White paper on

Mainstreaming Decentralized Urban Water Management Solutions for Sustainable Cities

BlueTech RESEARCH | Berkeley UNIVERSITY OF CALIFORNIA | eawag aquatic research

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Executive Summary

Climate change, rapid urbanization and other grand challenges increasingly force cities to rethink their urban (water) infrastructure. In particular, decentralized urban water management solutions, which can recover valuable resources close to the source are increasingly applied to remediate water scarcity, sanitation or environmental pollution challenges. Yet, although interesting demonstration projects with decentralized solutions (from here on labeled 'decentralized UWM solutions') are underway in several world regions, actors developing and implementing this transformative innovation are not effectively coordinating their efforts and sharing the latest knowledge. While effective technologies, business models, or regulative frameworks increasingly exist that could inform, inspire and improve similar activities elsewhere, details of local successes and failures are still (too) rarely shared or transferred across space. Drawing from experience on the mainstreaming of other transformative infrastructure solutions (like renewable energies, electric mobility or circular waste management), we posit that the global diffusion of decentralized UWM solutions has been significantly slowed down by this lack of interaction among key stakeholders, and the resulting lack of an effective innovation ecosystem.

Against this backdrop, Eawag, UC Berkeley, and BlueTech Research organized an international roadmapping workshop in Zurich on June 12-14, 2023, aimed at creating a platform for exchange among leading firms, cities, regulators, researchers, funders and NGOs working on innovative decentralized UWM solutions. The workshop employed a structured roadmapping exercise on how different decentralized UWM solutions could scale-up and mainstream in the next 10-30 years. This document summarizes the motivation and rationale for organizing this event and presents key outcomes of the discussion at the workshop. The report first provides background information on the global state of the art and systematizes the different types of decentralized UWM solutions that are currently emerging globally. It then outlines pathways for mainstreaming three types of solutions discussed in-depth at the workshop: Building-scale non-potable water systems, district-scale resource recovery systems, and decentralized nutrient management systems.

Participants concluded that these three solutions are likely to diffuse in distinct mainstreaming trajectories determined by different key drivers, technologies, as well as institutional frameworks enabling or hindering effective resource reuse. At the same time, common challenges exist, including limited potential for realizing economies of scale, immature industry structures, insufficient coordination among key stakeholders, lack of supporting policies and regulative frameworks, as well as persistent lock-ins to long-established ways of doing things in utilities, governments and incumbent firms. The report systematizes these commonalities and differences and explores ways in which synergies between the different roadmaps could be leveraged. It then outlines concrete actions to be taken in the short- to mid-term future to turn the three solutions into mature options ready for use by utilities, urban planners, funders and policy makers in their quest to develop circular and sustainable cities.

Acknowledgements
The main authors would like to thank Eawag and the Swiss National Science Foundation for providing funding for this event. We gratefully acknowledge the outstanding contributions of Sarina Wellauer, the workshop moderators, note takers and the full workshop planning team, as well as our speakers, for illuminating the challenges and opportunities around mainstreaming different decentralized UWM solutions. We greatly appreciate the enthusiasm and engagement of all participants, whose thoughtful involvement made the workshop a great success and yielded the insights presented in this report. All remaining omissions and mistakes are the sole responsibility of the main author team.

Contens

Decentralized UWM solutions – Key definitions & the global picture

Decentralized UWM solutions come in many different shapes and forms and are often described with conflicting terminologies. As such, it is imperative to define upfront what we consider as 'decentralized UWM solutions'. Three key clarifications are of importance:

1) **Decentralized:** This term was chosen to encompass solutions that manage (waste)water close to the source in systems that span from single household appliances to building-, premise-, precinct- or district- scales, thus encompassing a broad set of solutions ranging from 'on-site', to 'modular' or 'distributed' system designs. The focus lies on solutions that diverge from expansive pipe-based infrastructures in technical and organizational terms. At the same time, we acknowledge that many decentralized solutions still depend on centralized water supplies or sewer systems to some degree in 'hybrid' configurations.

2) **Urban water management:** This term here represents a broad view on the management of water flows within a city, including drinking water, waste-water, grey-, yellow- and blackwater, rain/stormwater, groundwater, surface water, etc. and the full value/service chain from freshwater provision over rain/stormwater management to the release of treated water back into the environment. It thus encompasses an integrated view on water supply, sanitation and drainage issues in urban contexts.

3) **Solutions:** A third key specification is that decentralized solutions do not only solve urban hygiene, drainage and/or environmental pollution problems, but in addition enable the efficient recovery and reuse of valuable resources (water, nutrients, energy).

This definition was chosen to pitch the discussion toward advanced decentralized UWM solutions' potential contributions to creating next generation urban infrastructure systems that are able to address wicked sustainability challenges. First, by circulating water in closed loops, decentralized solutions can create a climate resilient water source for households, buildings and neighborhoods, which can be put into use relatively flexibly and quickly. Second, they combine reducing environmental pollution (e.g. caused by combined sewer overflows of lacking treatment capacity in centralized plants) with turning 'waste' flows into valuable resource streams. For example, the heat in wastewater can be reused locally for heating purposes and recovered nutrients can provide a substitute for fossil fuel-based fertilizers in local agriculture. Third, decentralized solutions can create manifold environmental and social co-benefits, especially if water, energy and nutrients are reused locally and/or in combination with blue-green infrastructures that contribute to enhancing biodiversity, cooling, livability, etc. Decentralized solutions thus exhibit a huge potential in increasing cities' agility in responding to climate change, rapid urbanization, or pollution problems in a circular economy logic.

Despite these significant benefits, decentralized UWM solutions have remained a niche solution. Few implementations at scale have occurred and if innovative decentralized UWM systems have been built, they were typically seen as one-of-a-kind demonstration or pilot projects that are hard to replicate or scale. Figure 1 outlines that this situation has quite dramatically changed over the past years. The figure on the one hand maps some of the most high-profile 'lighthouse initiatives' (also see Box 1-3) for decentralized UWM solutions, as analyzed in recent research projects.[1] On the other hand, it shows the organizations present at the workshop. The figure thus provides an indicative illustration that decentralized solutions are on a global expansion track and promoted not just by niche players anymore, but also by key utilities, investors, firms, technology experts and NGOs.

Figure1: Key lighthouse initiatives for decentralized solutions and organizations participating in the workshop.

1 See, for example: LIGHTHOUSE https://www.eawag.ch/en/department/sandec/projects/sesp/lighthouse/
BARRIERS https://www.eawag.ch/en/department/ess/projects/cirus-barriers-to-on-site-uwm/
4S https://www.eawag.ch/en/department/sandec/projects/sesp/4s-small-scale-sanitation-scaling-up/
ANCHOR https://www.interregnorthsea.eu/anchor
Run4Life https://run4life-project.eu/
or the SEI initiative on gridless solutions: https://www.sei.org/projects/sei-initiative-on-gridless-solutions

The global diffusion of decentralized solutions and their increasing salience is also reflected in high-level policy discourses and academic work (Vairavamoorthy, 2023; Schelbert et al., 2023; dos Santos et al., 2023; WaterEurope, 2022; Contzen et al., 2021; Macura et al., 2021; Gambrill et al., 2020; Liu et al., 2020; Larsen et al., 2016). At the same time, many hurdles for broader mainstreaming still exist. One key challenge is that decentralized UWM solutions are a radical expansion beyond the 'business as usual' approach to water and sanitation with its well-established technological solutions, regulations, norms and beliefs. Evidence from comparable infrastructure sectors like energy, mobility or waste management suggests that in such contexts, mainstreaming is a complex, systemic innovation problem. Innovators cannot simply develop new technologies and products and sell them on a pre-existing mass-market. They must rather become change agents that pro-actively alter regulations, create novel business models and expand established 'ways of doing things' before the innovation can develop and diffuse. Long-term and strategic action is thus needed and actors from many interrelated, yet commonly separated (siloed), fields need to come together and develop joint agendas in a coherent innovation ecosystem (Binz and Truffer, 2017).

