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Nature Communications

https://doi.org/10.1038/s41467-026-72300-3

Article in Press

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Received: 29 July 2025

Accepted: 13 April 2026

Cite this article as: Wang, S., Huang, Y., Shao, Y. *et al.* Unlocking energy-carbon-water synergies in global water supply system maintenance. *Nat Commun* (2026). https://doi.org/10.1038/s41467-026-72300-3

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Unlocking Energy-Carbon-Water Synergies in Global Water Supply System Maintenance

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Abstract

Drinking water system maintenance faces rising energy, carbon, and water pressures, but integrated optimization strategies remain limited. Here we developed an energy-carbon-water nexus framework to quantify the resource efficiency gains of replacing conventional unidirectional flushing with air scouring, ice pigging, and their combined use across pipe, city, and regional scales. At the pipe scale, air scouring and ice pigging reduced energy use by 12%-68%, carbon footprint by 7%-84%, and water use by 56%-91% relative to unidirectional flushing. When scaled to 258,000 km of pipelines across 50 cities and regions, emerging technologies reduced annual energy use by 4.40×10^7-4.80×10^7 kWh, carbon emissions by 2.26×10^8-7.56×10^8 kg CO_2, and water use by 4.12×10^7-6.12×10^7 m^3. Prioritizing large-diameter pipes yielded resource and economic cost savings equivalent to 4-19 years of unidirectional flushing over a 30-year transition. These findings reveal substantial opportunities to improve resource efficiency in water infrastructure maintenance and advance sustainable urban water systems.

Introduction

Ensuring the reliable performance of water supply systems is essential for safeguarding drinking water safety[1]. It is estimated that 10%-60% of waterborne disease outbreaks are linked to deficiencies in these systems[2, 3]. Globally, more than 2.5 million kilometers of water supply pipelines have an average age of over 53 years and are approaching the critical stage at which structural and functional failures commonly occur[4, 5, 6, 7, 8]. To provide high-quality drinking water under ever-tightening environmental regulations, water utilities must proactively maintain water supply pipelines, including pipe cleaning, pipe rehabilitation, pipe renewal, and pipe repair, with the goal of mitigating risks to water quality (Supplementary Figure 1)[9,10,11,12,13]. Pipe cleaning is a critical component of pipeline maintenance throughout the entire service life[14]. It is not only required routinely but also serves as an essential step before and after rehabilitation, following renewal (prior to commissioning) and after repair (Fig. 1)[15, 16]. It is estimated that 65,000 pipe cleaning operations are carried out globally each year, and approximately 70,000 km of water mains undergo cleaning following renewal[5, 6, 16]. However, unidirectional flushing (UF) is the most widely used technology and consumes large amounts of water. For example, more than 13 million m^3 of water are consumed annually for cleaning urban water supply pipes in Beijing, representing about 2% of the city's total annual residential water use[17]. This water use also carries significant energy consumption, carbon emissions, and financial costs[18, 19].

Fig. 1

Currently, three common methods are used to clean water supply pipes, namely UF, air scouring (AS), and ice pigging (IP), as illustrated in Fig. 2a-c, with their underlying mechanisms described in Supplementary Note 1 and Supplementary Note 2[20]. UF removes sediments and biofilms by applying water flow at high velocity (Supplementary Figure 2), whereas AS (Supplementary Figure 3) and IP (Supplementary Figure 4) employ compressed air and ice slurry, respectively, to generate shear stresses that are tens of times greater than those produced by UF[21]. Because of this, both emerging technologies offer substantial performance improvements. AS requires only 37%-77% of the water used in UF, while IP uses just 10%-17%, yielding substantial reductions in energy, carbon emissions, and economic costs[18, 19, 20, 21].

Fig. 2

Energy resources, carbon emissions, and water availability, are central themes in contemporary environmental research, with water supply systems operated by utilities playing a crucial role[23, 24, 25]. Globally, an estimated 590 billion m^3 of drinking water is supplied annually, representing 10%-15% of total water extraction, and this activity accounts for up to 8% of global energy consumption and 2%-4% of carbon emissions[26, 27, 28]. To confront escalating water demand, tightening energy constraints, and the imperative of net-zero emissions, water utilities are deploying targeted mitigation strategies. These include expanding multi-source water supplies and enhancing leakage control to alleviate water scarcity, as well as optimizing water distribution system scheduling and updating inefficient motors and pumps to curtail energy consumption and carbon emissions[24, 29, 30, 31]. However, despite these advancements, the routine pipe cleaning processes in water supply systems often overlook their own significant contributions to energy consumption, carbon emissions, and water use. These intertwined factors form a complex energy-carbon-water nexus (the intricate connections and dependencies among energy, carbon and water in system) and pose persistent challenges for sustainable resource management.

The energy-carbon-water nexus is fundamental to achieving sustainable resource management[21, 28]. However, in practice, the current focus within water supply systems tends to center on broader climate policies and global sustainability initiatives, which often obscure the nuanced operational practices essential for effective strategic management[32, 33, 34]. To bridge this gap, a paradigm shift towards examining the intricate mechanics governing daily maintenance within these systems is necessary, particularly the operational frameworks governing pipe cleaning activities. Investigating the trade-offs within the energy-carbon-water nexus in pipe cleaning could provide critical tools and design strategies to optimize energy use, carbon emissions, and water consumption (Supplementary Note 3). However, such analyses remain scarce, and comprehensive quantitative assessments of the lifecycle nexus and associated economic costs are still limited. The life cycle of pipe cleaning includes pressure testing, cleaning agent preparation, pipe cleaning, and post-cleaning wastewater management, and each stage contributes differently to environmental and economic burdens. Despite the potential significance of these impacts, existing research on pipe cleaning has primarily emphasized water quality changes in the pipe, as well as the characterization of sediments and biofilms on the pipe walls, focusing on their physical, chemical, and microbial characteristics[20, 21]. Consequently, investigations into the environmental impacts and economic costs of pipe cleaning practices are limited and insufficiently detailed[35, 36]. Moreover, global selection of pipe cleaning strategies has not been systematically evaluated from an energy-carbon-water nexus perspective. Owing to variations in geographic conditions, network configurations, and economic constraints, the strategies employed worldwide exhibit considerable heterogeneity[23, 37]. Therefore, developing sustainable and cost-effective pipe cleaning strategies that incorporate regional diversity is essential for mitigating the substantial impacts associated with energy consumption, carbon emissions, water usage, and economic costs inherent in pipe cleaning.

In this study, we develop a multi-level pipe cleaning energy-carbon-water nexus optimization framework that integrates life cycle assessment (LCA), scenario-based optimization, and sensitivity analysis to quantify the energy use, carbon footprint, water consumption, and economic cost of emerging pipe cleaning technologies relative to conventional UF across pipe-, city-, and regional-scale systems. By characterizing how population, water and wastewater energy intensity, carbon emission intensity, and water/electricity rates influence the environmental and economic performance of pipe cleaning technologies across 50 cities and regions, this study aims to inform the selection of pipe cleaning strategies that account for network characteristics and regional factors. This study finally aims to identify effective technological transition pathways and generate decision-support insights for sustainable management of global water supply systems to unlock multi-dimensional synergies across energy savings, carbon mitigation, water conservation, and economic performance.

Results

Influence of technological choices on energy consumption, carbon footprints and water

consumption

As pipe diameter increases, the energy consumption per unit pipe length (km of pipe) for UF, AS, and IP gradually increases (Supplementary Figure 5), whereas the energy consumption per unit pipe volume (m^3 pipe) for these technologies steadily decreases (Fig. 3). The volume of pipe is defined as the volume of pipe used to convey one cubic meter of water, expressed in units of m^3 pipe in this study. Regarding different pipe diameters, the energy consumption per unit volume of pipe (m^3 pipe) of UF is consistently larger than that of AS and IP. In the pipe diameter of 100, 150, 200 and 300 mm, the energy consumption per unit volume of pipe (m^3 pipe) of AS is larger than that of IP. When the pipe diameter is larger than 400 mm, the energy consumption per unit volume of pipe (m^3 pipe) of AS is smaller than that of IP. This is due to the fact that although the water consumption of IP is smaller than that of AS, IP needs to produce ice slurry. As pipe diameter increases, both the ice slurry production time and the associated energy demand rise, leading to a progressively larger share of total energy consumption attributable to ice slurry production.

From the perspective of carbon footprint, when all pipes are cleaned during the daytime (Fig. 3), the carbon footprint per unit volume of pipe (m^3 pipe) increases with pipe diameter, largely because the reliance on alternative water sources becomes more substantial. In this study, the alternative water source is defined as other water sources utilized by residents in place of tap water during service interruptions caused by pipe cleaning, with bottled water considered as a representative substitute. As the diameter of the cleaned pipe increases, a larger number of residents experience service interruptions, leading to a corresponding increase in the carbon footprint per unit pipe volume (m^3 pipe). When the pipe diameter is less than 500 mm, the order of carbon footprint per unit volume of pipe (m^3 pipe) is AS>IP; when the pipe diameter reaches 600 mm, the carbon footprint per unit volume of pipe (m^3 pipe) of IP exceeds that of AS. This is because the fluid flow velocity in the pipe during AS is very high (exceeding 1 m s^{-1} in a pipe with a diameter of 600 mm), while the flow velocity in the pipe with a diameter of 600 mm during IP is relatively low (less than 0.5 m s^{-1}). Although IP consumes less water, it causes a longer service interruption, resulting in a higher carbon footprint per unit volume of pipe (m^3 pipe) compared with AS. Based on the sensitivity analysis of operating parameters and pipe characteristics, the carbon footprints of the three cleaning technologies all decrease with the increase in cleaning velocity, while increasing with rising daily water velocity and water consumption coefficient (Supplementary Note 4 and Supplementary Figure 6).

In this study, bottled water is used as a representative substitute, as its production and distribution contribute additional carbon emissions. Daytime cleaning coincides with peak residential water demand, increasing reliance on bottled water and the associated carbon footprint, in contrast, nighttime cleaning aligns with low demand, minimizing the need for alternative water sources and effectively eliminating these emissions. Thus, the nighttime pipe cleaning scenario was established, excluding the carbon footprint associated with bottled water. When pipes are cleaned at night, the carbon footprint per unit volume of pipe (m^3 pipe) is much lower than that generated during daytime cleaning, with a reduction range from 1.7% to 40.0% (Fig. 3). Particularly, pipes with larger diameters yield a greater reduction in carbon footprint per unit pipe volume when cleaned at night rather than during the daytime. As the pipe diameter increases, the reduction rate of the carbon footprint per unit volume of pipe in AS is larger than that in UF and

IP. When the pipe diameter is no more than 400 mm, the carbon footprint per unit volume of pipe follows the order of AS>IP. However, when the pipe diameter is greater than 400 mm, the carbon footprint per unit volume of pipe follows the order of AS<IP. In the actual pipe cleaning operations, pipes with diameters greater than 300 mm are typically cleaned at night.

In terms of water consumption, the three technologies are ranked in the order of UF>AS>IP for different pipe diameters (Fig. 3). As the pipe diameter increases, the water consumption per unit pipe length (km pipe) for the three technologies gradually increases, while the water consumption per unit volume of pipe (m^3 pipe) gradually decreases (Supplementary Figure 5). Specifically, the water consumption for UF decreases from 18 to 12 m^3 water per m^3 pipe as diameter increases from 100 to 600 mm; for AS, it declines from 8 to 3 m^3 water per m^3 pipe over the same range; and for IP, it drops from 2.8 to 1.2 m^3 water per m^3 pipe. This trend indicates a scale effect in water consumption across the three cleaning technologies as pipe diameter increases.

