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Water Infrastructures at Crossroads of Adaptive Futures

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Amid a perfect storm of climate emergency, runaway urban growth and crumbling pipes, it's clear that our traditional engineering-based, technical approach to water infrastructure planning requires improvements. It is time to replace the outdated approach driven by unreliable long-term forecasts and adopt a smarter, adaptive framework that includes socio-economic considerations to build sustainable cities our communities deserve.

Engineers have spent decades studying water systems – from repairing leaky pipes in London, to modelling Cape Town's "Day Zero", to battling lead contamination in Flint – and one conclusion is undeniable: our water systems are fundamentally unprepared for deepening uncertainty! These sprawling pipe networks, stretching thousands of kilometres under our feet, are not just invisible – they are ageing (over half of the pipes in metropolitan London are from the Victorian era). These networks are struggling under climate shocks, involving more frequent and more severe droughts and floods, with cities like those in the United Arab Emirates having even explored desperate measures, such as towing icebergs from Antarctica to address droughts and water shortages[1]. Furthermore, our inability to account for the complex interplay between technology, society and human behaviour makes planning and management of these complex systems a 'wicked' problem[2].

As water distribution systems struggle under those challenging conditions, their ability to deliver enough water of good quality to the urban population diminishes over time, leading to service problems such as leakage, pressure drops and deterioration of water quality. Planning what to do to maintain or improve water service to users in the short and long term is a monumental challenge.

Technical Approach to Traditional Master Planning

Planning for these systems has traditionally been approached through 'master planning' (Figure 1). A master plan is normally developed by an engineering team to improve a water distribution system over the long term, e.g., 25 to 50 years. It involves decisions about where to add or replace pipes, pumps and reservoirs, depending strongly on future demand forecasting[3]. There are several issues with this traditional approach to master planning, but the key problem is that we are shockingly bad at predicting the long-term future! Just think of Albert Einstein famously remarking in 1934 that "there is not the slightest indication that nuclear energy will ever be obtainable" or about the Time magazine prediction in a 1996 article that a permanent lunar base would be established long before the year 2000 and that humans would have already flown past Venus and landed on Mars!

Forecasting water demand decades in advance is extremely challenging due to various uncertain factors, including population growth and urbanisation. Who would've imagined only 40 years ago a 60-fold increase in population size and a 15-fold increase in built-up areas in Shenzhen, China?[4] Even a long-established metropolis, like New York, which is squeezed onto three islands with little room to grow, expanded its population between 2006 and 2019 by 10%. Although a decline seemed impossible, COVID-19 reversed the decades of growth and proved even the most resilient cities aren't immune to unexpected changes. These examples also illustrate the importance of adaptive planning, an approach that lets us adjust decisions when changes occur, such as a sudden shift from rapid growth to a decline in demand. But how do we prepare for shocks we can't even imagine?

The Challenge for Sustainable Water Distribution Systems

With budgets always tight, we've traditionally waited too long to replace water pipes, often until they burst or can't meet demand or when other street work is being done and the opportunity is taken to renew water pipes. This is like ignoring potholes until the road collapses before fixing them. This reactive approach is obviously short-sighted. It relies on rigid forecasts that assume we can accurately predict demand, yet they often fail to capture real-world surprises such as sudden population booms or unexpected droughts. Although research has proposed improvements, such as optimizing which pipes to replace and when[5] and incorporating uncertainties about future demand[6] ensuring the long-term sustainability of urban water systems remains a formidable challenge.