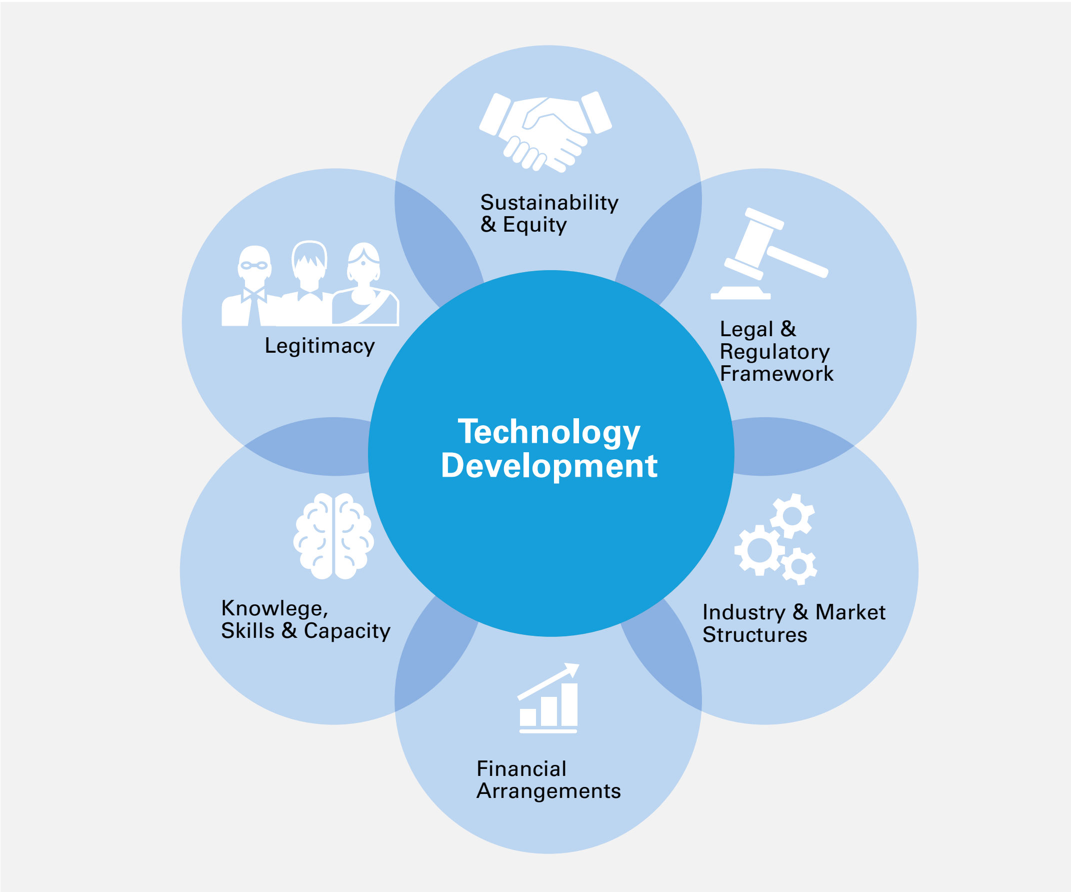

Figure 2: Key innovation ecosystem resources needed for mainstreaming decentralized UWM solutions
Source: based on (Schelbert et al., 2023; Hacker and Binz, 2021)

Figure 2 outlines that – in addition to technology development – six key resources usually need to be created that jointly enable mainstreaming (Hacker and Binz, 2021; Schelbert et al., 2023). They comprise 1) adapting legal & regulative frameworks, 2) developing mature industry & market structures, 3) mobilizing financial investment, 4) creating adequate knowledge, skills & capacity (for technology development, but also O&M and regulation), 5) legitimizing the innovation and emerging industry, and 6) showcasing the sustainability and equity of the proposed solutions. If one or several of those elements are missing, chances are high that innovation does not scale and/or organized opposition arises (see e.g. Hacker and Binz, 2021; Schelbert et al., 2023). For decentralized solutions, some of these elements have been successfully created in specific market segments, regions and/or demonstration projects. Yet, at a global level, many bottlenecks in these resource stocks persist, pointing to a need to further structure discussions in the field, develop mainstreaming roadmaps for different solutions, and create a 'global innovation ecosystem' that jointly and strategically pushes a transformative agenda.

A second key complication is that many different types of decentralized solutions are currently emerging in parallel, which are designed to tackle specific problem constellations (i.e. creating a new water source for drought-prone cities / recovering nutrients in a circular economy rationale / building energy-neutral neighborhoods, etc.). There is thus no one-size-fits-all response for designing decentralized UWM solutions and the drivers and barriers for mainstreaming specific system configurations differ from each other. Systematizing this diversity was a key challenge addressed through the workshop.

Systematizing the diversity of decentralized UWM solutions

Decentralized UWM solutions range from circular appliances like recycling showers, through household-scale greywater systems, to building-scale wastewater reuse plants and even complex district-scale resource recovery systems. These solutions arguably share a key similarity in being transformative to the incumbent system in urban (waste-)water management once they are able to scale beyond single demonstration and lighthouse projects. At the same time, they strongly differ in their core technologies, design criteria, needs for regulative change, user friendliness, etc. As such, before thinking about mainstreaming decentralized solutions in general, they need to be divided into a manageable subset of analytically distinct 'ideal types.'

Thinking undertaken beforehand, and the subsequent discussions at the workshop, evolved from the perspective of cities' key development challenges related to urban water management, and helped identify five key challenges that are typically addressed with decentralized UWM solutions:

a) Remediating water scarcity (e.g. San Francisco, Bengaluru, Beijing)
b) Managing nutrient flows in a circular economy logic (e.g. Paris, Geneva, Vermont)
c) Developing energy neutral / net zero neighborhoods (e.g. Hamburg, Helsingborg, Gent)
d) Managing stormwater, reducing combined sewer overflows (e.g. New York, Milano, Copenhagen)
e) Increasing urban biodiversity and livability (e.g. Melbourne, Sydney, Barcelona)

In all five cases, mitigating environmental pollution and protecting public health are key baseline objectives. Some of these challenges may furthermore be addressed in parallel. E.g. stormwater management and enhancing biodiversity are closely interrelated and often tackled concomitantly, e.g. with 'blue-green' infrastructures. These two challenges were thus combined into one category in Table 1. The table translates the remaining four key challenges into four analytically distinct design approaches for decentralized UWM solutions, which differ in terms of core technologies, application scales, managing entities, etc. The workshop focused mainly on the first three design approaches (water scarcity; energy & greenhouse gas emissions; nutrient management). The fourth approach related to stormwater management, biodiversity and livability was left to future exchanges as its basic design logic differs quite substantively from the other three. However, we fully acknowledge that effective stormwater management can make highly valuable contributions to the other challenges, particularly water scarcity and nutrient management.

Table 1 illustrates how the typical design approaches of solutions A-C differ from each other: Water-scarcity problems have so far mostly been tackled with packaged treatment plants that allow the reuse of greywater or wastewater for non-potable uses (gardening, toilet flushing, cooling, etc.). These systems are operated at household to neighborhood scales and are typically managed by private actors. Energy-focused solutions, in turn, apply more complex source separation, vacuum sewer and resource recovery systems, which are typically installed at a district-scale and managed by utilities. Solutions focusing on nutrient management often rely on urine source separating toilets and separate urine treatment and/or dry sanitation systems which have been applied at a building to neighborhood scales. Boxes 1-3 provide illustrative examples of real-world implementations of each system configuration.