Fig. 3

The global geographic spatial patterns of energy-carbon-water-economy

Daytime cleaning of large-diameter pipes incurs relatively high carbon footprints per unit volume of pipes (m^3 pipe), while AS achieves lower energy consumption and footprints than IP at larger diameters, therefore, a combined AS+IP strategy is proposed. Specifically, pipes with diameters of 100-400 mm are cleaned using IP, whereas pipes with diameters of 500-600 mm are cleaned using AS. The UF, AS, and IP strategies each employ UF, AS, and

IP, respectively. For all strategies (UF, AS, IP, and AS+IP), pipes with diameters of 100-300 mm are cleaned during daytime, while those with diameters of 400, 500, and 600 mm are cleaned at night. This study selected 50 cities and regions across six continents (Asia, Europe, Africa, North America, South America, and Oceania) to investigate the application of the UF, AS, IP, and AS+IP strategies in water supply networks (Fig. 4 and Supplementary Figures 7-12). The lengths of individual water supply networks in these cities and regions range from 20 to 50,000 km, with a combined total length of approximately 258,000 km (Fig. 5a and Supplementary Table 1). The selected cities and regions encompass both densely populated and sparsely inhabited areas, span developed and developing countries, and generally exhibit high levels of drinking water accessibility through piped networks[38, 39, 40, 41].

Across the 50 cities and regions, the baseline UF strategy exhibits substantial resource consumption and environmental burden, with annual energy consumption, carbon footprints, and water consumption reaching 9.96×10^7 kWh,1.22×10^9 kg CO_2, and 6.88×10^7 m^3, respectively (Fig. 4). In contrast, other three cleaning strategies (AS, IP, and AS+IP) achieve significant reductions in these impacts. IP provides the greatest overall improvements, reducing annual energy consumption by 4.48×10^7 kWh (45%), carbon footprints by 7.56×10^8 kg CO_2 (62%), and water consumption by 6.12×10^7 m^3 (89%). AS+IP yields similarly substantial benefits, lowering energy consumption by 4.80×10^7 kWh (48%), carbon footprints by 7.48×10^8 kg CO_2 (61%), and water consumption by 5.88×10^7 m^3 (86%). AS also delivers meaningful reductions, decreasing annual energy consumption by 4.40×10^7 kWh, carbon footprints by 2.26×10^8 kg CO_2, and water consumption by 4.12×10^7 m^3, corresponding to reductions of approximately 45%, 19%, and 60%, respectively. Economic analysis indicates that although AS, IP, and AS+IP strategies require an initial investment in cleaning devices, their water and energy savings allow 45 of the 50 cities and regions to offset the full economic cost of UF within the first year. Among these cities and regions, IP reduces the first-year economic cost by approximately 1.17×10^6 USD, while AS+IP achieves a reduction of about 1.03×10^7 USD. The remaining five cities, each with pipe lengths under 200 km, fail to reach break-even in the first year. Four cities achieve cost parity within two years, whereas one system with an exceptionally short network (less than 24 km) requires approximately seven to eight years (Supplementary Figure 13).

The AS+IP strategy generally achieves the lowest energy consumption in over 90% of the 50 cities, whereas AS and IP show considerable variation across different locations. IP and AS+IP consistently exhibit the lowest values for carbon footprints, approximately half that of AS. IP also achieves the lowest water consumption. The economic costs follow the order IP < AS+IP < AS. Further analysis shows that, for IP and AS+IP, annual water savings exceed 1.00% of total annual water use in 11 cities, with Bend (United States) reaching the highest value at 4.05%. In nine cities, the first-year economic cost savings exceed 0.01% of local gross domestic product (GDP), reflecting meaningful regional economic impact (Supplementary Figure 14 and Supplementary Table 2)[42]. Overall, the other three cleaning strategies substantially reduce energy consumption, carbon footprints, and water consumption, while maintaining favorable economic performance.

Fig. 4

Global Selection of Pipe Cleaning strategies for Water Supply Networks

Due to the significant differences in the scale of the served population among various cities, it is difficult to identify the driving force of the pipe structure and regional characteristics on cleaning costs and technology choices merely by comparing the total amount. The pipe volume per capita (PVPC) is introduced to provide an indicator of pipe scale per capita and is defined as the total pipe volume of a water supply network divided by the served population. The pipe networks can be classified into three types: dense pipe network (0-0.2 m^3 pipe $capita^{-1}$), moderate pipe network (0.2-0.4 m^3 pipe $capita^{-1}$), and sparse pipe network (0.4-1.2 m^3 pipe $capita^{-1}$) based on the data distribution across 50 cities and regions (Fig. 5b). The pipe networks with PVPC of 0.1 m^3 pipe $capita^{-1}$, 0.3 m^3 pipe $capita^{-1}$ and 0.8 m^3 pipe $capita^{-1}$ were selected as representatives of dense pipe network, moderate pipe network and sparse pipe network respectively to explore the influence of PVPC on the energy consumption, carbon footprint, water consumption, and economic cost of pipe cleaning. The pipe diameters of these three types of pipe networks all range from 100 to 600 mm (see details in Method section). Meanwhile, the water rate (Fig. 5c) and electricity rate (Fig. 5d) in these cities and regions were collected. According to the distribution of water rates and electricity rates, it is respectively divided into low water rate (0-1.0 USD m^{-3}), medium water rate (1.0-3.0 USD m^{-3}), high water rate (3.0-10.0 USD m^{-3}), low electricity rate (0-0.1 USD kWh^{-1}), medium electricity rate (0.1-0.2 USD kWh^{-1}), and high electricity rate (0.2-0.4 USD kWh^{-1}), respectively.

The energy consumption for pipe cleaning increases with rising PVPC, as shown in Fig.

5e. Across the three cleaning technologies, electricity use associated with the production of cleaning water and subsequent wastewater treatment accounts for 100% of total electricity use in UF strategy, 48%-86% in AS strategy and 16%-25% in IP strategy (Fig. 3), demonstrating that energy intensities of drinking water supply and wastewater treatment are primary drivers of total electricity consumption. This study further assessed how the energy intensity of drinking water supply and wastewater treatment influences the energy consumption of pipe cleaning. Since the volume of drinking water used for pipe cleaning equals the volume of wastewater discharged, the energy intensities of drinking water supply and wastewater treatment are combined into a single variable as water-energy intensity (1.0-2.0 kWh m^{-3}). Water-energy intensity refers to the energy intensity of drinking water supply (e.g., water extraction, transportation, treatment, and distribution), and wastewater processes (e.g., collection, biochemical treatment, advanced treatment, and effluent discharge). Lower water-energy intensity values are associated with conventional water supply and wastewater treatment technologies, whereas higher water-energy intensity values reflect advanced treatment technologies (e.g., membrane treatment) with higher energy consumption per unit volume of water. The influence of water-energy intensity on energy consumption follows the order of strategies: UF>AS>IP≈AS+IP (see details in Supplementary Note 5). Across pipe networks with varying PVPC, AS exhibits the lowest energy demand when the water-energy intensity is 1.0 kWh m^{-3}, whereas AS+IP becomes the most energy-efficient option at intensities of 1.5 and 2.0 kWh m^{-3}. These patterns indicate that regions with strong constraints on energy resources can tailor the choice of pipe cleaning strategies according to local water-energy intensity.

From the aspect of carbon footprint, networks with a PVPC of 0.1 m^3 $capita^{-1}$ exhibit carbon footprints that are slightly higher than or comparable to those with a PVPC of 0.3 m^3 $capita^{-1}$, but remain lower than those of networks with a PVPC of 0.8 m^3 $capita^{-1}$. Meanwhile, the influences of the electricity-related carbon emission factor (Fig. 5f and Supplementary Note 6) and alternative water demand index (Fig. 5g) on the carbon footprint of pipe cleaning were investigated. The electricity-related carbon emission factor refers to the amount of carbon dioxide produced per kWh of electricity generated in a particular area, with a range of 0.2 to 1.2 kg CO_2 kWh^{-1}. The alternative water demand index is defined as the ratio of alternative water sources used by residents during pipe cleaning water outages to the water supplied through the pipes, ranging from 0.1 to 0.3. Across all strategies, IP and AS+IP have relatively low carbon footprints, with IP performing marginally better than AS+IP. The alternative water demand index exerts a stronger influence on carbon footprints than the electricity-related emission factor, likely because alternative water supply constitutes a substantial share of total carbon impacts (Fig. 3c). The alternative water demand index can be reduced by conducting pipe cleaning while avoiding peak water-use periods. For example, pipe cleaning in residential zones can be scheduled outside peak demand windows such as between 6:00 and 8:00 a.m. and between 8:00 and 10:00 p.m., and the frequency can be reduced during summer. In addition, the benefits of lowering the alternative water demand index are particularly pronounced in systems using UF and AS strategies, whereas the gains are comparatively modest in networks operating under IP and AS+IP strategies.

Water consumption increases proportionally with PVPC across all four strategies. Under the same PVPC conditions, all four strategies follow the pattern of UF>AS>AS+IP>IP, and

IP exhibits a greater advantage (Fig. 5h). Consequently, in regions with high PVPC and limited water resources, IP can be prioritized. From the perspective of economic cost, UF only requires the opening and closing of the valves of the pipes to be cleaned, AS requires additional equipment such as air compressors, and IP requires ice slurry generators as well as NaCl consumables. These differences in initial investment lead to varying payback periods under different pipe network conditions. This study explores the impacts of initial investment, pipe networks with different lengths and densities, and varying water and electricity rates on the economic cost of pipe cleaning (Supplementary Note 7). When the water rate is 0.5 USD m^{-3}, UF incurs the lowest first-year economic cost for pipe networks shorter than 65 km, whereas IP achieves the lowest first-year cost for networks longer than 65 km. When the water rate rises to 3.0 USD m^{-3}, UF has the lowest first-year economic cost for networks shorter than 300 km, while IP becomes the most cost-effective option for networks longer than 300 km. For pipe networks longer than 300-500 km, the savings in water and energy costs achieved by AS, IP, and AS+IP can offset the expenses for equipment and consumables within a single year, compared with UF. With water rates rise, the first-year economic cost advantage of IP over AS and AS+IP gradually becomes more pronounced. In European cities, the water rate is mostly over 3.0 USD m^{-3}, where IP has a greater economic cost advantage compared to UF, AS, and AS+IP.

The impact of the water rate on the first-year economic cost of pipe cleaning is the most significant, exceeding the effects of PVPC and electricity rate (Fig. 5i-l and Supplementary Figure 15). When the water rate increases from 1.0 to 3.0 USD m^{-3}, the first-year economic cost of UF, AS, IP, and AS+IP increases by 51.28% to 135.81%. In comparison, when the electricity rate increases from 0.1 to 0.15 USD kWh^{-1}, the first-year economic cost growth rate is 2.21% to 6.58%. When PVPC increases from 0.1 to 0.3 m^3 capita^{-1}, the first-year economic cost increases by 19.06% to 35.88%.

Fig. 5

Pipe cleaning strategies for sustainable transition management

Since the energy, carbon, and water savings of AS and IP depend strongly on pipe diameter, transition pathways must be planned carefully to maximize environmental and economic benefits. Using water supply network data from 50 global cities and regions, six transition strategies (AS-100, IP-100, AS+IP-100, AS-600, IP-600, and AS+IP-600) were evaluated in terms of the energy consumption, carbon footprints, water consumption and economic costs over a 30-year transition period. In the AS-100, IP-100, and AS+IP-100 strategies, UF is replaced by AS, IP, and AS+IP beginning with small-diameter pipes (100 mm), whereas the AS-600, IP-600, and AS+IP-600 strategies initiate the same substitutions from large-diameter pipes (600 mm). The implementation timeline for each strategy can be adjusted to local conditions, and all transitions proceed at a uniform annual rate over the 30-year period. In addition, cumulative saving ratios for energy consumption, carbon footprint, water consumption, and economic cost are obtained by summing annual savings and normalizing them to the baseline UF values, thereby capturing the long-term environmental and economic benefits generated throughout the transition[43].