Key issues for sustainable urban water planning:

- **Anticipating the Future** - Instead of relying on a single scenario, we must plan for diverse future scenarios, including droughts, floods, and demand spikes (or drops). For example, Cape Town's "Zero Day" crisis revealed the danger of single-track planning when reservoirs nearly ran dry.
- **Taking Long-Term Perspectives** - Infrastructure can last 100+ years, yet many plans stop at 20-30 years. Singapore's NEWater programme, launched in 2003, anticipated future climate risks by investing in recycled water decades before it was needed.
- **Ensuring Decision Robustness** - Systems need to handle short-term shocks. Think of a water network capable of meeting soaring demand on an extremely hot day without faltering.
- **Including Broader Objectives** - It's not just about cost! For example, resilience (resisting crisis and bouncing back from it) matters as much as cost. Plans should ensure that systems can bounce back quickly, not just optimise for normal operating conditions.
- **Building Policy Flexibility** - Instead of rebuilding entire systems, we can add flexible infrastructure to boost existing networks. Take Amsterdam's modular stormwater storage under parks and parking lots; it activates as rainfall intensifies to prevent flooding of the streets, providing flexible flood control.
- **Engaging Diverse Experts and Stakeholders** - Top-down planning often misses vital social values and the realities of political and governance pressures. Involving local communities, engineers, and policymakers can lead to more adaptive and robust solutions.
- **Developing Strategic Visions** - Long-term renewal strategies are essential. For instance, while realistic pipe renewal is projected to be around 150 years in Japan, some estimates in the UK extend to millennia ("Water companies in England 'will take 2,000 years to replace pipe network', highlighting the need for strategic, forward-thinking planning", Guardian, 2022)!

Transitioning to Sustainable Water Distribution Systems

Just like the world is moving away from fossil fuels to fight climate change, our water systems need a major transition from the "fix-it-when-it-fails" approach to truly sustainable solutions. With cities changing fast and the climate emergency becoming a reality, we can't rely on patchwork fixes anymore. The last 20+ years of rapid global changes have taught us one hard lesson: essential infrastructure, e.g., energy and water systems, must evolve sustainably.

Water Futures for Navigating Deep Uncertainty

At the Water Futures project (https://waterfutures.eu/), we recognise that our water systems are at a crossroads (Figure 1). While new Internet-of-Things (IoT) sensors, AI and advanced models promise to transform water management[7], most cities remain trapped in a cycle of crisis response rather than prevention. Planning water infrastructure for an uncertain future is like plotting a journey using a public transport map (e.g., the London Underground or New York Subway), but stretched over decades. Each line represents a design pathway for our water system. Just as commuters face unpredictable disruptions (delays and closures), we must build systems that pivot seamlessly when droughts strike, demand surges, or policies shift.

The Art of Adaptive Design

Modular treatment plants, adaptive pricing, diversified water sources (e.g., desalination, rainwater harvesting, reuse), and differently sized pipes act like "alternative routes" on our map. The goal isn't to predict the future, as we're notoriously bad at that, but to create a network of viable pathways, each triggered by clear signals (like a transport app warning of delays). And just as public transport must balance speed, cost and accessibility, water solutions must reconcile competing needs: farmers vs. cities, today's costs vs. tomorrow's risks. The result? A system where no surprise leaves us stranded, and every adaptation keeps the network flowing sustainably.

Scenarios for Stress-Testing Our Map

A transport map with few lines leaves travellers stranded when disruptions hit. Similarly, water infrastructure needs a "scenario library" of plausible futures, such as droughts, floods and population booms, to stress-test designs[8]. Here's where AI steps in: tools like ChatGPT and DeepSeek help generate rich, realistic scenarios when prompted with examples, ensuring our roadmap bends but doesn't break. The more scenarios we explore, the more resilient our systems become. Flexibility isn't just convenient, it's the difference between gridlock and flow.

The Human Factor

To avoid tunnel vision, we blend tech with real human behaviour. By revisiting the mathematical foundations of decision theory under conditions of uncertainty and ambiguity,[9,10] and testing new axioms through behavioural experiments, we've uncovered key insights, such as preferences are time-varying and experience-specific; stakeholders often prioritize healthcare or education over flood prevention or improved water supply, unless they've recently experienced a disaster. Memory fades, but risks don't. That's why our "Living Labs" engage communities early in the process. We ensure that solutions align with people's informed preferences, budget constraints, willingness to pay, and core values. We design economic and social instruments tailored to local characteristics, nudging decisions toward sustainable urban water systems that reduce short, medium and long-term risks for users. After all, infrastructure isn't just about pipes and pumps, it's for people.