Table 1: Four key challenges and design approaches for decentralized UWM solutions

	A – Water scarcity	**B – Energy & GHG emissions**	**C – Nutrient management**	**D – Stormwater & biodiversity, livability**
Solution title	Onsite non-potable water reuse	District-scale resource recovery systems	Decentralized nutrient management	Blue-green infrastructures
Technology	Packaged rainwater, greywater, or wastewater treatment plants	Source separation, vacuum sewers, separate treatment and resource recovery	Urine source separation & treatment; dry sanitation; separate blackwater treatment	Nature-based solutions, tanks, wetlands, green roofs, etc.
Scale	Household to neighborhood	Neighborhood to district	Building to neighborhood	Building to district
Managing entity	Private actors	Utilities	Cooperatives, private actors and/or utilities	Private actors, utilities, and/or cities
Outputs	Treated water, resilience against droughts, environmental protection	Energy, fertilizer, water, ‘stand-alone’ circular infrastructure solutions	Fertilizer, environmental protection, circular economy solutions	Service’ water, climate adaptation, biodiversity, livability
Mainstreaming mechanism	Standardization and automation, economies of scale in production	New urban planning paradigms, expert networks, consultants	Pull from city governments, end users and agriculture	Pull from cities, real estate developers and residents
Examples	San Francisco, Bengaluru	Hamburg, Helsingborg	Paris, Geneva	Melbourne, Zurich

Onsite non-potable water reuse: San Francisco and Bengaluru


Source: San Fransisco Public Utilities Commission


Source: City and County of San Fransisco


Source: Binz, C. 2023


Source: Miörner, J. 2022

San Francisco and Bengaluru are two leading examples of citywide installation of On-site Non-Potable Water Reuse Systems (ONWS). In San Francisco, ONWS were developed to alleviate increasing water stress. In 2015, a city ordiannce mandating ONWS for large new buildings was implemented. Today, all commercial, mixed-use and residential buildings over 9290 m² are required to install ONWS. As of February 2024, 40 ONWS were in operation and 66 systems were in the permitting process. In Bengaluru, local authorities have created an even larger mass- market for ONWS through a series of local mandates aimed at combating pollution and water scarcity. All new residential buildings with more than 20 flats or a floor area of more than 2000 m² and all commercial buildings with a floor area of more than 2000 m² are required to install ONWS and reuse all their wastewater onsite (Fig. 3). To date, more than 3’000 systems are installed in the city and about 20% of the city’s wastewater is managed in decentralized systems.

A key difference between San Francisco and Bengaluru concerns the connection of ONWS to the city›s water and sewer system. In San Francisco, buildings covered by the ordinance must set up collection, storage and redistribution systems for non-potable reuse. However, they also get connected to the centralized water and sewer network, as a backup against system failures. In this city, ONWS treat and reuse combined wastewater, greywater, rainwater, stormwater, air conditioning condensate and/or foundation drainage. Typical ONWS consist of a water collection system, a treatment system, and a non-potable water distribution system. Treatment of waste- or greywater typically involves primary pre-treatment and secondary biological treatment (activated sludge processes, often membrane bioreactors (MBRs), as well as tertiary treatment (e.g. chlorine disinfection) to ensure compliance with local regulative requirements. The treated water is used for indoor (e.g. toilet flushing and laundry) and outdoor (e.g. irrigation) purposes. ONWS are managed by private actors, with both CAPEX and OPEX being borne by building owners, developers and/or building residents.

In Bengaluru, a very wide variety of ONWS designs exist. Private actors are responsible for the design, construction, operation and maintenance of ONWS. Investment and operating costs are usually borne by the building owners and residents. However, the local regulators provide limited guidance, monitoring and enforcement. Many systems are poorly operated and maintained and do not reach their legally required effluent qulity. ONWS in Bengaluru typically consist of small-scale treatment plants using primary treatment combined with various biological treatment processes, including aerobic and, to a lesser extent, anaerobic technologies (Fig. 4). The treated water is used for onsite non-potable uses (e.g., toilet flushing, irrigation and car washing) and increasingly for offsite uses (e.g., laundries, public parks and construction sites in the neighborhood). Innovation dynamics around ONWS are strong in the city with local firms upgrading existing ONWS to allow them to attain effluent qualities high enough for advanced onsite reuse or for selling to offsite customers through online trading platforms and water tanker transportation arrangements.

The mainstreaming of ONWS has already started in the US and India. In India, the city of Hyderabad has adopted a reuse mandate similar to Bengaluru's, and decentralized water reuse projects are emerging in Pune, Mumbai and Delhi. In the US, the National Blue Ribbon Commission for Onsite Non-potable Water Systems is actively promoting the diffusion of ONSW. States such as Colorado, Hawaii, Washington and Minnesota have already developed strategies to promote ONWS that are inspired by San Francisco's regulative framework, which provides standardised guidelines for effective ONWS planning & operation. The experience of San Francisco and Bengaluru both show that great potential for mainstreaming ONWS lies in creating a supportive legal framework coupled with an entrepreneurial ecosystem around ONWS, including the development of an industry based on business models for designing, building and operating ONWS to achieve economies of scale.

Further reading:

Afghani, N., Schelbert, V., Lüthi, C., & Binz, C. (2023). On-site water reuse systems in San Francisco, United States. Lighthouse synthesis report. Eawag. www.sandec.ch/lighthouse

Kulranjan, R., Palur, S. and Nesi, M. (2023). How Water Flows Through Bengaluru: Urban Water Balance Report. Water, Environment, Land and Livelihoods (WELL) Labs at Institute for Financial Management and Research. Bengaluru. https://welllabs.org/bengaluru-urban-water-balance-report-well-labs/

Miörner, J.; Schelbert, V.; Lüthi, C.; Binz, C. (2023). On-site Water Reuse Systems in Bengaluru, India. Lighthouse Synthesis Report. Eawag. www.sandec.ch/lighthouse

San Francisco Water Power Sewer. (n.d.). https://sfpuc.org/construction-contracts/design-guidelines-standards/onsite-water-reuse

WateReuse, National Blue Ribbon Commission for Onsite Non-Potable Water Systems (n.d.). https://watereuse.org/educate/national-blue-ribbon-commission-for-onsite-non-potable-water-systems/

District-scale resource recovery: Hamburg and Helsingborg

Hamburg and Helsingborg host two lighthouse initiatives for district-scale resource recovery systems. The Jenfelder Au is a sustainable urban development project in Hamburg, Germany, which aims to serve as a model for future-oriented and energy-efficient urban development (Fig. 1). Local residents are supplied by the Hamburg Water Cycle (HWC), an innovative wastewater disposal and energy supply system. The HWC has been in operation since 2017 and currently serves around 630 apartments with 1,500 residents, making it the largest residential area in Europe with an operational decentralised UWM solution. Eventually, the HWC will serve around 835 homes and 2,000 people. Like Jenfelder Au, the H+ area in Helsingborg, Sweden, is a sustainable urban development project (Fig. 3). The H+ area is served by the "Tre-Rör-Ut" system, which aims to recover water, nutrients and energy from local waste streams. Tre-Rör-Ut has been in operation since 2020 and currently serves around 900 people in 340 apartments and 32,000 m2 of office space. Eventually, the system will serve 2,500 people.

The most important component of both systems is the separate collection and treatment of different 'waste' flows. In the HWC, rainwater, greywater and blackwater are collected separately. While greywater is transported in conventional pipes, blackwater is transported through vacuum pipes, mixed with co-substrate (grease water residue from restaurants) and pumped to the fermenter, where biogas is produced. A co-generation plant then produces electricity and heat, which are used in the district (Fig. 2). The HWC also enables the reuse of treated greywater and produces soil amendments from the fermentation residues. As demand for treated greywater is still lacking, it is currently discharged into the sewer. Rainwater is retained on green areas and collected in a pond where it percolates and evaporates. The HWC project was driven and implemented by Hamburg›s water utility, HAMBURG WASSER, which developed the system together with research and practice partners.