Over the 30-year transition period, all six strategies achieved substantial resource and economic benefits when aggregated across 50 water supply networks, resulting in energy savings of 2.94×10^8-1.08×10^9 kWh, carbon footprint reductions of 1.80×10^9-1.57×10^{10} kg CO_2, water savings of 3.37×10^8-1.32×10^9 m^3, and economic cost reductions of 1.60×10^9-6.12×10^9 USD (Fig. 6a and Supplementary Figures 16-21). At the level of individual network, the pipe cleaning strategies starting from large-diameter pipes (AS-600, IP-600, AS+IP-600) consistently achieved higher cumulative energy, water savings and economic cost reductions than the corresponding small-diameter strategies (AS-100, IP-100, AS+IP-100). Among these, AS+IP-600 achieved the greatest energy savings in 48 networks, while IP-600 delivered the largest water savings in all 50 networks and the highest economic cost reductions in 49 networks.

In terms of carbon footprint, cities dominated by small-diameter pipes achieved larger reductions when transition strategies were initiated from large-diameter pipes. In Phoenix and Auckland, where 100-250 mm pipes constitute 81.14% and 91.56% of the total network, respectively, strategies starting at 600 mm produced carbon reductions that were 2.66-3.09 times and 3.41-4.08 times greater than those of the corresponding small-diameter strategies. Conversely, cities with a high share of large-diameter pipes showed the opposite trend. In Guangzhou, where pipes with diameters of 100 to 250 mm constituting 15.72% of the total network, strategies starting from small-diameter pipes outperformed those beginning at 600 mm, with IP-100 and AS+IP-100 achieving 1.40-1.49 times greater carbon reductions than IP-600 and AS+IP-600, respectively.

Cumulative saving ratios were calculated by summing annual savings and normalizing them to the baseline UF annual values, representing the number of baseline UF years effectively saved over the 30-year transition. Across 50 water supply networks, large-diameter strategies (AS-600, IP-600, AS+IP-600) achieved average cumulative saving ratios of 9.66-11.46, 4.47-12.84, 13.52-19.29, and 12.06-17.11 for energy consumption, carbon footprint, water consumption, and economic cost, respectively, equivalent to approximately 4-19 years of baseline UF value saved (Fig. 6b-e). By comparison, small-diameter strategies (AS-100, IP-100, AS+IP-100) reached average cumulative saving ratios of 2.94-3.98, 1.73-5.98, 5.11-7.67, and 4.61-7.26 for energy consumption, carbon footprint, water consumption, and economic cost, respectively, corresponding to roughly 1-8 years of baseline UF value saved. These results highlight the substantial long-term savings potential of the strategies and provide a quantitative measure of the resource and economic benefits achievable over a 30-year transition.

Although strategies starting with large-diameter pipes generally provide the highest cumulative benefits, practical implementation typically follows a staged approach. Emerging technologies are generally initially piloted on a limited number of small-diameter pipes, which have simpler structures, offer easier control of flow and pressure, and affect fewer users. This approach enables rapid verification of technical feasibility and timely adjustments while minimizing operational and social risks. Once validated, the technologies can be scaled up to large-diameter pipes, achieving maximal reductions in energy consumption, carbon footprint, water use, and economic costs.

Fig. 6

Discussion

This study not only compares the performance of different pipe cleaning technologies on individual metrics, but also unlocks the synergistic interactions among water, energy, and carbon in water supply systems. Emerging pipe cleaning technologies reduce both direct water use and reliance on alternative water supply, cascading through the system to lower energy consumption and carbon emissions. The interdependence among water use, energy consumption, and carbon emissions helps explain why emerging cleaning technologies can generate simultaneous benefits across the energy-carbon-water nexus[44]. However, the performance of the same technology varies across cities and regions because of differences in network scale, pipe diameter distribution, alternative water demand, water rates, and energy intensity of water supply. Because interventions in large-diameter pipes require more resources and serve larger areas, prioritizing AS, IP, and their combined application in these segments creates a stronger leverage effect, enabling each unit of technological input to generate greater system-level water, energy, carbon, and economic benefits. Accordingly, pipe maintenance in water supply systems can be reframed from a routine operational activity to a strategically optimizable sustainability intervention. Previous studies have primarily focused on the engineering performance, water consumption, or localized economic costs of individual cleaning technologies[45]. By contrast, this study develops a multiscale, pipe-city-region, energy-carbon-water nexus framework that evaluates technology performance in the context of coupled network structures and regional conditions, thereby advancing pipe maintenance research from technology comparison to system-level optimization.

Based on our findings, we propose a multi-tiered policy framework to translate technical insights into actionable strategies for sustainable urban water management. Differences in energy use, carbon emissions and water consumption, together with the pronounced influence of pipe diameter, indicate that maintenance policies should be aligned with regional network characteristics. Cities with extensive, resource-intensive networks or tight water and energy constraints should prioritize AS and IP. Conversely, smaller or more dispersed systems can adopt a hybrid approach, selectively applying UF, AS, and IP based on specific pipe diameter and network functions rather than a one-size-fits-all solution. This differentiated allocation of cleaning strategies is also consistent with existing long-term planning and tiered management approaches in some jurisdictions. For example, Ontario promotes graded management of drinking water systems through risk assessments based on the drinking water quality management standard (DWQMS) and municipal asset management frameworks[46]. To institutionalize this shift, regulators should integrate the multi-criteria resource implications of cleaning technologies into utility performance and performance benchmarks. Embedding these metrics into the approval process for maintenance schedules, and technology upgrades would steer utilities beyond sole reliance on short-term cost criteria, encouraging decisions that enhance water quality while improving overall resource efficiency and environmental performance. In the United Kingdom, this framework could align with the drinking water inspectorate's long-term planning requirements for drinking water quality, as well as with the office of water services' (Ofwat) performance regulation and asset health review processes[47, 48]. In Victoria, Australia, it could also be integrated into water utilities' annual reporting and decision-making around water mains cleaning programs[49]. At a systemic level, the city classification and representative-network framework developed in this study can guide differentiated transition pathways for crafting urban and regional transition pathways. Upgrading infrastructure via pipe cleaning should be formally incorporated into broader policies for drinking water security, water conservation and climate mitigation. In Metro Vancouver and Ontario, current drinking water management and demand management frameworks already integrate water quality protection, climate resilience, infrastructure upgrading, water conservation and long-term affordability within a common policy framework, providing a practical basis for embedding resource-efficient pipe cleaning strategies into local water planning[50, 51]. Dedicated funding mechanisms, clear project roadmaps, and robust performance monitoring can then accelerate the long-term transition from conventional UF to advanced technologies, enabling cities to capture significant co-benefits in energy savings, emission reductions, and water conservation.

This study, while comprehensive, acknowledges certain limitations and uncertainties. From a technical transition perspective, it is necessary to consider the regional optimization of spatial division and the scheduling of equipment, as well as the service life and maintenance status of local pipelines. In terms of data representativeness, the analysis is restricted to cities with relatively comprehensive and stable water supply network data; regions with sparse, fragmented, or rapidly evolving infrastructure could not be included due to limited or inconsistent datasets. Furthermore, differences in data sources and reporting years across cities may introduce variability that affects parameter consistency and the comparability of results. Methodologically, the LCA conducted here focuses on the operational stage of pipe cleaning, while indirect energy and water use linked to equipment maintenance, end-of-life treatment, and alternative water supply arrangements is represented in a simplified manner, potentially leading to an underestimation of full life-cycle impacts. The daytime cleaning scenario assumes user reliance on bottled water, which may not fully capture behavioral dynamics in multi-source supply systems. The optimization of cleaning cycles for water supply pipes, including shortening of intervals, emergency interventions or temporary adjustments, may require further investigation based on pipe anomalies (e.g., blockages), external disturbances (e.g., extreme weather and pipe bursts). These limitations point to promising directions for future work, including more explicit characterization of indirect resource flows, improved modelling of alternative water supply patterns and user behavior, and the inclusion of more diverse regional network configurations to enhance the robustness and generalizability of the assessment framework.

Several promising directions could extend the current work and further advance sustainable pipe cleaning research. First, data driven and artificial intelligence (AI) enabled modeling approaches could be developed to optimize pipe cleaning strategies, including scheduling, technology selection, and operational procedures, thereby improving the efficiency and proactivity of maintenance. Second, digital twin frameworks for urban water networks offer opportunities to integrate pipe condition data with cleaning strategies, enabling predictive assessments and scenario-based simulations that support real-time decision-making and dynamic resource allocation. Third, future research could more explicitly incorporate policy, economic, and social dimensions by linking dynamic cost factors (e.g., water rates, equipment and energy prices, market conditions) with multi-agent or game-theoretic models representing utilities, regulators, and users, thereby informing adaptive policy mechanisms that guide pipe cleaning strategies toward sustainable energy-carbon-water outcomes.

Methods

In this study, we develop a multi-level pipe cleaning energy-carbon-water nexus optimization framework illustrated in Fig. 7. This framework evaluates the impacts of emerging pipe cleaning technologies, AS and IP, relative to UF on energy use, carbon footprint, water consumption, and economic cost at the pipe, city, and regional scales (Supplementary Note 8). Our systematic analysis evaluates pipe cleaning strategy performance across diverse water supply networks by examining the interaction between network characteristics (pipe volume per capita, total length) and regional factors (water-energy intensity, electricity-related carbon emission factors, and water and electricity rates). By evaluating multidimensional environmental-economic trade-offs in pipe cleaning strategies, our framework incorporates technology selection, pipe diameter, device lifespan, and transition timelines to maximize cumulative benefits and provide operational optimization guidance. This approach provides a basis for designing comprehensive transition pathways to achieve sustainable urban water management.

Fig. 7

Pipe-level energy consumption, carbon footprint and water consumption of the three pipe cleaning technologies

The functional unit for this analysis is defined as the cleaning of one kilometer of pipe length or one cubic meter of pipe volume, allowing for a consistent comparison of the three pipe cleaning technologies across pipes of varying diameters. The LCA boundary for UF, AS, and IP is illustrated in Supplementary Figures 22-24. For each technology, the total volume of water consumed when cleaning one kilometer of pipe is defined as equation (1) to equation (4):

$$A=\frac{\pi}{4}\times\left(\frac{D}{1000}\right)^2 \tag{1}$$

$$a=\frac{\pi}{4}\times\left(\frac{d}{1000}\right)^2 \tag{2}$$

$$V_T= WDC_T\times A\times 1000 \tag{3}$$

$$V_{Tm}= \frac{V_T}{A\times 1000} \tag{4}$$

where D (mm) and A (m^2) are the diameter and the cross-sectional area of the pipe being cleaned, respectively; while d (mm) and a (m^2) are the diameter and the cross-sectional area of the downstream effluent discharge pipe used in AS, respectively; V_T represents the total volume of water consumption when cleaning per kilometer of pipe using the three technologies including UF, AS, and IP (m^3 km^{-1} pipe); WDC_T represents the water consumption coefficients obtained from practical engineering applications (the ratio of water consumed to the volume of pipe cleaned, dimensionless) for each technology, corresponding values for UF, AS, and IP are provided in Supplementary Table 3; V_{Tm} denotes the total volume of water consumed per cubic meter of pipe cleaned using the three technologies (m^3 m^{-3} pipe). The applicable range for UF, AS, and IP is 100-600 mm, 80-1200 mm, and 80-750 mm, respectively[20, 52, 53]. The overlapping applicable range for these three technologies is primarily concentrated between 100 mm and 600 mm. Based on a market survey of commonly used water supply pipe diameters, eight representative diameters are selected: 100 mm, 150 mm, 200 mm, 250 mm, 300 mm, 400 mm, 500 mm, and 600 mm.

