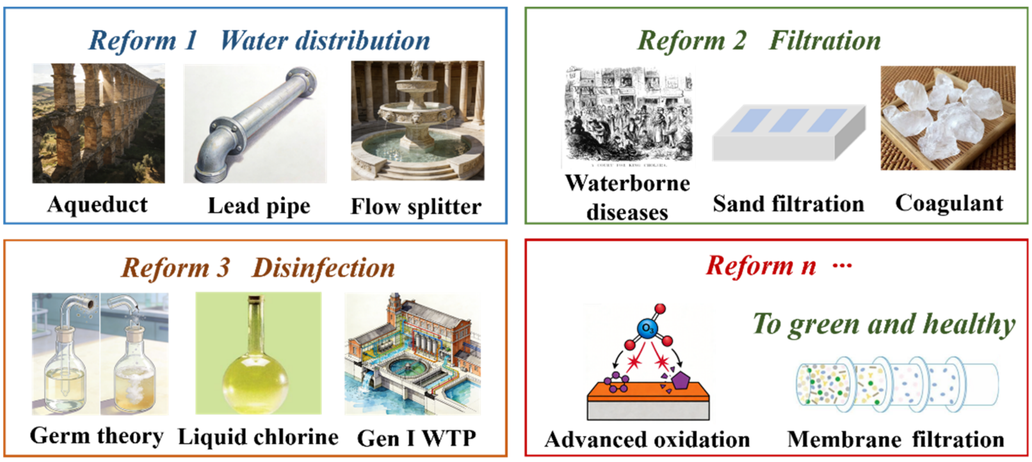



**Figure 2.** Paradigms of urban water supply.

The second paradigm centered on filtration, driven primarily by public health crises associated with waterborne diseases such as cholera and typhoid during the process of urbanization. As the causal relationship between drinking water contamination and disease transmission became increasingly recognized, the objective of water treatment shifted from improving aesthetic quality to mitigating health risks. Subsequently, low-rate filtration technologies, such as slow sand filtration, were developed, and with the growing demand for large-scale water supply, rapid filtration processes coupled with coagulation were progressively introduced and intensified. These advances established turbidity removal as a core function of centralized water treatment systems.

The third paradigm was characterized by disinfection. With the establishment of germ theory, municipal water supply systems incorporated chlorination as a routine treatment barrier, integrated with upstream processes such as coagulation, sedimentation, and filtration, thereby forming standardized and reproducible treatment trains [10]. In China, early waterworks such as the Yangshupu Water Treatment Plant in Shanghai, China exemplified this transition, where the adoption of chlorination further advanced the systematization and modernization of treatment processes. Consequently, the conventional treatment train of coagulation-sedimentation-filtration-disinfection was established, marking the formation of the first generation of drinking water treatment technologies.

## 3. Green and Healthy Requirements for Urban Water Supply

Following the three major paradigm shifts of water distribution, filtration, and disinfection, modern urban water supply systems have largely achieved safe and reliable delivery based on centralized treatment and distribution networks, accompanied by relatively mature frameworks for controlling pathogenic risks. However, safety does not necessarily equate to health. Since the 1970s, the detection of disinfection by-products (DBPs) and refractory organic contaminants in drinking water has revealed chemical health risks beyond microbiological safety. Consequently, the concept of health-oriented water supply has evolved from preventing acute waterborne diseases to reducing chronic exposure to disinfection by-products and trace organic contaminants across the entire water supply chain. In response, ozone-activated carbon processes, which effectively control DBP precursors and reduce DBP formation potential, have gradually evolved into a second-generation treatment paradigm characterized by advanced treatment. Meanwhile, enhanced coagulation, biological filtration, powdered activated carbon adsorption, and advanced oxidation processes have been increasingly adopted to compensate for the limitations of conventional treatment systems [11].

Almost in parallel with health considerations, green requirements have also gained increasing attention. With industrialization and advances in analytical technologies, drinking water treatment has achieved progressively higher contaminant removal efficiency, but often at the cost of increased chemical consumption and potential by-product formation, which conflicts with principles of green development. Green treatment approaches emphasize minimizing disturbances to the natural properties of water. Accordingly, physical, physicochemical, and biological processes are generally regarded as having relatively limited impacts on water's intrinsic characteristics, whereas chemically intensive processes may alter natural chemical compositions, introduce new substances, and generate secondary by-products, and are therefore often considered less environmentally benign. This recognition has driven the search for treatment pathways that rely more on physical separation, involve lower chemical inputs, and offer greater process controllability to meet increasingly stringent water quality objectives [12–14].