In Helsingborg, the city commissioned the region›s water utility (NSVA) and waste utility (NSR) to plan an advanced source recovery system in the context of a major urban redevelopment project. In the newly built Oceanhamnen district, three separate pipes collect blackwater, greywater and organic food waste, and transport them to the 'RecoLab' treatment plant (Fig. 4). A vacuum system transports blackwater, while pressurized sewers transport food waste and greywater. The wastewater and food waste are treated separately in upflow anaerobic sludge blanket reactors, where liquid effluent and biogas are separated. The biogas is then processed into vehicle fuel used by the city's buses and the liquid effluent is used to recover struvite (a phosphate fertiliser) and ammonium sulphate (a nitrogen fertiliser), both of which are turned into fertilizer pellets for reuse in agriculture. The remaining dewatered sludges can be used as fertilizer. Greywater is treated using biological process and nanofiltration membranes. But, due to legal barriers, it is not yet reused in the district.

In both cases, strong political support and leadership by the utilities were crucial for project realisation. The policy vision of creating 'net zero' or 'energy neutral' city districts was a strong iniital pull factor in both cities. The H+ systems has induced replication plans in other Swedish cities, with discussions about the implementation of similar systems currently taking place in Östra Ramlösa, Visby (without organic waste separation) and in Stockholm (the Stockholm Royal Seaport project). In contrast to ONWS, this type of solution is being disseminated not through market mechanisms, but through expert networks, engineering consultants, city governments, as well as the suppliers of key system components.

Further reading:

Augustin, K., Skambraks, A.-K., Li, Z., Giese, T., Rakelmann, U., Meinzinger, F., Schonlau, H., and Günner, G. (2014). Towards sustainabe sanitation – the HAMBURG WASSER Cycle in the settlement Jenfelder Au. Water Supply, 14(1), 13-21. https://doi.org/10.2166/ws.2013.158

HAMBURG WASSER (n.d.). Hamburg Water Cycle.
https://www.hamburgwasser.de/umwelt/vorsorge/hamburg-water-cycle

NSVA (2021). Tre-Rör-Ut [Three Pipes Out].
https://projekt.nsva.se/kommuner/helsingborg/tre-ror-ut/

Schelbert, V.; Lüthi, C.; Binz, C. (2023). Hamburg Water Cycle in the Jenfelder Au, Hamburg, Germany. Lighthouse Synthesis Report. Eawag.
www.sandec.ch/lighthouse

Schelbert, V.; Lüthi, C.; Binz, C.; Miörner, J. (2023). "Tre-Rör-Ut" in Helsingborg, Sweden. Lighthouse Synthesis Report. Eawag.
www.sandec.ch/lighthouse

Decentralized nutrient management: Geneva and Paris

Source: Coopérative Équilibre

Source: Coopérative Équilibre

Source: Anyoji Beltrando / Paris & Mètropole Aménagement

Source: Ville de Paris / Paris & Mètropole Aménagement

Two very different lighthouse projects for decentralized nutrient management can be found in Geneva and Paris. In Geneva, the Coopérative Équilibre has been demonstrating the feasibility of decentralized nutrient management for more than a decade. Driven by the inhabitant's ecological mindset, the cooperative has implemented 'low-tech' compost toilet systems in three housing projects, serving approximately 145 people. In Paris, a major urine source separation project is currently being implemented in the Saint-Vincent-de-Paul (SVdP) neighborhood. Paris is struggling with embracing future growth while avoiding further eutrophication of the Seine River. This highly innovative urban development project aims to create an eco-neighborhood of around 600 homes, shops and other facilities with circular infrastructure systems (Fig. 3). Construction of the SVdP began in 2018 and will be completed in 2024. Ultimately, more than 4000 people will be connected to the local urine source separation system.

Although both Équilibre and SVdP practice nutrient management, the two projects differ strongly in terms of technology choices and management bodies. In the case of Équilibre, all housing projects are managed by a housing cooperative, which was founded in Geneva in 2005, and which is now responsible for the development, implementation and monitoring of innovative sanitation solutions. Technological decisions are taken by the cooperative's planning office, with input from members and future residents, and differ between housing projects. For example, in the housing project ‘Les Vergers’, urine-diverting toilets are installed on a voluntary basis (Fig. 1 and 2). The feces are collected directly under the toilet bowl and turned into compost through vermicomposting. The urine is fed separately into carbon filters, which support bacteria in decomposing the urine into a colorless and odorless fertilizer ‘Pitribon’, which is used in the cooperative›s own gardens. Two housing projects are currently under construction and at least five more are in the planning phase. In these housing projects, the urine and feces of around 400 and 1310 people respectively will be processed into fertilizer, water for irrigation and compost using various technologies such as the ‹Pitribon› method, vermicomposting and vermifiltration.

In contrast to the ‘bottom-up’ nature of Les Vergers, the SVdP urine source separation project was driven by elected municipal officials who decided to introduce urine diversion toilets and dry urinals in all buildings in the renovated neighborhood. The urine is transported via a separate urine collection network to a local treatment plant, where a concentrated fertilizer is produced in a multi-stage process using nitrification, activated carbon filters and distillation. The expected production volume is 47,000 liters of fertilizer per year, which will initially be used on Parisian green spaces by the City›s Green Spaces and Environment Department. A small-scale demonstration project has already been carried out, involving the installation of urinals for women on site (Fig. 4). Once completed, both the urine collection network and the local treatment plant will be managed as public infrastructure, with only the operation of the treatment plant being outsourced to a private company. The investments related to the urine separation project were subsidized by the region›s public water agency.

Both models see increasing diffusion. Cooperative Équilibre’s approach is getting replicated in Switzerland, e.g. in mountain huts and in new projects in the cities of Bern, Zurich and Fribourg. Mushrooming of similar projects in a grassroots cooperative culture, combined with political support by progressive regional governments, is the key diffusion channel. In France, source separation projects are increasingly being disseminated, with project numbers quickly increasing, especially since the installation of urine source separation and treatment solutions are receiving subsidies in the Seine-Normandy region. The SVdP project will be key in demonstrating the economic and ecological benefits of this approach at scale. Further mainstreaming could be facilitated by upcoming regulative changes that allow for the use of human-excreta-based fertilizers in agriculture, thus spurring stronger economic incentives for urine source separation projects.

Further reading:

Coopérative Équilibre (n.d.). KOMPOSTTOILETTEN IN STÄDTISCHEN GEBIETEN? DAS GELINGT! Zusammenfassung des Merkblatts für Bauträger.

Joveniaux, A. (2023). Rapport d’étude sur les projets développés par la coopérative d’habitation Équilibre et les dynamiques en faveur de la séparation à la source en Suisse. [Study report on the projects developed by the housing cooperative Equilibrium and the dynamics in favour of source separation in Switzerland]. https://www.leesu.fr/ocapi/wp-content/uploads/2023/05/joveniaux_2023_REX_Rapport-Equilibre-et-Dynamiques-suisses_vf.pdf

Joveniaux, A., Legrand, M., Esculier, F. and De Gouvello, B. (2022). Towards the development of source separation and valorization of human excreta? Emerging dynamics and prospects in France. Front. Environ. Sci. 10:976624.

OCAPI – Programme de recherche & action sur les systèmes alimentation/excretion et la gestion des urines et matières fécales humaines. (n.d.) https://www.leesu.fr/ocapi/

Pakizer, K., Fischer, M., & Lieberherr, E. (2022). Entrepreneurial strategies for transformative change: An application to grassroots movements for sustainable urban water systems. Journal of Cleaner Production, 375, 134003.

Mainstreaming roadmaps

At the workshop, three separate mainstreaming roadmaps were developed for each of these system configurations outlined above and the results juxtaposed in an overarching synthesis. Senior experts from utilities, firms, cities, NGOs, academia and funding organizations from around the world were involved in developing each roadmap in a 1.5 day workshop. The roadmaps emerged from an interactive process that moved through three stages:

1) Creating a vision for each solution for 2033 and 2050.
2) Identifying key barriers to mainstreaming in four action fields: Technology development; regulative frameworks; industry & market structures; legitimacy.
3) Discussing concrete actions to overcome these barriers and sequencing key interventions on a timeline.