Because pipe cleaning activities can lead to temporary water outages, residents may need to rely on bottled water to meet a portion of their daily needs. To account for this, we assume the use of 0.5-liter bottles to supply approximately 30% of daily water requirements during the cleaning period[54]. For pipelines ≤ 300 mm in diameter cleaned during daytime operations, all three technologies necessitate the provision of alternative water sources. For pipes > 300 mm in diameter (cleaned at night), no alternative supply is required for IP and AS. The volume of alternative water required has been calculated as equation (5) to equation (7):

$$T_{T\text{-}water}=\frac{V_T}{A\times v_{T\text{-}cleaning}\times 3600}+0.6 \tag{5}$$

$$V_{T\text{-}alternative}=A\times v_{daily}\times T_{T\text{-}water}\times 3600\times 0.3 \tag{6}$$

$$C_{T\text{-}bottled\ water}=\frac{V_{T\text{-}alternative}}{0.5}\times 1000 \tag{7}$$

where $T_{T\text{-}water}$ represents the duration of water outage resulting from cleaning one kilometer of pipe (h km^{-1} pipe), the additional 0.6 hours included in equation (5) accounts for preparation time before cleaning (e.g., opening water valves); $v_{T\text{-}cleaning}$ represents the fluid velocity during pipe cleaning process for UF, AS and IP (m s^{-1}); v_{daily} is the daily flow rate in the pipe being cleaned (m s^{-1}) (Supplementary Table 3). $V_{T\text{-}alternative}$ represents the volume of alternative water source (e.g., bottled water) required during the outage caused by cleaning one kilometer of pipe. This volume is calculated as 30% of the daily water consumption without cleaning (m^3 km^{-1} pipe). Across all scenarios, essential consumer water needs during outages are met through the supply of bottled water packaged in standard 0.5-liter plastic bottles[54]; $C_{T\text{-}bottled\ water}$ is the total number of bottles required to cover the outage associated with cleaning one kilometer of pipe (bottle km^{-1} pipe).

The energy consumption associated with preparation, the cleaning process, and post-cleaning wastewater treatment for three methods is calculated as equation (8) to equation (9):

$$E_T=V_T\times D_{water}+V_T\times D_{wastewater}+T_{T\text{-}device}\times P_{T\text{-}device} \tag{8}$$

$$E_{Tm}=\frac{E_T}{A\times1000} \tag{9}$$

where E_T is the total electricity consumption required to clean one kilometer of pipe (kWh km^{-1} pipe); D_{water} and $D_{wastewater}$ are the energy intensities of drinking water production and wastewater treatment (kWh m^{-3}), respectively; $T_{T\text{-}device}$ represents the duration of device operation per kilometer of pipe cleaned, this value is set to 0 h for UF and 24 h for IP, whereas for AS it corresponds to the time needed for the gas-liquid mixture to traverse the discharge pipe; $P_{T\text{-}device}$ is the power rating of device used in cleaning process (kW); E_{Tm} is the total electricity consumption per cubic meter of pipe cleaned (kWh m^{-3} pipe). The devices used in AS and IP are assumed to have a 15-year service life.

The carbon footprints associated with cleaning 1 km of pipe and 1 m^3 of pipe are calculated using SimaPro 9.4.0.1, following a LCA approach[55, 56]. Details of the goal and scope definition, inventory analysis, life cycle impact assessment, uncertainty assessment, and sensitivity analysis of LCA are provided in Supplementary Note 9. Life cycle inventories for wastewater treatment processes and alternative water supply are provided in Supplementary Table 4 and Supplementary Table 5.

City- and regional-level energy-carbon-water nexus of pipe cleaning

Water supply networks, spanning from urban to regional scales, consist of pipes with diverse diameters. Each pipe diameter is assigned an index (n) as follows: 100 mm (n=1), 150 mm (n=2), 200 mm (n=3), 250 mm (n=4), 300 mm (n=5), 400 mm (n=6), 500 mm (n=7) and 600 mm (n=8). The total length of a city- or regional-level water supply system is denoted as L_{pipe}. The distribution of pipe lengths by diameter (100 mm, 150 mm, 200 mm, 250 mm, 300 mm, 400 mm, 500 mm and 600 mm) is represented by the dimensionless fractions a_n (n=1, 2, 3…8), which satisfy the equation (10):

$$\sum_{n=1}^{8} a_n=1 \tag{10}$$

This study evaluates four scenarios, UF, AS, IP, and a combined AS+IP scenario. For the UF, AS, and IP scenarios, pipes with diameters of 100 to 300 mm are cleaned during the daytime, whereas pipes with diameters of 400, 500, and 600 mm are cleaned at night, due to the higher carbon footprint of daytime cleaning for large-diameter pipes. In the AS+IP scenario, IP technology is applied to 100-300 mm pipes during the day and to 400 mm pipes at night, while AS technology is used for 500-600 mm pipes at night.

The annual energy consumption, carbon footprint, water consumption, and economic cost of UF, AS, and IP scenarios in a specific city are calculated as equation (11) to equation (14):

$$WC=(\sum_{n=1}^{8} V_{T\text{-}n}\times a_n\times L_{pipe})/t \tag{11}$$

$$ENC=(\sum_{n=1}^{8} E_{T\text{-}n}\times a_n\times L_{pipe})/t \tag{12}$$

$$CF=(\sum_{n=1}^{8} C_{T\text{-}n}\times a_n\times L_{pipe})/t \tag{13}$$

$$\begin{aligned}ECC=[(\sum_{n=1}^{8} (V_{T\text{-}n}\times R_W+E_{T\text{-}n}\times R_E+S_n)\times L_{pipe}\\ +cost_{T\text{-}device}\times C_{T\text{-}device}+T_{T\text{-}device}\times e_{cp}]/t\end{aligned} \tag{14}$$

where *WC*, *ENC*, *CF* and *ECC* represent annual water consumption (m^3), energy consumption (kWh), carbon footprint (kg CO_2) and economic cost (USD) for pipe cleaning across the entire area, respectively; $V_{T\text{-}n}$, $E_{T\text{-}n}$, and $CF_{T\text{-}n}$ represent the water consumption (m^3 km^{-1} pipe), energy consumption (kWh km^{-1} pipe) and carbon footprint (kg CO_2 km^{-1} pipe) for the three technologies to clean each kilometer of pipe with a diameter represented by n, respectively (e.g., $V_{IP\text{-}1}$ represents the water consumption for IP to clean each kilometer of pipe with diameter of 100 mm); R_W represents the water rate (USD m^{-3}); R_E represents the electricity rate (USD kWh^{-1}); S_n represents the cost of sodium chloride using IP to clean each kilometer of pipe (USD km^{-1} pipe); $cost_{T\text{-}device}$ represents the economic cost per device used in the three technologies (USD $piece^{-1}$); $C_{T\text{-}device}$ represents the device quantity (piece); t represents the cleaning cycle of the pipes. In this study, t is set to 2.5 years, based on the regulations for pipe cleaning frequency across different regions and the estimated material accumulation return period[57, 58]. $T_{T\text{-}device}$ represents the cleaning duration for the three pipe cleaning technologies; e_{cp} denotes the labor cost, set at 40 USD per hour[58]. In the economic cost assessment, the procurement cost of cleaning equipment (e.g., air compressors, ice slurry generators) is treated as a one-time capital investment incurred only in the first year of technology deployment. The equipment is assumed to operate throughout its service life without requiring repeated purchases in subsequent years. The cost comparison is intended to evaluate whether the cost savings achieved by the emerging technology within a single year are sufficient to offset the one-time equipment procurement cost.

The annual water consumption, energy consumption, carbon footprint, and economic cost of AS+IP strategy in a specific city are calculated as equation (15) to equation (18):

$$WC=\left(\sum_{n=6}^{8} V_{AS\text{-}n}\times a_n+\sum_{n=1}^{5} V_{IP\text{-}n}\times a_n\right)\times L_{pipe}/t \tag{15}$$

$$ENC=\left(\sum_{n=6}^{8} E_{AS\text{-}n}\times a_n+\sum_{n=1}^{5} E_{IP\text{-}n}\times a_n\right)\times L_{pipe}/t \tag{16}$$

$$CF=\left(\sum_{n=6}^{8} CF_{AS\text{-}n}\times a_n+\sum_{n=1}^{5} CF_{IP\text{-}n}\times a_n\right)\times L_{pipe}/t \tag{17}$$

$$\begin{aligned} ECC=[&\sum_{n=6}^{8}(V_{AS\text{-}n}\times R_W+E_{AS\text{-}n}\times R_E+S_n)\times a_n\times L_{pipe}\\ &+\sum_{n=1}^{5}(V_{IP\text{-}n}\times R_W+E_{IP\text{-}n}\times R_E)\times a_n\times L_{pipe}\\ &+cost_{AS\text{-}device}\times C_{AS\text{-}device}+cost_{IP\text{-}device}\times C_{IP\text{-}device}+T_{T\text{-}device}\times e_{cp}]/t \end{aligned} \tag{18}$$

where $cost_{AS\text{-}device}$ and $cost_{IP\text{-}device}$ represent the economic cost per device used in AS and IP (USD piece^{-1}), respectively; while $C_{AS\text{-}device}$ and $C_{IP\text{-}device}$ denote the quantities of devices required in AS and IP (piece), respectively. Data processing and visualization for this study are conducted using OriginPro 2021 (OriginLab Corporation, USA) and QGIS 3.28 LTR (QGIS.ORG Association, Switzerland).

Transition scenarios

A 30-year transition period is assumed for shifting from the conventional UF strategy to AS, IP, or a synergistic combination of AS+IP. Each transition strategy is modeled beginning at either 100 mm or 600 mm pipe diameter, resulting in six distinct transition pathways: IP-100, AS-100, AS+IP-100, IP-600, AS-600, AS+IP-600. The IP-100 strategy entails using IP to gradually replace baseline UF in pipes with diameters ascending from 100 mm to 600 mm (100 mm, 150 mm, 200 mm, 250 mm, 300 mm, 400 mm, 500 mm, and 600 mm). Likewise, the AS-100 and AS+IP-100 strategies involve the sequential substitution of UF with AS and AS+IP, respectively, in pipes with diameters ranging from 100 mm to 600 mm. Conversely, the IP-600 strategy begins with the largest pipes, using IP to replace UF in a descending sequence: 600 mm, 500 mm, 400 mm, 300 mm, 250 mm, 200 mm, 150 mm, and 100 mm. In parallel, the AS-600 and AS+IP-600 strategies represent the corresponding downward replacement sequences using AS alone and the AS+IP combination. Across 50 cities and regions, we quantify the cumulative reductions in energy consumption, carbon footprint, water consumption, and economic cost for these different strategies relative to the baseline UF over the 30-year period. We also calculate the annual cumulative reduction multiples of energy consumption, carbon footprint, water consumption, and economic cost for each strategy compared with the baseline, enabling a comparative assessment of their long-term performance.

Data availability

The data supporting the findings of this study are available within the manuscript and its Supplementary Information files. Source data are provided in https://doi.org/10.6084/m9.figshare.30889418.

References

1. Rosario-Ortiz, F., Rose, J., Speight, V., Gunten, U. & Schnoor, J. How do you like your tap water? *Science* **351**, 912-914 (2016).
2. Wolf, J. et al. Burden of disease attributable to unsafe drinking water, sanitation, and hygiene in domestic settings: a global analysis for selected adverse health outcomes. *Lancet* **401**, 2060-2071 (2023).
3. Craun, G. F. et al. Causes of outbreaks associated with drinking water in the United States from 1971 to 2006. *Clin. Microbiol. Rev.* **23**, 507-528 (2010).
4. BluePlan Engineering & Actual Media. *The Canadian infrastructure report card 2019.* http://canadianinfrastructure.ca/downloads/canadian-infrastructure-report-card-2019.pdf

(2019).