Health and greenness do not simply represent incremental additions to existing goals; rather, they signify a fundamental broadening of drinking water treatment objectives. Whereas the first generation of treatment focused on microbial risk control through disinfection, the second generation emphasized the reduction of disinfection by-product formation and enhanced control of trace organic contaminants through advanced treatment. The emerging third generation explores pathways toward lower chemical inputs and higher-quality water supply, establishing an evolutionary trajectory of drinking water treatment technologies. At present, relevant technologies remain under active development, and integrated process configurations oriented toward green and healthy water supply continue to evolve [15].

## 4. Pathways toward Green and Healthy Urban Water Supply

The realization of green and healthy urban water supply can be advanced along two complementary pathways within existing centralized treatment frameworks: the enhancement of natural processes and the upgrading of physical separation technologies. As a pretreatment barrier between water sources and treatment plants, riverbank filtration enables surface water to undergo infiltration and subsurface transport through alluvial aquifers, during which filtration, adsorption, and redox processes collectively attenuate a portion of contaminants. This natural attenuation improves raw water quality, reduces subsequent treatment loads, and to some extent mitigates the formation potential of disinfection by-products [16].

In comparison, membrane-based treatment represents a more effective pathway toward green water purification. Membrane processes primarily rely on physical separation mechanisms to remove contaminants and can operate with little or no chemical addition, thereby minimizing disturbances to the natural properties of water. As illustrated in Figure 3, ultrafiltration is effective in removing particulates, colloids, and high-molecular-weight organic matter, producing water with very low turbidity and enabling high-quality treatment of conventional water sources. Nanofiltration, with a molecular weight cut-off typically in the range of 200–2000 Da, provides enhanced removal of trace organic contaminants and divalent ions, making it suitable for advanced purification and water quality optimization. Reverse osmosis offers the highest removal efficiency for dissolved constituents, enabling deep desalination and the removal of most dissolved pollutants, and is therefore applicable to high-salinity or highly contaminated water sources [17–19].

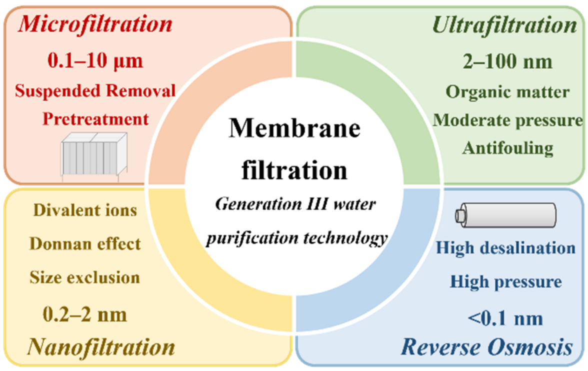



**Figure 3.** Membrane technology in urban water supply system.

Overall, the incorporation of microfiltration, ultrafiltration, nanofiltration, and reverse osmosis into drinking water treatment has driven the emergence of a third-generation treatment paradigm centered on membrane-based processes. Depending on source water quality and regional water demands, membrane technologies can partially replace first- or second-generation processes or be integrated with them to enhance technical and economic performance. On one hand, after conventional "coagulation-sedimentation" pretreatment, ultrafiltration (UF) or microfiltration (MF) can be employed to replace sand filtration or activated carbon filters to achieve refined removal of suspended solids, pathogenic microorganisms, and part of dissolved organic matter [20]. In the advanced treatment units of second-generation drinking water treatment system, nanofiltration (NF) can substitute part of the ozone-activated carbon process. On the other hand, membrane technologies can be coupled with conventional pretreatment units to construct multi-stage treatment systems, such as "pretreatment-UF/MF-disinfection" processes or "pretreatment + UF + NF/reverse osmosis" dual-membrane configurations, thereby significantly improving overall effluent water quality and effectively reducing dissolved organic matter and the formation of disinfection by-products [21].

At present, cost issues in third-generation water treatment systems based on membrane technologies have become a major research focus in both academia and engineering practice. Although membrane-based water supply systems exhibit relatively high initial investment requirements, mainly including membrane modules and associated operational equipment, their capital costs have declined significantly with the localization of membrane materials, large-scale manufacturing, and continuous optimization of integrated membrane processes [22]. The long-term operation and maintenance costs of membrane technologies are primarily associated with energy consumption and membrane fouling control, cleaning, maintenance, and replacement. However, related studies indicate that adopting low-pressure membrane technologies and diversified energy synergies, combined with cogeneration and waste heat utilization to optimize the overall energy consumption structure, can effectively reduce the total energy demand of membrane treatment systems. Moreover, continuous development of high-performance membrane materials can further improve energy utilization efficiency. Intelligent operation control and optimized pretreatment processes can effectively mitigate membrane fouling and extend membrane module service life, thereby reducing long-term operation and maintenance costs and enhancing the overall long-term economic performance of the system [23]. Furthermore, incorporating environmental impacts, economic feasibility, energy consumption, and toxicity into a life cycle assessment framework enables a systematic and comprehensive evaluation of membrane technology applications in water treatment processes. Related studies indicate that, under a life cycle cost assessment framework, although membrane-based water supply systems involve relatively high initial investments, optimizing operational management, energy configuration, and pretreatment processes can significantly enhance long-term operational performance, thereby effectively reducing unit water production costs and operation and maintenance expenses [24]. Meanwhile, membrane-based water supply systems can improve the stability of effluent water quality, reduce the risk-related costs associated with sudden water quality incidents, and enhance system resilience to flexibly cope with fluctuations in urban water supply. Within this comprehensive evaluation framework, membrane-based water supply systems have demonstrated favorable overall economic performance and sustainability advantages [25].