AI as the Ultimate Commuter

Modern water systems, armed with IoT sensor networks tracking flow and quality in real time[11], need AI that acts like a seasoned Underground traveller: agile, adaptive and intuitive. Today's AI often drowns in data, missing critical signals. Enter physics-informed graph neural networks as the "spatial map" for water[12]. These models map pipes like Tube stations, embedding hydraulic laws to predict flow, pressure or contamination risks. Yet, like Transport for London's duty to ensure fairness, the EU's AI Act demands these systems stay cyber-resilient (no hacked signals), equitable (no favouring wealthy neighbourhoods), and accountable (humans keep final control).

Water management is a high-stakes journey through uncertainty. By designing infrastructure like a transport map, i.e., with flexible pathways, scenario testing and AI that "reroutes" dynamically, we can improve resilience of our systems[13]. But success hinges on blending tech with human behaviour, ensuring solutions are not just smart, but socially rooted. The destination? A world where water systems adapt as effortlessly as a commuter dodging delays, keeping every community flowing sustainably.

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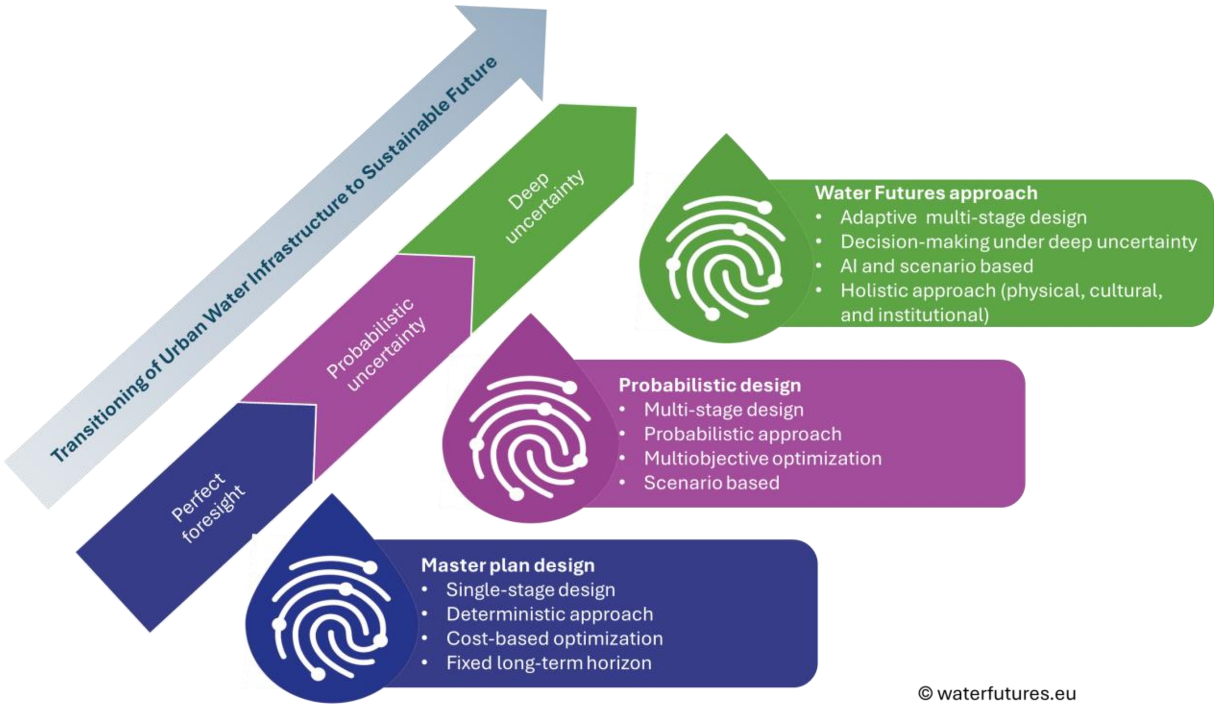

Figure 1. Transitioning of Urban Water Infrastructure to Sustainable Future – Water Futures Approach