Below, the key outcomes from these discussions have been synthesized.

Onsite non-potable water reuse systems

Visions 2033 and 2050: The vision for 2033 is making the Onsite non-potable water reuse systems (ONWS) approach an 'obvious choice' when planning cities that are resilient to climate change and droughts. Rain-, grey-, and wastewater are reused to protect the environment and create co-benefits in the broader hydrological context (e.g. including rainwater capture to address issues such as flooding and discharge from combined sewer overflows). By 2033, these solutions are developed to a degree that locally treated water is seen as a valued water source and end users have a desire to install onsite water reuse systems, in the same way that smart homes or electric cars have become aspirational consumer product categories, coupled with financial incentives that work in favor of diffusion. One key element of the vision is that streamlined permitting pathways and 'fit-for-purpose' technology and water quality standards exist, which make ONWS systems readily and easily permittable. By 2033, onsite water reuse is a field with low entry barriers and a strong business case, with high user desirability, and clear regulative frameworks. The vision for 2050 is that ONWS systems have developed into resource recovery systems that allow recovering not just service water, but also nutrients, energy, and potentially even drinking water. Market diffusion and economies of scale have led to a drop in technology costs by a factor of 5–10, which makes this solution accessible to all segments of society. Users can choose from a broad variety of products and services, the approach is just another option in the toolbox of urban planners and developers and is broadly taken for granted by relevant stakeholders and end users, whose increased awareness of the topic makes them routinely engage in water reuse and water conservation practices.

Key mainstreaming drivers & challenges: This solution currently has a very strong driver in that many cities around the world are confronted with pressing water scarcity issues and are thus developing ONWS to create a novel drought-resistant water source. To date, ONWS are provided mostly by private actors, so reducing market barriers (costs, water pricing, certification/labelling of high-quality ONWS suppliers), developing consistent technology and water quality standards, as well as creating trust and broader legitimacy, are key challenges. Another challenge is the relatively high energy requirements of ONWS in comparison to conventional centralized water supply systems.

Technology development: Key barriers to mainstreaming on the technology side relate not (only) to the treatment processes, but also to ensuring reliability, safety and consistent monitoring of the water qualities achieved by onsite systems. Innovations in real-time monitoring and (hygienic) water quality control, the development of novel (soft) sensors and surrogates, as well as systems enabling predictive maintenance, are urgently needed. These measures in turn need to be connected to well-enforced regulative frameworks. In India, where a market structure for off-site water reuse (e.g. reuse of treated wastewater in construction sites, laundries or office towers in the neighborhood) is quickly emerging, enhancing the availability and reliability of continuous effluent quality measurements would be a game-changing innovation enabling more trustful market exchanges.

Regulative frameworks: Developing (globally) streamlined, yet context-sensitive (in terms of water sources, reuse purpose, scale of implementation and geographic contexts) regulative frameworks, permitting systems and water quality standards play a central role in creating trust and enabling competitive markets for this solution. A primary limitation is the current inconsistency of regulative frameworks that guide water reuse within and across countries. In addition to ongoing regulative work in the US, Europe and Australia, international initiatives would be needed, aimed at streamlining regulations and quality standards for a broad range of input water categories and output reuse purposes. A key trade-off here exists between creating globally unified 'baseline' standards and national/local standards and regulative frameworks that are developed in ways that reflect different reuse purposes, application scales and socio-economic contexts. Relating nuanced categorizations of source water qualities and water reuse purposes to ideal treatment train typologies could pave the way for smoother permitting processes that guarantee hygienic water qualities at affordable prices. Another crucial issue is keeping regulative frameworks flexible enough to leave space for further technological innovation and subsequent adaptation to local contexts.

Industry & market structures: With the quickly widening range of available treatment technologies, developing standardized/packaged treatment trains for certain input/output requirements appears highly promising. A standardization of treatment trains would in most contexts allow firms to reap economies of scale in production and thus significantly reduce CAPEX. Combining more streamlined treatment train designs with automated and remote operation could in turn reduce OPEX. Regarding business models, a streamlining of services and more specialized expertise, especially in O&M, would be needed. On an urban scale, systems that allow for sharing of excess water between buildings and initiatives with an active involvement of 'prosumers (citizens with particularly high environmental consciousness/interest in wastewater treatment technologies) could prove highly effective as initial niche markets. Another key barrier for market formation are current water pricing models, which do not properly reflect the average lifetime costs of extra, new and/or marginal water supplies. Developing new (tiered) pricing models, which incentivize onsite water reuse in a politically- and user-sensitive, fair and equitable way, would be a key leverage point to speed up ONWS implementation.

Legitimacy: Bottlenecks in achieving legitimacy include existing actors and institutions that resist change and, more importantly, a lack of trust between the actors designing, building and operating onsite water reuse systems. To foster trust among key stakeholders and establish transparency in the sector, the creation of widely accepted standards is a prerequisite. Here, global agencies can advocate for the importance of adopting new standards, necessary regulative frameworks (e.g., enforcement through building codes) and monitoring procedures to push cities to act, even in places with low political motivation and/or limited consumer awareness and demand. Institutional structures to ensure accountability, in the case of failures, also need to be built. A potential intervention in this respect is creating an 'operator of last resort' – e.g. a local utility guaranteeing to temporarily take over the O&M of onsite systems if their system supplier and/or operator disappears. Finally, benchmarking cities with well-working onsite water reuse programs and thereby encouraging 'peer pressure' for others to follow would help with replication and scale up.

Synthesis of the roadmap & key interventions: Overall, the mainstreaming challenges for this first ideal-type solution depend on technology standardization, commercialization, upscaling, and mass-manufacturing dynamics typical for 'consumer market products'. In the short run, envisioned key interventions accordingly focus on reaping low-hanging fruits for improving technological performance, efficiency and reliability, improving O&M and cost structures, and increasing trust in existing solution providers. In the mid-term future, more challenging institutional changes have to be addressed that would be needed to create functional mass-markets. One key intervention relates to creating globally streamlined, yet context-sensitive, standards and regulative frameworks that would level the playing field for all involved players. Another key intervention concerns more deeply legitimizing onsite water reuse with investors, policy makers and end users. A key issue not yet strongly discussed for this solution are the equity implications that come with an implicit 'privatization' of (elements of) urban sanitation if this solution scales.

District-scale resource recovery systems

Vision for 2033 and 2050: The 2033 vision for this solution is that 33 systems comparable to the ones installed in Hamburg and Helsingborg are implemented in cities around the world (several of which in low- and middle-income countries), providing relatively large development areas (1'000–6'000 households) with a regenerative and circular infrastructure solution. In particular, the 'standalone' feature of this solution, i.e. that it does not depend on connections to a pre-existing grid, strongly supports its diffusion. The vision for 2033 is limited to 33 installed systems as infrastructure development and the necessary reorientation among utilities takes a lot of time, thus limiting this solution's short-term diffusion potential. In the long run (by 2050), the aspiration is that these systems are the go-to infrastructure solution for any new urban development project – be they greenfield or brownfield – and that they see substantial uptake also in retrofitting/upgrading projects worldwide.

Key mainstreaming drivers & challenges: This solution's key drivers are regulative dynamics: Cities and real-estate developers are increasingly pushed to develop 'net zero'/'energy neutral' or 'sustainable' buildings and city districts. As one utility representative put it: "Our duty is to anticipate future actions by regulators. We have to prepare ourselves for the wishes of our owners and clients". District-scale resource recovery systems can play a key role in fulfilling these increasingly demanding sustainability requirements. Given their high technical complexity and relatively large implementation scale, the main actors are not private firms, but rather (water, waste and energy) utilities that collaborate across silos in developing integrated resource recovery-oriented solutions.