In practice, a range of membrane-based treatment configurations has been developed, including direct ultrafiltration of raw water; powdered activated carbon-ultrafiltration membrane bioreactors; granular activated carbon-ultrafiltration or biofiltration-ultrafiltration systems; biofilm-assisted gravity-driven ultrafiltration; ultrafiltration-nanofiltration for treating hard water and emerging contaminants; and ultrafiltration-reverse osmosis for seawater desalination. For example, the city of

Herzliya in Israel has integrated "ultrafiltration (UF) + reverse osmosis (RO)" membrane processes with conventional coagulation-sedimentation-filtration treatment, which not only reduced the costs associated with traditional advanced treatment processes, but also significantly decreased equipment maintenance and replacement frequency due to the high separation efficiency and long service life of membrane systems, thereby further lowering long-term operational costs [26]. Similarly, Singapore's NEWater project has introduced membrane technologies into wastewater reuse, effectively reducing reliance on conventional chemical disinfection, decreasing chemical consumption and discharge, and simultaneously lowering source water procurement costs and the unit production cost of reclaimed water [27]. Together, these configurations provide flexible technological options for advancing green and healthy urban water supply systems [28–30].

Advancing leakage control and intelligent management through the conveyance and distribution stages is also a key pathway for the green transformation of urban water supply systems centered on membrane technologies [31]. Network leakage not only leads to water loss but also entails additional abstraction, treatment, and conveyance energy consumption, significantly increasing system carbon emissions and operational costs [32]. Accordingly, advanced leakage detection technologies based on acoustic monitoring, pressure sensors, and district metering enable rapid identification and precise repair of leaks, effectively reducing non-revenue water and minimizing unnecessary energy use and chemical dosing, thereby improving resource use efficiency at the source. Meanwhile, artificial intelligence and data-driven network management offer novel means for intelligent system control. By integrating real-time data on water flow, pressure, quality, and energy consumption, AI algorithms can dynamically optimize pump scheduling, pressure zones, and valve operations, achieving minimal energy consumption and prolonged equipment service life while ensuring supply reliability and water quality stability [33]. Furthermore, intelligent predictive models can anticipate fluctuations in water demand and potential operational risks, enhancing the system's capacity to respond to emergencies and extreme conditions, and thus improving the resilience of the water supply system.

## 5. Conclusions and Outlook

This manuscript has reviewed the evolutionary trajectory of urban water supply systems, encompassing their conceptual foundations, paradigm shifts, emerging requirements driven by green and health-oriented objectives, and the feasible pathways to achieve such transitions. Overall, urban water supply has evolved toward a modern configuration centered on centralized treatment and networked distribution. However, with growing awareness of water quality risks and increasingly complex development demands, the goals of water supply have expanded beyond ensuring safety and reliability to encompass health protection and environmental sustainability.

Looking forward, future urban water supply systems are expected to place greater emphasis on holistic coordination and multi-scale integration. Within a source-treatment-distribution-consumer framework, technological integration and management optimization will be further advanced, leading to systems characterized by lower environmental disturbance, higher water quality, enhanced resilience, and greater intelligence. These transformations will be essential for supporting sustainable urban development under increasing resource and environmental constraints. In the future, urban water supply conveyance and distribution systems are expected to shift from passive operation toward digitalized and intelligent coordinated management. IoT-based monitoring, digital twins, and AI-driven scheduling will enable real-time network state perception, precise leakage control, and energy-optimized pump operations. Meanwhile, the integration of renewable energy and resilient network design can enhance system safety and stability under extreme events. The deep integration of distribution networks with membrane treatment and intelligent management platforms will collectively support low-carbon, efficient, and smart third-generation urban water supply systems.

## Author Contributions

H.W.: Writing—original draft. H.L.: Conceptualization, Writing—review & editing, Funding Acquisition, Supervision. All authors have read and agreed to the published version of the manuscript.

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## Conflicts of Interest

The authors declare no conflict of interest.

## Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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