5. Plat, B., Lambry, A., Lavit, P. & Touanne, D. *FP2E/BIPE Report (7th edition): Public water and wastewater services in France – Economic, social and environmental data.* https://www.eureau.org/documents/resources/publications/member-publications/5299-public-water-and-waste-water-services-in-france/file (2019).
6. Steven, L. & Barfuss, P. E. *Water main break rates in the USA and Canada: a comprehensive study.* https://ipexna.com/wp-content/uploads/2024/03/study-caen-ipex-water-main-break-rates-in-the-usa-and-canada.pdf (2023).
7. EurEau. *Europe's Water in Figures: An overview of the European drinking water and waste water sectors (2021 edition).* https://www.eureau.org/resources/publications/eureau-publications/5824-europe-s-water-in-figures-2021/file (2021).
8. ASCE. *2021 Infrastructure report card for America's infrastructure.* https://infrastructurereportcard.org/wp-content/uploads/2017/01/Drinking-Water-2021.pdf (2021).
9. Lamb, C., Copeland, C., Moncrieff, C., Missaire, L. & O'Halloran, F. *A wave of change: The role of companies in building a water-secure world.* https://www.cdp.net/en/research/global-reports/global-water-report-2020 (2020).
10. Pericault, Y., Viklander, M. & Hedstrom, A. Modelling the long-term sustainability impacts of coordination policies for urban infrastructure rehabilitation. *Water Res.* **236**, 119912 (2023).
11. Malm, A., Ljunggren, O., Bergstedt, O., Pettersson, T. J. R. & Morrison, G. M. Replacement predictions for drinking water networks through historical data. *Water Res.* **46**, 2149-2158 (2012).
12. Manero, A. et al. Benefits, costs and enabling conditions to achieve 'water for all' in rural and remote Australia. *Nat. Water* **2**, 31-40 (2024).
13. Liu, S., Gunawan, C., Barraud, N., Rice, S. A., Harry, E. J. & Amal, R. Understanding, monitoring, and controlling biofilm growth in drinking water distribution systems. *Environ.*

Sci. Technol. **50**, 8954-8976 (2016).

14. Health Canada. *Guidance on monitoring the biological stability of drinking water in distribution systems.* https://www.canada.ca/content/dam/hc-sc/documents/services/publications/healthy-living/guidance-monitoring-biological-stability-drinking-water-distribution-systems/guidance-monitoring-biological-stability-drinking-water-distribution-systems.pdf (2022).
15. American Water Works Association (AWWA). *M28 Rehabilitation of Water Mains (Third Edition).* https://docs.cpuc.ca.gov/PublishedDocs/SupDoc/A2301001/6737/520515872.pdf (2014).
16. American Water Works Association (AWWA). *Replacement and flushing of lead service lines.* http://dx.doi.org/10.12999/AWWA.C810.17 (2017).
17. Yang, L. Application of air-water pulse pipeline flushing technology in water supply pipeline flushing (in Chinese). *J. Eng. Technol. Res.* **7**, 29-33 (2022).
18. Alsadi, A. Evaluation of carbon footprint during the life-cycle of four different pipe materials. PhD Thesis, Louisiana Tech University, Ruston, LA, USA (2019).
19. Yuan, W., Chen, F. & Ding, J. Practical analysis of cleaning water supply pipeline using air and water flushing technology. *IOP Conf. Ser.: Earth Environ. Sci.* **983**, 012088 (2022).
20. Huang, Y. et al. Review of ice slurry pigging techniques for the water supply industry: engineering design and application. *ACS ES&T Eng.* **2**, 1144-1159 (2022).
21. Huang, Y. et al. Application of ice pigging in a drinking water distribution system: impacts on pipes and bulk water quality. *Engineering* **40**, 122-130 (2024).
22. Huang, Y. et al. Enhanced ice slurry with low oxidant consumption for ultrafast in-situ removal of micropollutants sheltered in sediments of water supply pipelines. *Water Res.* **276**, 123256 (2025).
23. Khalkhali, M., Dilkina, B. & Mo, W. W. The role of climate change and decentralization in urban water services: a dynamic energy-water nexus analysis. *Water Res.* **207**, 117830 (2021).

24. Liu, L. et al. The importance of system configuration for distributed direct potable water reuse. *Nat. Sustain.* **3**, 548-555 (2020).

25. Larsen, T. A., Hoffmann, S., Lüthi, C., Truffer, B. & Maurer, M. Emerging solutions to the water challenges of an urbanizing world. *Science* **352**, 928-933 (2016).

26. Sharif, M. N., Haider, H., Farahat, A., Hewage, K. & Sadiq, R. Water-energy nexus for water distribution systems: a literature review. *Environ. Rev.* **27**, 519-544 (2019).

27. Capodaglio, A. G. Energy use and decarbonisation of the water sector: a comprehensive review of issues, approaches, and technological options. *Environ. Technol. Rev.* **14**, 40-68 (2025).

28. Climate Smart Utility (IWA), Motivate Action, https://climatesmartwater.org/carbon-neutrality/motivate-action/ (2025).

29. Lim, J., Kim, M. & Kwak, R. Zinc–iodine redox reaction enables direct brine valorization with efficient high-water-recovery desalination. *Nat. Water* **2**, 475-484 (2024).

30. Ahmad, S., Jia, H., Chen, Z., Li, Q. & Xu, C. Water-energy nexus and energy efficiency: a systematic analysis of urban water systems. *Renew. Sustain. Energy Rev.* **134**, 110381 (2020).

31. Szinai, J. K. et al. Climate change and its influence on water systems increases the cost of electricity system decarbonization. *Nat. Commun.* **15**, 10050 (2024).

32. Lèbre, É. et al. The social and environmental complexities of extracting energy transition metals. *Nat. Commun.* **11**, 4823 (2020).

33. Guy, J., Shears, E. & Meckling, J. National models of climate governance among major emitters. *Nat. Clim. Change* **13**, 189-195 (2023).

34. Delevaux, J. M. S. et al. Social–ecological benefits of land–sea planning at multiple scales in Mesoamerica. *Nat. Sustain.* **7**, 545-557 (2024).

35. Pourcel, F., Smith, I. E. & Duchesne, S. Slug flow simulation, a way to improve air scouring of water mains? *Procedia Eng.* **186**, 601-608 (2017).

36. Simunič, U., Pipp, P., Dular, M. & Stopar, D. The limitations of hydrodynamic removal of

biofilms from the dead-ends in a model drinking water distribution system. *Water Res.* **178**, 115838 (2020).

37. Cherukumilli, K., Ray, I. & Pickering, A. J. Evaluating the hidden costs of drinking water treatment technologies. *Nat. Water* **1**, 319-327 (2023).

38. Lord, J. et al. Global potential for harvesting drinking water from air using solar energy. *Nature* **598**, 611-617 (2021).

39. He, C. et al. Future global urban water scarcity and potential solutions. *Nat. Commun.* **12**, 4667 (2021).

40. Iftekhar, S. M., Blackmore, L. & Fogarty, J. Non-residential demand for recycled water for outdoor use in a groundwater constrained environment. *Resour. Conserv. Recycl.* **164**, 105168 (2021).

41. UNICEF & WHO. *Progress on household drinking water, sanitation and hygiene 2000-2022: special focus on gender.* https://washdata.org/reports/jmp-2023-wash-households (2023).

42. Schwabe, K., Nemati, M., Amin, R., Tran, Q. & Jassby, D. Unintended consequences of water conservation on the use of treated municipal wastewater. *Nat. Sustain.* **3**, 628-635 (2020).

43. Lohrmann, A., Farfan, J., Caldera, U., Lohrmann, C. & Breyer, C. Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery. *Nat. Energy* **4**, 1040-1048 (2019).

44. Huang, D. et al. Water-energy nexus analysis in an urban water supply system based on a water evaluation and planning model. *J. Clean. Prod.* **403**(1), 136750 (2023).

45. Vreeburg, J. H. G. & Boxall, J. B. Discolouration in potable water distribution systems: a review. *Water Res.* **41**, 519-529 (2007).

46. Ontario Ministry of the Environment. *Conservation and Parks. Drinking water quality management standard (DWQMS) (Draft Version 3.0).* https://ero.ontario.ca/public/2025-04/DWQMS%203.0%20Draft_0.pdf (2025).

47. Drinking Water Inspectorate. *Long-term planning guidance for the quality of drinking water supplies.* https://dwi-production-files.s3.eu-west-2.amazonaws.com/wp-content/uploads/2022/09/15114509/Long-term-planning-guidance-for-drinking-water-quality_Sept-2022.pdf (2022).

48. Ofwat. *PR24 final determinations: Delivering outcomes for customers and the environment.* https://www.ofwat.gov.uk/wp-content/uploads/2024/12/7.-PR24-final-determinations-Delivering-outcomes-for-customers-and-the-environment-1.pdf?utm_source=chatgpt.com (2024).

49. Coliban Water. *Safe drinking water act annual report 2022-2023.* https://coliban.com.au/files/2023-11/Safe%20Drinking%20Water%20Act%20Annual%20Report%202022_23.pdf?utm_source=chatgpt.com (2023).

50. Metro Vancouver. *Drinking water management plan update.* https://metrovancouver.org/services/water/drinking-water-management-plan-update?utm_source=chatgpt.com (2026).

51. Government of Ontario. *Municipal asset management planning.* https://www.ontario.ca/page/municipal-asset-management-planning?utm_source=chatgpt.com (2019).

52. Vidlárová, P. J. & Heviánková, S. Comparison of modern drinking water network maintenance methods: evaluation of removed deposits in the form of total suspended solids (TSS). *Int. J. Environ. Res. Public Health* **18**, 4311 (2021).

53. Antoun, E. N., Dyksen, J. E. & Hiltebrand, D. J. Unidirectional flushing: a powerful tool. *J. AWWA* **91**, 62-72 (1999).

54. Sheefa, D. E., Handler, R. M. & Barkdoll, B. D. Eco-efficiency analysis of water distribution system flushing into a containment pond. *J. Environ. Manage.* **321**, 115987 (2022).

55. Tu, Q., Guo, J., Li N., Qi, J. & Xu, M. Mitigating grand challenges in life cycle inventory

modeling through the applications of large language models. *Environ. Sci. Technol.* **58**, 19595-19603 (2024).

56. Wang, H. et al. China's electric vehicle and climate ambitions jeopardized by surging critical material prices. *Nat. Commun.* **14**, 1246 (2023).
57. Sunny, I., Husband, P. S. & Boxall, J. B. Impact of hydraulic interventions on chronic and acute material loading and discolouration risk in drinking water distribution systems. *Water Res.* **169**, 115224 (2020).
58. Fann, S. et al. *Demonstration of ice pigging technology to remove biofilms in water distribution systems.* https://apps.dtic.mil/sti/tr/pdf/AD1070998.pdf (2019).

Acknowledgements

The research work was supported by National Natural Science Foundation of China (Nos. 72573020 S.W., 72103022 S.W., 52470017 F. D., 52293445 N.L.) and National Key Research and Development Program of China (2023YFF0614500 T.Z.).

Author Contributions Statement

S.W., Y.H., and F.D. designed the study, conducted the modeling and analyses, prepared the figures, and wrote the manuscript. Y.S. and T.Z. contributed to methodology development. S.S. and K.F. performed data analysis. N.L., B.F., and A.N. reviewed language and revised manuscript. S.W., Y.H., Y.S., T.Z., S.S., K.F., N.L., B. F., A.N., and F.D. provided supervision, read and approved the final manuscript.

Competing Interests Statement

The authors declare no competing interests.

Figure Legends (for main text figures)

Fig. 1 Schematic diagrams of water supply systems and pipe cleaning applications throughout their lifecycle. **a** Scope of pipe cleaning implementation. **b** Pipe cleaning throughout the lifecycle of a water supply pipe.

Fig. 2 The mechanism of three common pipe cleaning technologies. **a** The mechanism of unidirectional flushing. **b** The mechanism of air scouring. **c** The mechanism of ice pigging. Ice pigs are formed when ice slurry is pumped into a pipe and propelled downstream by upstream water pressure, generating high shear stress to effectively remove sediments, scales and biofilms from the pipe wall[20, 21, 22].