Technology development: Technology development is not the key bottleneck for this solution anymore. User interfaces, vacuum sewers, treatment processes, etc. have matured to a degree, where cities aiming to install this solution can patch together proven approaches to a well-working system. Yet, standardized packages of technologies offered at low prices are still lacking. Also, knowledge exchange on the installation and O&M challenges of these systems could be strongly improved. Creating novel lobby groups, umbrella organizations or 'advocacy coalitions' spanning different stakeholder categories and countries would be a powerful intervention to leverage the experiences from early lighthouse initiatives in follow-up implementation projects. Emulating the approach of the US National Blue Ribbon Commission for Onsite Non-potable Water Systems for promoting district-scale resource recovery systems in other regions, such as across the EU, could be a potentially impactful system intervention.

Regulative frameworks: A key challenge is that local laws, rules, and regulations usually need to be adapted when installing district-scale resource recovery systems. Utilities tend to remain locked-in to path dependent trajectories that promote business as usual solutions. Sensitizing them to the opportunities and challenges that come with installing such approaches through study tours, workshops, courses and events would be key. In the mid- term future, the current lack of technology standardization is a key challenge also for this solution. Early lighthouse initiatives typically tended to develop highly innovative technology variants to increase their "hype factor". For broader diffusion and replication, increasing technology standardization at national and international levels and establishing clear roles and responsibilities for stakeholders, and developing awareness and buy-in from urban planners, developers and technology/service providers would be crucial.

Industry & market structures: Key barriers for diffusion are the lack of well-established industrial suppliers, cognitive lock-in among planners, as well as a lack of demand for the system outputs (water, energy, and in particular, fertilizer). While customers for the water and energy (biogas) produced locally can often be found, the fertilizer produced in existing projects is still too low in volume and thus too expensive for wide-spread application in agriculture. While e.g. new fertilizer regulation in the EU is likely to incentivize market uptake, the current low scales of production remain a significant diffusion barrier. On the supply side, specialized technology suppliers and/or engineering consultants are yet to fully engage in this innovative space. Quickly initiating a series of follow-up implementation projects would be important to enhance industry interest and maintaining the expertise created in early lighthouse projects. On the demand side, one key intervention would be scaling up human-based fertilizer production to a level where it becomes a competitive source of nutrients for agriculture. 'Niche' markets would have to be actively created, e.g. by leveraging new EU fertilizer regulations or developing certification schemes for fertilizer, soil amendments and other outputs from district-scale resource recovery systems. Building up the volumes necessary for sustainable returns on investment by, e.g., consistently delivering products of quality and at the necessary scale, such as nutrients for farmers and biogas for energy users, remains a key issue to be tackled in the mid- to long-term.

Legitimacy: A key legitimation challenge for this solution is that utilities have to engage in the early stages of urban development projects with convincing arguments on why this type of solution is viable and makes sense. In the past, successful projects often relied heavily on passionate (groups of) individuals who engaged in the relevant planning processes early on. These actors struggled not only with lock-ins within incumbent organizations (utilities, firms, government), but also with a lack of interest and problem understanding among planners, policymakers and real estate developers. In the mid-term, urban planning departments and consultants should play a more important role as intermediaries between utilities, real estate developers, political decision makers, householders and output end-users. Another potential 'nudge' could come from asking explicitly for the implementation of district-scale resource recovery solutions in architectural competitions. In the mid-term, creating more sophisticated lifecycle-based cost-benefit analyses, as well as related advocacy and outreach campaigns would be important tools to better communicate and demonstrate the economic, social and environmental benefits of this type of solution. Closely related, establishing more holistic sustainability planning, such as through "urban sustainability master plans" in city administrations could create stronger incentives for implementation. Especially the 2050 vision requires developing convincing storylines on the benefits of the approach beyond "novelty and virtue", clearly showcasing the value of producing fertilizers, recycled water, biogas, energy and/or heat for creating sustainable cities.

Synthesis of the roadmap & key interventions: Overall, this solution's mainstreaming roadmap strongly differs from the prior example in that its mainstreaming dynamics depend on utilities, city governments and real-estate developers, who are in turn dependent on broader policy dynamics. In the short run, key interventions focus on convincing key political stakeholders and real-estate developers about the benefits of district-scale solutions. Overcoming siloed and locked-in 'ways of doing things' in utilities and in city planning and development departments, pushing more holistic planning practices in cities, and improving the networking and exchange of best practices between and beyond existing lighthouse initiatives, are key short-term interventions. In the mid-term, more challenging institutional changes have to be addressed, such as those related to more deeply legitimizing district-scale resource recovery with key decision makers and investors, harmonizing policy and governance arrangements across regions and countries and standardizing technology and quality requirements. In particular, creating full value chains for the system's main outputs and making them competitive with existing fertilizer, energy or water sources is a key strategic challenge.

Decentralized nutrient management

Vision for 2033 and 2050: The 2033 vision for this solution is that projects around the world showcase that 80% of the key nutrients (Nitrogen, Phosphorous and Potassium) from urban waste streams can be recovered through decentralized treatment. A key design requirement for reaching this goal is separating input streams at the source through the use of no-mix toilets. End products include high-quality fertilizer, as well as treated brown water and/or eco-humus. Application scales of this solution can vary from appliance to building or district scales, depending on the system design. Not one technology family will be able to reach the vision, so portfolios of context-appropriate technologies are needed. The 2050 vision aims at achieving 'net zero' nutrient balances in cities. This implies recovering all nutrients that would otherwise have entered the sewer system (and the local environment) and conveying them to reuse in agriculture or urban environments including urban farming.

Key mainstreaming challenges and ways to address them: This solution does not feature one clearly defined key driver but is rather pushed by a number of interrelated enabling factors. A major factor here is regulative: Governments around the world are developing comprehensive 'circular economy' strategies, in which decentralized nutrient recovery solutions can play an important role. In addition, the Ukraine war and recent price spikes in mineral fertilizers have highlighted the strategic advantages of developing local and crisis-resistant fertilizer supplies. At the same time, this solution is confronted with mainstreaming challenges that somewhat resemble the ones outlined for ONWS. An important additional driver is that separation of nutrients at the source decreases the burden on sewer systems and existing wastewater treatment plants, decreasing costs and decreasing greenhouse gas emissions such as N_2O as nitrification is minimized. Assessing nutrient recovery thus has to be considered in line with the full UWM system and the sector's broader net zero greenhouse gas emission targets.

Technology development: Technology development has to happen in various interrelated fields, encompassing dry and/or water-based urine diverting toilets, urine collection and treatments, fecal material collection and treatment, including vermicomposting processes. Some technologies like the Vuna process or alkaline urine dehydration have already reached the commercialization stage. Others like the URIDIS process, Sanitation 360 and the UGold Technology are still under development[2]. Considerable complexity will have to be managed when mainstreaming this solution, not just in pushing relevant nutrient recovery technologies to mass-manufacturing, but also in standardizing the design of piping systems, urine transport, O&M arrangements, management and treatment solutions for the remaining waste streams (i.e. fecal solids). In the mid-term, upskilling relevant experts and craftsmen, including architects, engineers, plumbers and contractors, for decentralized resource management systems and creating related certification programs are a key priority.

Regulative frameworks: As with the other solutions, developing supportive regulative frameworks is a key challenge. Relevant short-term interventions range from adapting laws and regulations which currently prohibit nutrient recovery from human sources to extending testing certification, developing O&M guidelines, regulating water reuse when derived from urine processing, and designing tax incentives for resource recovery and the use of human-derived fertilizer in agriculture. In the mid-term, implementing regulative mandates and incentive structures that induce market creation will be important. These might include mandates for management of nutrients at the building scale, as well as regulations for establishing full resource recovery value chains. In terms of longer-term challenges, developing more unified regulative frameworks would also be key for this solution. Involving the particularly broad set of stakeholders relevant for this solution in standard setting procedures would be important. A key challenge is also related to re-balancing and adapting government subsidies issued for operating onsite resource recovery technologies when compared to the costs of running centralized systems, especially since this approach (similar to ONWS) tends to convert sanitation from a public service to a private practice.