Fig. 3 Pipe-level energy consumption, water consumption, and carbon footprints for cleaning 1 m^3 of pipe using unidirectional flushing (UF), air scouring (AS), and ice pigging (IP). **a** Energy consumption for cleaning 1 m^3 of pipe using UF, AS, and IP. **b** Water consumption for cleaning 1 m^3 of pipe using UF, AS, and IP. **c** Carbon footprint for cleaning 1 m^3 of pipe using UF, AS, and IP during the daytime. **d** Carbon footprint for cleaning 1 m^3 of pipe using UF, AS, and IP at night. Error bars represent the 95% confidence interval (CI).

Fig. 4 Annual water consumption (WC), energy consumption (ENC), carbon footprint (CF), and first-year economic cost (ECC) of unidirectional flushing (UF), air scouring (AS), ice pigging (IP), and AS+IP strategies in 10 global cities and regions. AS+IP indicates a combined strategy, in which pipes with diameters of 100-400 mm are cleaned using IP, while pipes with diameters of 500-600 mm are cleaned using AS. For all strategies, pipes with diameters of 100-300 mm are cleaned during daytime, whereas those with diameters of 400-600 mm are cleaned at night. Error bars represent the 95% confidence interval (CI).

Fig. 5 Distributions of key parameters and their effects on energy consumption, carbon footprint, water consumption, and economic cost of unidirectional flushing (UF), air scouring (AS), ice pigging (IP), and AS+IP strategies in water supply systems. **a-d** The distribution of total pipe length, pipe volume per capita (PVPC), water rate and electricity rate in 50 cities and regions. Box plots show the distribution of the data, with the center line representing the median, the upper and lower edges of the box representing the 75th and 25th percentiles, respectively, and the whiskers extending to 1.5× the interquartile range. Individual points beyond the whiskers are shown as outliers. The mean value is indicated by a square inside the box. **e** Effect of PVPC and water-energy intensity on the energy consumption of pipe cleaning. **f** Effect of PVPC and electricity-related carbon emission factor on the carbon footprint of pipe cleaning. **g** Effect of PVPC and alternative water demand index on the carbon footprint of pipe cleaning. **h** Effect of PVPC and water consumption coefficient on the water consumption of pipe cleaning. **i-l** Effect of water rate on the first-year economic cost of pipe cleaning. AS+IP indicates a combined strategy, in which pipes with diameters of 100-400 mm are cleaned using IP, while pipes with diameters of 500-600 mm are cleaned using AS. For all strategies, pipes with diameters of 100-300 mm are cleaned during daytime, whereas those with diameters of 400-600 mm are cleaned at night.

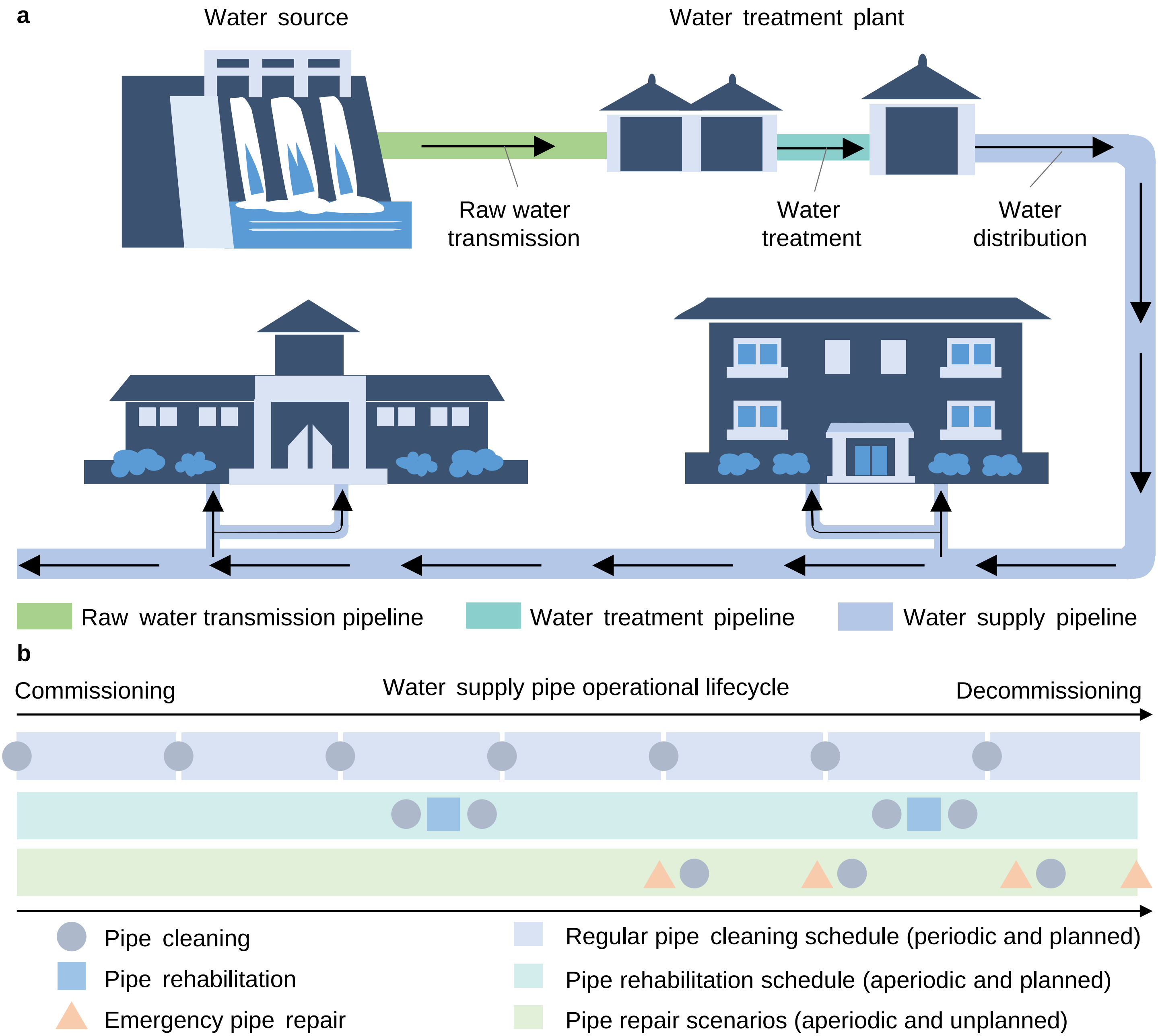
Fig. 6 Projected water and energy savings, carbon footprint reduction, and economic benefits from pipe cleaning strategy transitions. **a** Projected savings in water consumption (WC), energy consumption (ENC), carbon footprint (CF), and economic cost (ECC) from AS-100, IP-100, AS+IP-100, AS-600, IP-600, and AS+IP-600 strategies relative to baseline UF over a 30-year transition period in ten cities and regions. **b-e** Cumulative WC-saving ratio, ENC-saving ratio, CF-saving ratio, and ECC-saving ratio for AS-100, IP-100, AS+IP-100, AS-600, IP-600, and AS+IP-600 compared with baseline UF across 50 cities and regions. AS-100, IP-100, and AS+IP-100 indicate transitions from traditional unidirectional flushing (UF) to air scouring (AS), ice pigging (IP), and combined AS+IP strategies, respectively, starting from 100 mm pipes, while AS-600, IP-600, and AS+IP-600 indicate the corresponding transitions starting from 600 mm pipes. Cumulative WC-saving ratio, ENC-saving ratio, CF-saving ratio, and ECC-saving ratio are obtained by summing annual WC, ENC, CF, and ECC savings and normalizing them to the baseline UF values, respectively. Error bars represent the 95% confidence interval (CI).

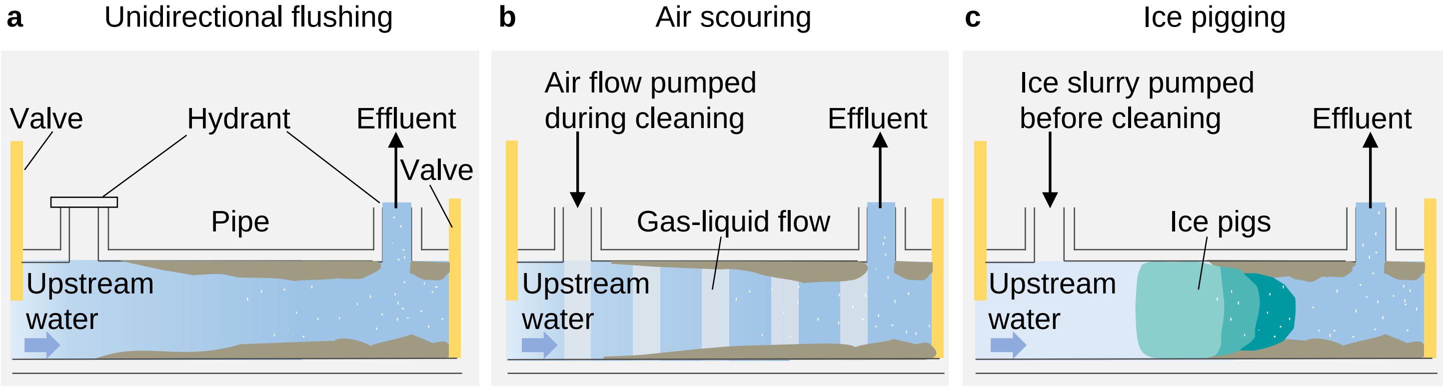
Fig. 7 Technical flowchart of the multi-level pipe cleaning energy-carbon-water nexus optimization framework. Water-energy intensity refers to the energy intensity of drinking water supply and wastewater treatment processes.

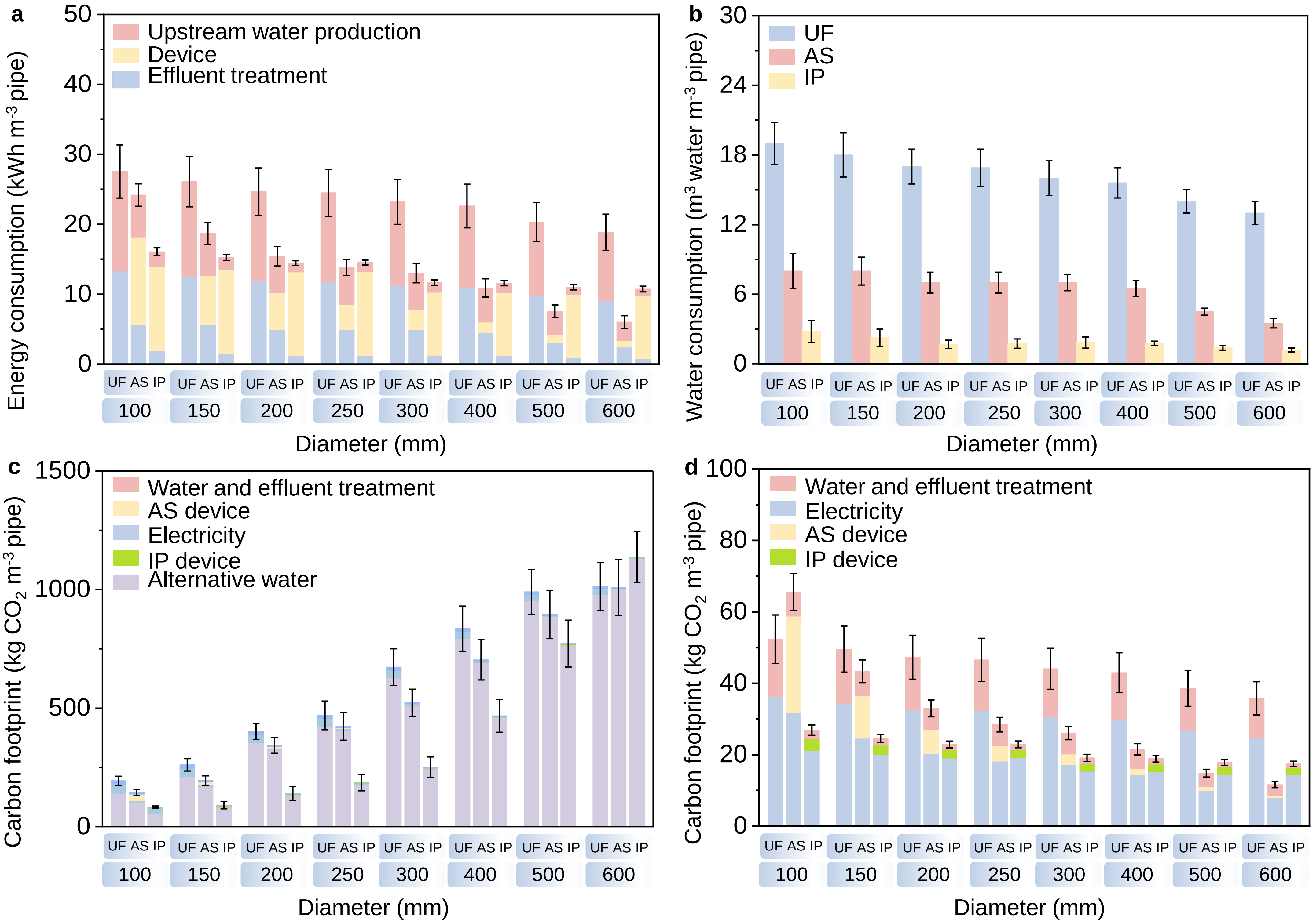
Editorial Summary:

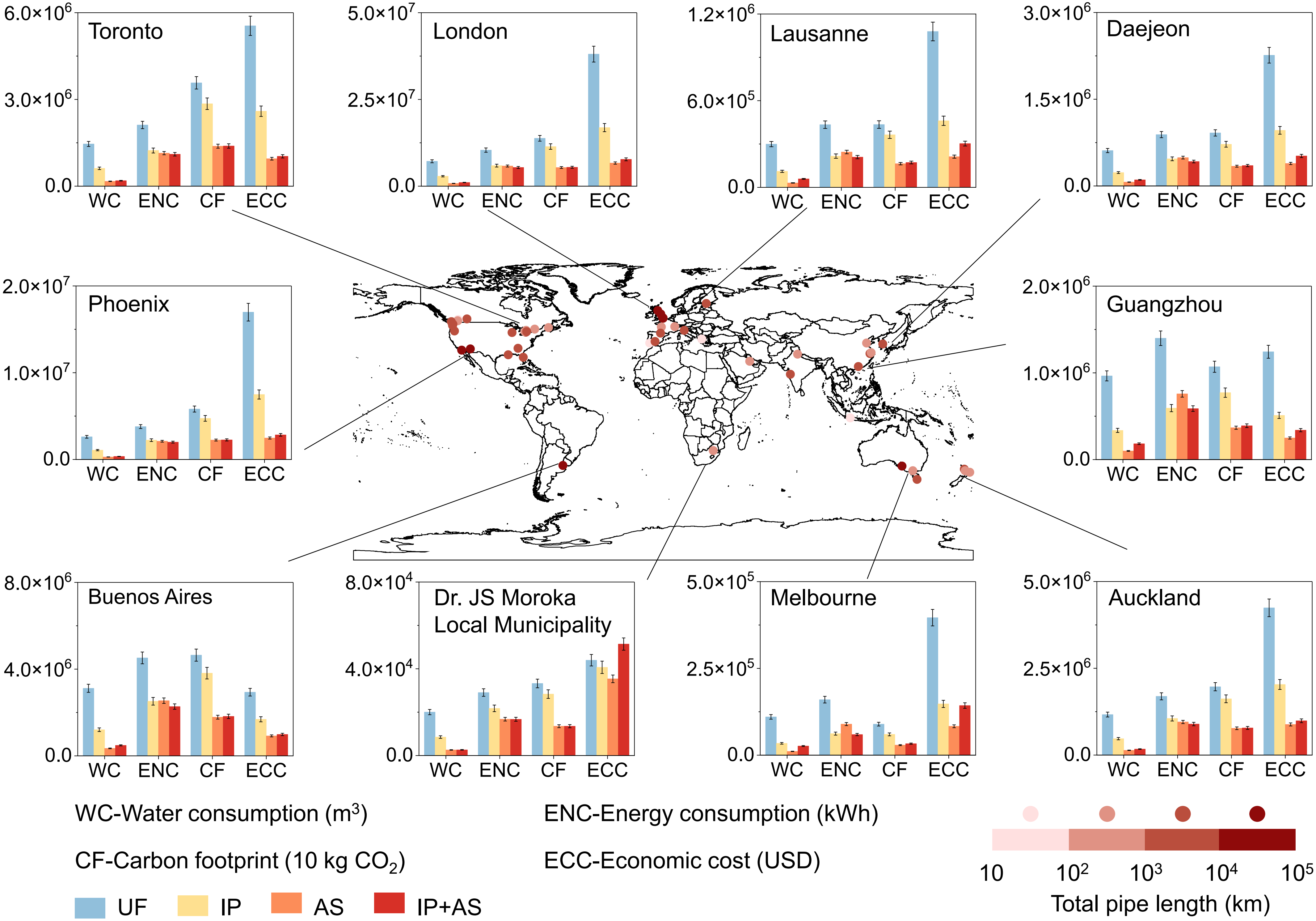
Emerging pipe cleaning technologies in water supply system unlock energy-carbon-water synergies across pipe, city, and regional scales by reducing energy use, carbon emissions, water consumption, and costs relative to unidirectional flushing.

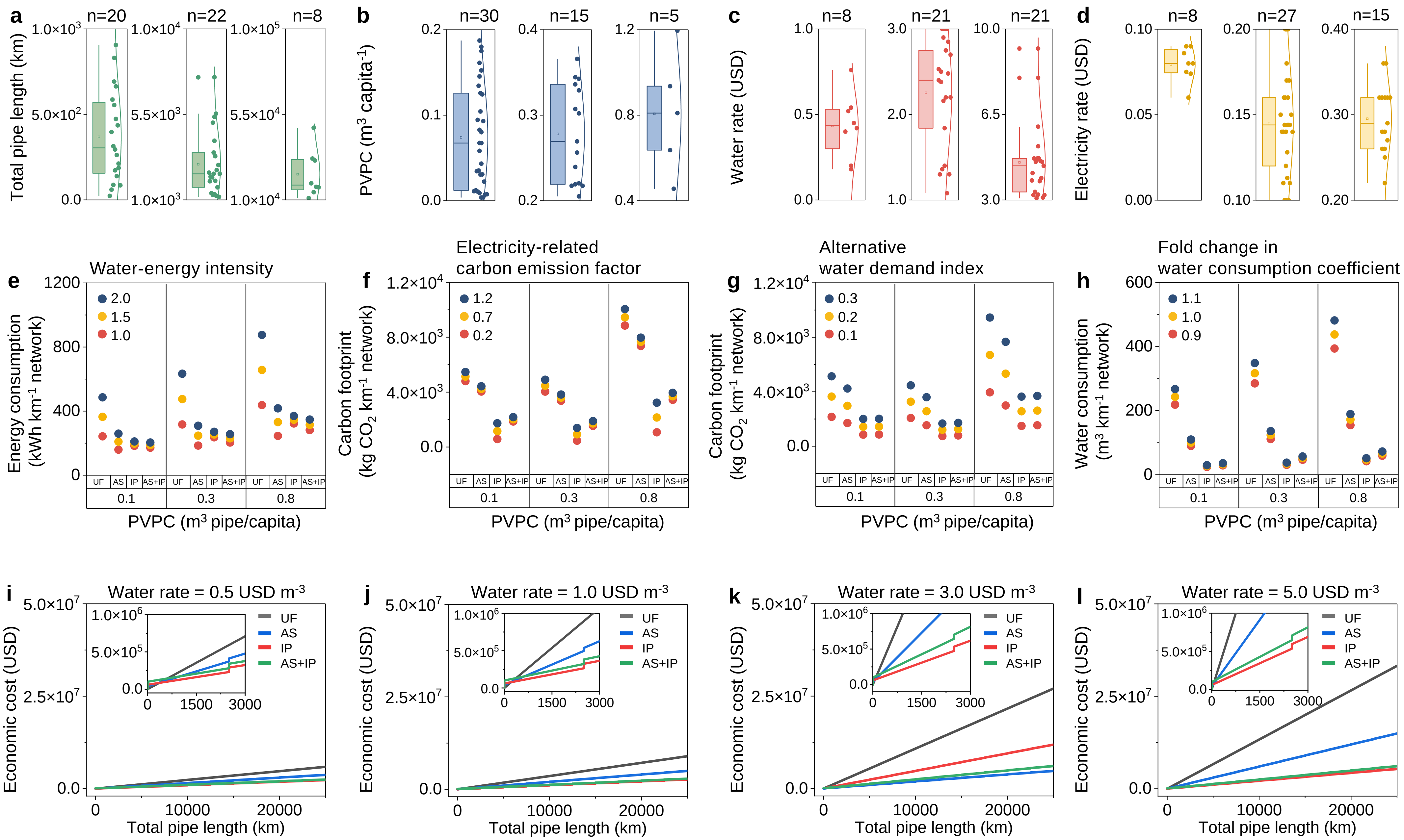
Peer Review Information: *Nature Communications* thanks Love Opeyemi David and the other anonymous, reviewer(s) for their contribution to the peer review of this work. A peer review file is available."

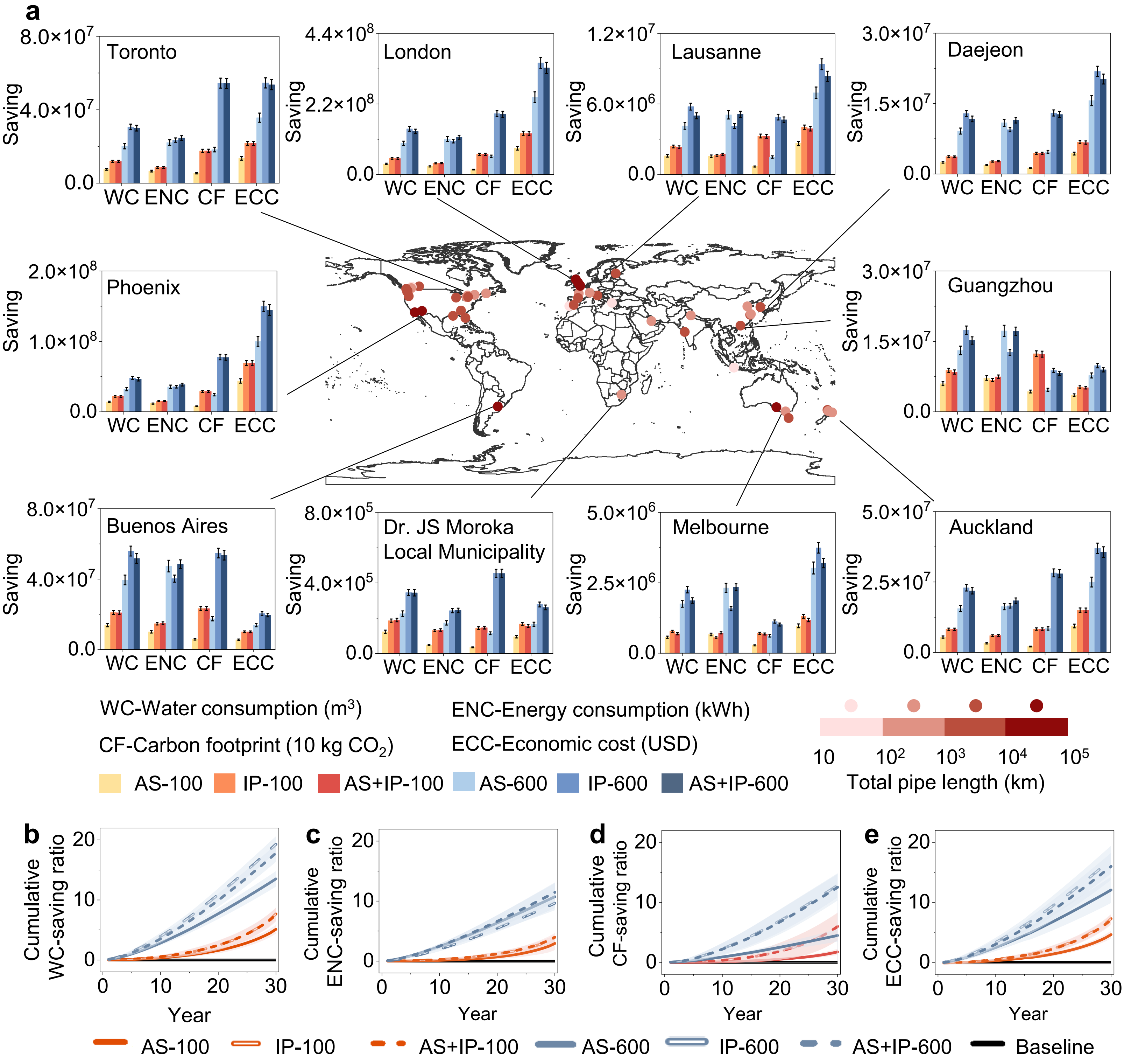

a
Water source
Water treatment plant
Raw water transmission
Water treatment
Water distribution
Raw water transmission pipeline
Water treatment pipeline
Water supply pipeline
b
Commissioning
Water supply pipe operational lifecycle
Decommissioning
Pipe cleaning
Pipe rehabilitation
Emergency pipe repair
Regular pipe cleaning schedule (periodic and planned)
Pipe rehabilitation schedule (aperiodic and planned)
Pipe repair scenarios (aperiodic and unplanned)