Industry & market structures: Reaching mass manufacturing, reaping economies of scale and thus reducing the costs of establishing and operating decentralized resource management systems together comprise important short-term challenges. This dynamic could be catalyzed by raising additional investments for the small and medium enterprises active in this field from development financiers and philanthropists, but also by developing improved business models. In order to boost market creation, setting up deeper collaborations with agriculture is key. In the mid-term, suitable case studies should be used to identify, analyze and refine appropriate business models in high-, middle-, and low-income contexts. In the long term, for a broader 'industrialization', integrated supply chains and buy-in from related industries (agriculture and, potentially, the chemical fertilizer sector) would be needed. This can be achieved with long-term advocacy, knowledge dissemination and networking strategies.

Legitimacy: In the short run, developing a clear value proposition for this solution is highly important. Due to the lack of tangible success stories, an easily approachable evidence base must be actively created that outlines this solution's contribution to climate mitigation and resilience, environmental protection, as well as increased circularity and cost efficiency. One key aspect to be highlighted is that diverting nutrients out of the conventional UWM systems could be a key intervention for N_2O mitigation. Decentralized nutrient management could thus be a key measure to reach ambitious net zero greenhouse gas emission goals. In the mid-term, new certification systems for this solution's end products, premium branding strategies, developing new planning laws, and creating effective stakeholder platforms for knowledge exchange, will be important. A similar mid-term challenge relates to increasing acceptance from the public, elected officials and end users. Engaging the media, providing free sample products, and developing public outreach campaigns could be highly effective to help achieve this objective.

2 See: URIDIS https://www.hydrohm.com/uridis.html; Sanitation 360 https://sanitation360.se/; UGold https://acweb.uq.edu.au/project/ugold-decentralised-nutrient-recovery-urine-microbial-electroconcentration-cells

Synthesis of the roadmap & key interventions: Overall, this third solution comprises a configuration that is at an earlier stage of development than the other two, with core drivers being more diverse and context dependent. It also differs from the other cases in providing a 'platform technology' with many potential synergies with the other decentralized solutions. It also requires the buy-in from upstream household users as well as end users in the agricultural sector. As such, its mainstreaming trajectory is more complex and diversified and depends on a mix of bottom-up technology development and activism, combined with conventional commercialization strategies, as outlined for the first solution. Creating evidence and novel business models, aligning incentives, along with advocacy and active market formation, industrialization, regulative changes and improving operational capacities, will all be needed to reach the 2050 vision.

Synthesis and next steps

Overall, the workshop proved that decentralized UWM solutions represent a dynamic innovation field with an increasing number and variety of designs and real-world implementations across the globe. The field has moved from primarily conceptual and academic discussions towards a quickly growing set of functional technologies, as well as regulative and organizational models with tangible benefits for tackling urban development challenges including climate change, water scarcity and resource circularity. However, at this stage, different solutions are still being pursued in isolation with little exchange of lessons learnt or joint standardization, upscaling or public outreach activities. In other terms, this emerging field has not yet developed an effective (global) innovation ecosystem, which could help coordinate and speed up the mainstreaming of decentralized UMW solutions. It was beyond the scope of the workshop to formulate a strategy on how a comprehensive global innovation system could be strategically built up. However, some salient similarities and differences in the constructed roadmaps could inform future activities in this direction.[3]

Key differences between the roadmaps

The three roadmaps outlined above depend on key actors, drivers, as well as preferences for technological and organizational solutions that differ from each other. They also differ in terms of key rationalities and potential mainstreaming trajectories. ONWS solutions strongly depend on a 'market' logic, in which mainstreaming happens through companies that provide products and services that create value to customers and profits to the firm, while local governments and utilities transform their role into 'intermediaries' that monitor and regulate system performance and set the right boundary conditions for market diffusion. District-scale resource recovery systems, in turn, depend on a more traditional 'state' rationale that sees utilities as the main responsible actors for implementing solutions, which respond to demands from the public and policy makers. Mainstreaming here happens through expert networks spanning utilities, city administrations, planners and real estate developers. Decentralized nutrient management, finally, rests on a more complex mix of 'community', 'sustainability' and 'market' rationales, which push for deep cultural changes in local communities and among policy makers, planners and engineers to establish circular economy principles and climate change mitigation as the key goals for the sector.

From an innovation studies point of view, having such diversity in objectives and development strategies is a good thing, as it creates diversity and increases innovativeness in the search for transformative urban infrastructure paradigms. Many fundamental questions around how to

3 It is interesting to note that very similar discussions are currently ongoing within the European Space Agency (ESA) looking at life support systems for space, and how they can be made of value for earth.

create sustainable cities will not be resolved with one single silver bullet solution. Therefore, it would be dangerous to focus on one particular technological and institutional configuration prematurely. It is also very likely that certain solutions will primarily be applicable to certain socio-economic contexts and/or only to greenfield or major (re)developments and hence only apply to all parts of a city, while others can organically penetrate new and existing installations and so be applicable across the urban fabric. At the same time, the fundamental differences that currently exist between the three solution's implementation rationalities could also hinder the formulation of conjoint development strategies and thus slow down future mainstreaming dynamics.

Key synergies across the roadmaps

In contrast to these differences, the three approaches discussed at the workshop also share some key common values. Among others, they relate to:

(1) rethinking our (decades/centuries) old approaches to providing water, sanitation and related services and their associated policies, regulative frameworks, funding and incentive mechanisms;

(2) recognizing that new UWM paradigms will have to be developed and diffused that are able to adapt to a changing world – including the changes already being experienced as a result of climate change;

(3) embracing circular economy thinking and closing resource loops closer to the household/community

Rather than continuing to diffuse different decentralized UWM solutions in separate communities and to different audiences, we thus propose focusing on some key synergy potentials among the three roadmaps outlined above.

In terms of technologies, common challenges relate to 1) improving water quality monitoring; 2) implementing combined recovery of water, energy and nutrients; and 3) enabling product standardization, technology mass-manufacturing and standardized O&M procedures. Related to the first challenge, guaranteeing the safe O&M of a high number of distributed systems through advanced sensoring and remote-control technologies (that may be based on different key parameters than conventional systems) would enable business model innovation across the board. Regarding the second issue, especially the roadmap on decentralized nutrient management emphasized the need to adopt a more holistic and systemic framework on the resources contained in waste flows and to establish smart ways to recover them. Related to the third challenge, the introduction of high-throughput technology manufacturing, global standardization, certification and advocacy activities, combined with improved economic incentive structures, would clearly be needed.

In terms of institutional and organizational arrangements, a shared challenge is the shift needed in the role of utilities in planning, managing and operating all three solutions. Even though utilities' specific roles differ substantially between the three roadmaps, a common issue is that they need to build up innovation capabilities in fields that go beyond business-as-usual activities and taken on new 'integrative', 'intermediary' or 'enabling' function. Developing these new roles will require a long-term vision including adapting the business model over time.

Also, policy makers, regulators, city administrations, and urban planners would need to fully embrace the future diffusion of decentralized UWM systems and actively manage the hybridization they bring to centralized structures. A need for more strategic and integrated urban infrastructure planning is critical in this regard and becomes particularly salient when bringing nature-based solutions into the picture, as is increasingly done in Australian cities. Booming megacities in low- and middle-income countries like Bengaluru or Jakarta have almost no alternative than broadly adopting decentralized solutions without first fully establishing centralized infrastructures. How to manage and incentivize such processes is an open and highly relevant question.

Overall, it is evident that decentralized UWM will strongly expand in relevance in the years and decades to come. By focusing on successful demonstration/ lighthouse projects and understanding their drivers and barriers, we have gained increasing insights into how these systems may develop in the future and how and where they can improve the ways we deal with water, energy and nutrients in cities. One key aspect of going from one-off demonstrations to approaches and technologies that can be used routinely by water utilities and urban planners, will be the importance of to continuing to share knowledge and pursue a vision with a view to most effectively disseminating good experiences around the world.