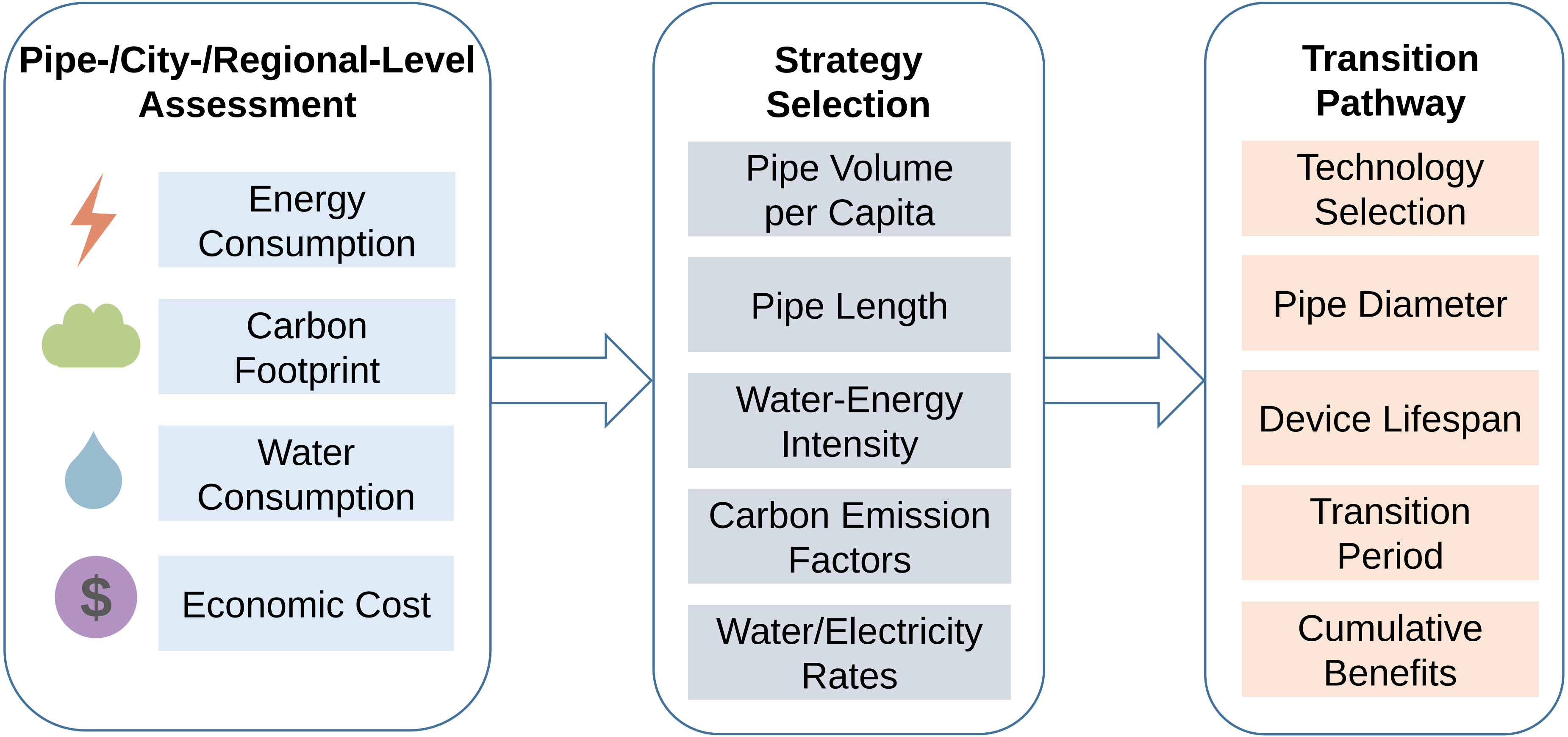

a
Unidirectional flushing
Valve
Hydrant
Effluent
Valve
Pipe
Upstream water
b
Air scouring
Air flow pumped during cleaning
Effluent
Gas-liquid flow
Upstream water
c
Ice pigging
Ice slurry pumped before cleaning
Effluent
Ice pigs
Upstream water


a
Energy consumption (kWh m^{-3} pipe)
0
10
20
30
40
50
Upstream water production
Device
Effluent treatment
UF AS IP
100
150
200
250
300
400
500
600
Diameter (mm)
b
Water consumption (m^3 water m^{-3} pipe)
0
6
12
18
24
30
UF
AS
IP
UF AS IP
100
150
200
250
300
400
500
600
Diameter (mm)
c
Carbon footprint (kg CO$_2$ m^{-3} pipe)
0
500
1000
1500
Water and effluent treatment
AS device
Electricity
IP device
Alternative water
UF AS IP
100
150
200
250
300
400
500
600
Diameter (mm)
d
Carbon footprint (kg CO$_2$ m^{-3} pipe)
0
20
40
60
80
100
Water and effluent treatment
Electricity
AS device
IP device
UF AS IP
100
150
200
250
300
400
500
600
Diameter (mm)


Toronto
6.0×10^6
3.0×10^6
0.0
London
5.0×10^7
2.5×10^7
0.0
Lausanne
1.2×10^6
6.0×10^5
0.0
Daejeon
3.0×10^6
1.5×10^6
0.0
Phoenix
2.0×10^7
1.0×10^7
0.0
Guangzhou
2.0×10^6
1.0×10^6
0.0
Buenos Aires
8.0×10^6
4.0×10^6
0.0
Dr. JS Moroka Local Municipality
8.0×10^4
4.0×10^4
0.0
Melbourne
5.0×10^5
2.5×10^5
0.0
Auckland
5.0×10^6
2.5×10^6
0.0
WC
ENC
CF
ECC
WC-Water consumption (m³)
ENC-Energy consumption (kWh)
CF-Carbon footprint (10 kg CO₂)
ECC-Economic cost (USD)
UF
IP
AS
IP+AS
10
10²
10³
10⁴
10⁵
Total pipe length (km)


a
n=20
n=22
n=8
Total pipe length (km)
1.0×10^3
5.0×10^2
0.0
1.0×10^4
5.5×10^3
1.0×10^3
1.0×10^5
5.5×10^4
1.0×10^4
b
n=30
n=15
n=5
PVPC (m³ capita⁻¹)
0.2
0.1
0.0
0.4
0.3
0.2
1.2
0.8
0.4
c
n=8
n=21
n=21
Water rate (USD)
1.0
0.5
0.0
3.0
2.0
1.0
10.0
6.5
3.0
d
n=8
n=27
n=15
Electricity rate (USD)
0.10
0.05
0.00
0.20
0.15
0.10
0.40
0.30
0.20
e
Water-energy intensity
2.0
1.5
1.0
Energy consumption (kWh km⁻¹ network)
1200
800
400
0
UF
AS
IP
AS+IP
0.1
0.3
0.8
PVPC (m³ pipe/capita)
f
Electricity-related carbon emission factor
1.2
0.7
0.2
Carbon footprint (kg CO₂ km⁻¹ network)
1.2×10^4
8.0×10^3
4.0×10^3
0.0
UF
AS
IP
AS+IP
0.1
0.3
0.8
PVPC (m³ pipe/capita)
g
Alternative water demand index
0.3
0.2
0.1
Carbon footprint (kg CO₂ km⁻¹ network)
1.2×10^4
8.0×10^3
4.0×10^3
0.0
UF
AS
IP
AS+IP
0.1
0.3
0.8
PVPC (m³ pipe/capita)
h
Fold change in water consumption coefficient
1.1
1.0
0.9
Water consumption (m³ km⁻¹ network)
600
400
200
0
UF
AS
IP
AS+IP
0.1
0.3
0.8
PVPC (m³ pipe/capita)
i
Water rate = 0.5 USD m⁻³
Economic cost (USD)
5.0×10^7
2.5×10^7
0.0
1.0×10^6
5.0×10^5
0.0
0
1500
3000
UF
AS
IP
AS+IP
0
10000
20000
Total pipe length (km)
j
Water rate = 1.0 USD m⁻³
Economic cost (USD)
5.0×10^7
2.5×10^7
0.0
1.0×10^6
5.0×10^5
0.0
0
1500
3000
UF
AS
IP
AS+IP
0
10000
20000
Total pipe length (km)
k
Water rate = 3.0 USD m⁻³
Economic cost (USD)
5.0×10^7
2.5×10^7
0.0
1.0×10^6
5.0×10^5
0.0
0
1500
3000
UF
AS
IP
AS+IP
0
10000
20000
Total pipe length (km)
l
Water rate = 5.0 USD m⁻³
Economic cost (USD)
5.0×10^7
2.5×10^7
0.0
1.0×10^6
5.0×10^5
0.0
0
1500
3000
UF
AS
IP
AS+IP
0
10000
20000
Total pipe length (km)


a
Toronto
London
Lausanne
Daejeon
Phoenix
Guangzhou
Buenos Aires
Dr. JS Moroka Local Municipality
Melbourne
Auckland
Saving
WC ENC CF ECC
8.0×10^7
4.0×10^7
0.0
4.4×10^8
2.2×10^8
1.2×10^7
6.0×10^6
3.0×10^7
1.5×10^7
2.0×10^8
1.0×10^8
8.0×10^5
4.0×10^5
5.0×10^6
2.5×10^6
5.0×10^7
2.5×10^7
WC-Water consumption (m3)
ENC-Energy consumption (kWh)
CF-Carbon footprint (10 kg CO2)
ECC-Economic cost (USD)
AS-100
IP-100
AS+IP-100
AS-600
IP-600
AS+IP-600
10
10^2
10^3
10^4
10^5
Total pipe length (km)
b
c
d
e
Cumulative WC-saving ratio
Cumulative ENC-saving ratio
Cumulative CF-saving ratio
Cumulative ECC-saving ratio
0
10
20
30
Year
AS-100
IP-100
AS+IP-100
AS-600
IP-600
AS+IP-600
Baseline


Pipe-/City-/Regional-Level Assessment
Energy Consumption
Carbon Footprint
Water Consumption
$
Economic Cost
Strategy Selection
Pipe Volume per Capita
Pipe Length
Water-Energy Intensity
Carbon Emission Factors
Water/Electricity Rates
Transition Pathway
Technology Selection
Pipe Diameter
Device Lifespan
Transition Period
Cumulative Benefits