Key action areas

Even if at this stage, we are unable to predict how the field will develop in the future, the deliberations during the workshop brought up a number of action lines that will need to be tackled in the coming years and where coordination among the participants of the workshop and additional actors could be critical. First, the sector needs more streamlined technology and water quality standards to promote decentralized solutions across different implementation scales (household; building; district) and contexts (water stressed; flood prone; nutrient polluted; low-, middle- and high-income; etc.). In particular, process performance standards for different source/product water combinations, and which technologies can achieve these, will have to be clarified. Standards need to define the technical and operational conditions under which a decentralized UWM system at different application scales is likely to provide the required output quality reliably and consistently. Most probably, a one-size-fits-all approach will remain elusive, but standards should be set through a context-sensitive 'fit-for-purpose' approach.

A second major action field relates to scaling decentralized solutions, reaping economies of scale in production, and inducing interactive learning with O&M providers, regulators, policy makers, existing service providers and planners, and other decision makers. To successfully do so, sufficiently large entry markets need to be created and supported through government incentives to enable experimentation at large enough scales. Third, the synergies and frictions of decentralized and centralized solutions in 'hybrid' system configurations require focused attention. Finally, encompassing (environmental, economic and social) impact assessment frameworks are needed to identify and transparently communicate the benefits of decentralized and hybrid configurations.

The following interventions may be taken to support the mainstreaming of decentralized UWM:

- Establish a well-curated database and website collating snapshots of good practices for decentralized UWM solutions from around the world. Collating success cases could create positive peer pressure and legitimize the innovative UMW approaches with decision makers, investors and end users around the world.
- Developing clear and potentially global fit-for purpose water quality standards for treated water and other outputs of decentralized UWM systems.
- Creating international advocacy groups and epistemic communities or cooperating with existing ones – e.g. the "National Blue Ribbon Commission for Onsite Non-potable Water Systems", IWA specialist groups, Water Europe, Global Circular Water, 50L Home Coalition, EU projects such as 'P2Green', or 'ANCHOR'[4].

- Mobilizing follow-up funding for global networking and knowledge exchange, e.g. for
  1) Research projects (Horizon Europe, Belmont Forum, NGOs)
  2) Expert meetings (funded through research institutes, utilities, and/or external donors)
  3) Demonstration projects and lighthouse initiatives (cities, technology suppliers and developers)

4 See: P2Green: https://p2green.eu/; ANCHOR: https://www.interregnorthsea.eu/anchor

As outlined at the beginning, creating lobby groups, umbrella organizations or advocacy coalitions spanning different stakeholder categories and countries would be instrumental for creating a global innovation ecosystem, which effectively synthesizes experiences from lighthouse initiatives, induces knowledge sharing and develops joint advocacy activities. Among others, emulating the approach of the "National Blue Ribbon Commission for Onsite Non-potable Water Systems" in the US for promoting decentralized UWM solutions across the EU (and other parts of the world) could be a particularly interesting intervention.

References and further reading

Binz, C. and Truffer, B. (2017). Global Innovation Systems – A conceptual framework for innovation dynamics in transnational contexts. *Research Policy* 64(7): 1284-1298. https://doi.org/10.1016/j.respol.2017.05.012

Contzen, N., Kollmann, J. & Mosler, HJ. (2023). The importance of user acceptance, support, and behaviour change for the implementation of decentralized water technologies. *Nat Water* 1, 138–150. https://doi.org/10.1038/s44221-022-00015-y

dos Santos, A.J., Barazorda-Ccahuana, H.L., Caballero-Manrique, G. et al. (2023). Accelerating innovative water treatment in Latin America. *Nat Sustain* 6, 349–351 https://doi.org/10.1038/s41893-022-01042-z

Gambrill, M., Gilsdorf, RJ. and Kotwal, N. (2020). Citywide inclusive sanitation – business as unusual: shifting the paradigm by shifting minds. *Frontiers in Environmental Science*. 201. https://doi.org/10.3389/fenvs.2019.00201

Hacker, M. and Binz, C. (2021). Institutional barriers to on-site urban water reuse – An analytical framework and systematic literature review. Environmental Science and Technology 55(12): 8267-8277. https://doi.org/10.1021/acs.est.0c07947

Larsen, T. A., Hoffmann, S., Lüthi, C., Truffer, B., & Maurer, M. (2016). Emerging solutions to the water challenges of an urbanizing world. *Science*, 352(6288), 928–933. https://doi.org/10.1126/science.aad8641

Liu, L., Lopez, E., Dueñas-Osorio, L. et al. (2020). The importance of system configuration for distributed direct potable water reuse. *Nat Sustain* 3, 548–555 https://doi.org/10.1038/s41893-020-0518-5

Macura, B., Barquet, K., Lambe, F. and Soto Trujillo, A. (2021). Percieved unknowns about gridless water, sanitation and energy services. *Stockholm Environmental Institute.* https://doi.org/10.51414/sei2021.032

Schelbert, V., Binz, C. and Lüthi, C. (2023). Lighthouse Initiatives in the Urban Water and Sanitation Sector. An Integrative Assessment of Lighthouse Initiatives for Decentralised Urban Wastewater Treatment and Reuse Systems (DUWTRS). DOI: https://www.eawag.ch/fileadmin/Domain1/Abteilungen/sandec/publikationen/SESP/Lighthouse/lighthouse_report.pdf

Vairavamoorthy, K. (2023). Sanitation: time for a change of tactics. *IWA – The Source Magazine* November 2, 2023. Accessed 01.03.2024 at https://thesourcemagazine.org/sanitation-time-for-a-change-of-tactics/

WaterEurope (2022). THE VALUE OF WATER - TOWARDS A WATER-SMART SOCIETY. Accessed 04.04.2024 at https://watereurope.eu/wp-content/uploads/2023/11/WE-Water-Vision-2023_online.pdf

Image sources

Anyoji Beltrando, My Lucky Pixel / Paris & Métropole Aménagement (2024) The future Sant-Vincent-de-Paul neighborhood, Mairie du 14e. Accessed 01.02.2024 at Faire Paris autrement : le projet – Mairie du 14e

Binz, Christian. (2023). Residential apartment block in Bengaluru employing decentralized water reuse.

City and County of San Francisco (n.d.) San Francisco Permit Center. Accessed 01.02.2024 at https://sf.gov/location/san-francisco-permit-center

Coopérative Équilibre (n.d.). KOMPOSTTOILETTEN IN STÄDTISCHEN GEBIETEN? DAS GELINGT! Zusammenfassung des Merkblatts für Bauträger.

Helsingborgs Stad (2022) Oceanhamnen. Accessed 01.02.2024 at https://api.getanewsletter.com/v3/preview_mail/2969647/?public_key=1a51f6f3bb-baea7356bfe2407d793447

Krafft Angerer/HAMBURG WASSER (n.d.) HAMBURG WATER Cycle. Accessed 01.02.2024 at https://www.hamburgwasser.de/umwelt/vorsorge/hamburg-water-cycle/#c2060

Miörner, Johan. (2022). Decentralized water reuse plant at a hospital in Bengaluru.

Perfekt, Sara/NSVA (2022) Reco Lab. Accessed 01.02.2024 at https://api.getanewsletter.com/v3/preview_mail/2899086/?public_key=364727e460c9054b61dd893683f85a68

Ulrich Perrey/HAMBURG WASSER (n.d.). Jenfelder Au residential area. Accessed 01.02.2024 at https://www.hamburgwasser.de/umwelt/vorsorge/hamburg-water-cycle/#c2060

San Francisco Public Utilities Commission (n.d.) Black water treatment system at Mission Rock in San Francisco.

Ville de Paris/Paris & Métropole Aménagement (2019). Dry urinal prototype. Accessed 01.02.2024 at Saint-Vincent-de-Paul experiments with urine collection and recycling (blog-saintvincentdepaul-leprojet.fr)

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