Hamburg Water Cycle

in the Jenfelder Au, Hamburg, Germany

The Jenfelder Au in Hamburg, Germany is a sustainable city development project, served by the "Hamburg Water Cycle" (HWC), a spearheading template for resource-recovery from source-separated water and wastewater, first of its kind at neighbourhood scale.

Operational since 2019, the "HWC" currently serves ca. 630 apartments, 1'500 people (ultimately 835 apartments, 2'000 people).

Collection & Transport

Blackwater (toilet) and greywater (bath/shower, laundry, and kitchen) are separately collected and transported to the treatment plant. Vacuum pipes transport blackwater, conventional technology transports greywater. Rainwater is retained on green areas and collected in the Kühnbach-pond, where it percolates and evaporates.

Treatment

Blackwater is collected in two vacuum tanks, mixed with co-substrate (imported grease water from restaurant grease traps and reflux from the fermenter) and pumped into the fermenter, where biogas is produced and stored. An activated carbon filter cleans the biogas, before a co-generation plant generates electricity and heat, which are both used directly in the district.

The HWC provides for non-potable water reuse from greywater treatment and utilisation of fermentation residues. However, greywater quality standards are not met, greywater is discharged into the main sewer. Two installed experimental treatment plants shall help identifying a suitable treatment method. Likewise, investigations on utilisation of fermentation residues (for fertiliser production) were carried out without a usable result.

Products

Biogas for energy and heating; (greywater for water reuse).

Benefits

Sorting blackwater and greywater at source and using low-flush vacuum toilets and pipes lower water consumption and increases biogas production. Greywater separation allows water reuse. Integration of a rainwater pond creates co-benefits such as landscaping, liveability, and mitigates extreme weather events

Lighthouse Synthesis Report

Introduction

The Jenfelder Au is a sustainable urban development project in Jenfeld (district of Wandsbek), situated in the federal state of Hamburg, Germany. Between 1970 and 1990, Jenfeld increasingly developed into a low-income social structure, with many families depending on welfare measures and financial support [4]. Against this background, local politicians decided to upgrade the Jenfeld district by building a major urban development project on the grounds of the Lettow-Vorbeck barracks, later called Jenfelder Au [17]. Former military grounds owned by the State Government, the area was sold to the federal state of Hamburg. In April 2005, the Senate of Hamburg approved an urban development model for the site [24, 26]. From 2005 to 2011, a development plan was established, which stipulated that the project should serve as a role model for future-oriented and energy-efficient urban development. Innovative energy- and resource-saving approaches were to be implemented at neighbourhood scale [9].

HAMBURG WASSER, Hamburg's publicly owned utility for water supply and wastewater management, has a dedicated innovation department. In 2000, this department was tasked to analyse its existing water management systems and look for alternatives that increase sustainability [25]. As a result, together with the Frauenhofer Institute for Systems and Innovation Research (ISI) in Karlsruhe, the innovation department developed the Hamburg Water Cycle (HWC). The HWC is a concept for circular wastewater disposal and energy supply in urban areas. Its essential feature is the separate collection and treatment of different wastewater flows. In contrast to conventional systems, the HWC treats partial streams within the neighbourhood. It produces fermenting blackwater (wastewater from toilets) for biogas production, treats greywater (domestic wastewater without faecal contamination) for possible water reuse, and uses nature-based solutions for rainwater management. In 2005/06, the innovation group started looking for a suitable implementation area. In 2007, HAMBURG WASSER successfully approached the district of Wandsbek with the idea to realise the HWC in the Jenfelder Au. Because climate change mitigation and adaptation are key topics since 2007/08 at EU, national and the federal state levels, and at HAMBURG WASSER, this created a supportive political framework for realising the HWC, which has been developed at scale since 2012. With 630 residential units connected to the HWC to date (and eventually 835 units), the Jenfelder Au is currently the largest residential neighbourhood in Europe to use a decentralised urban wastewater treatment and reuse system (DUWTRS). The commissioning of the HWC system took place in fall 2016. In spring 2017, the first residents moved into the Jenfelder Au and blackwater treatment has been operational since May 2019. The initial plan envisaged redirecting the treated greywater into the rainwater collection pond ('Kühnbach pond'). However, since the required effluent standards are not (yet) met, the greywater is currently discharged into the main sewer. Adequate and efficient greywater treatment methods are still being tested, and in late 2019/early 2020, two experimental greywater treatment plants were constructed for this purpose.

The HWC is considered a lighthouse initiative with international recognition and has won several prizes and awards.[1] Delegations from around the world have visited the site and use it as inspiration for developing their own sustainable UWM systems.

System Set-Up: Technology Description

The HWC is based on a circular approach: wastewater is used to generate energy, the greywater cycle can be closed locally and rainwater retained in the immediate residential environment. The most important component of HWC is the separate treatment of different water flows. Rainwater, blackwater (wastewater from toilets) and greywater (wastewater from kitchens, bath sinks & showers and laundry), are separately collected and treated differently. A vacuum-based sewer system transports the blackwater; and conventional technology transports greywater. By sorting blackwater at source and using low-flush vacuum toilets, water consumption decreases, while blackwater concentration and, thus, the potential for biogas recovery increases. Greywater separation allows for efficient water reuse. At the service yard, the contents of the blackwater

1 'Gold Award' of the 'International Urban Landscape awards' (2009), VKU Innovation Prize (2013), Winner of BMBF's 'Excellent Landmarks in the Land of Ideas' (2013).

are fermented in a biogas plant and connected to a cogeneration plant for heat and energy production. Rainwater is retained on green areas, where it percolates and evaporates. Some of it is pumped into the Kühnbach pond, where it creates co-benefits in the neighbourhood, i.e. increasing liveability and resilience to extreme storm events or heat waves.

haust gas, is transferred via heat exchangers to a water circuit. From this water circuit, heat is extracted for the residential area's heating supply (Power: Electrical power: 60 kWel; Thermal power: 92 kWth). Because the settlement is still under construction, the cogeneration plant does not yet run at capacity and relies too much on co-substrate, transported by trucks from Meck-

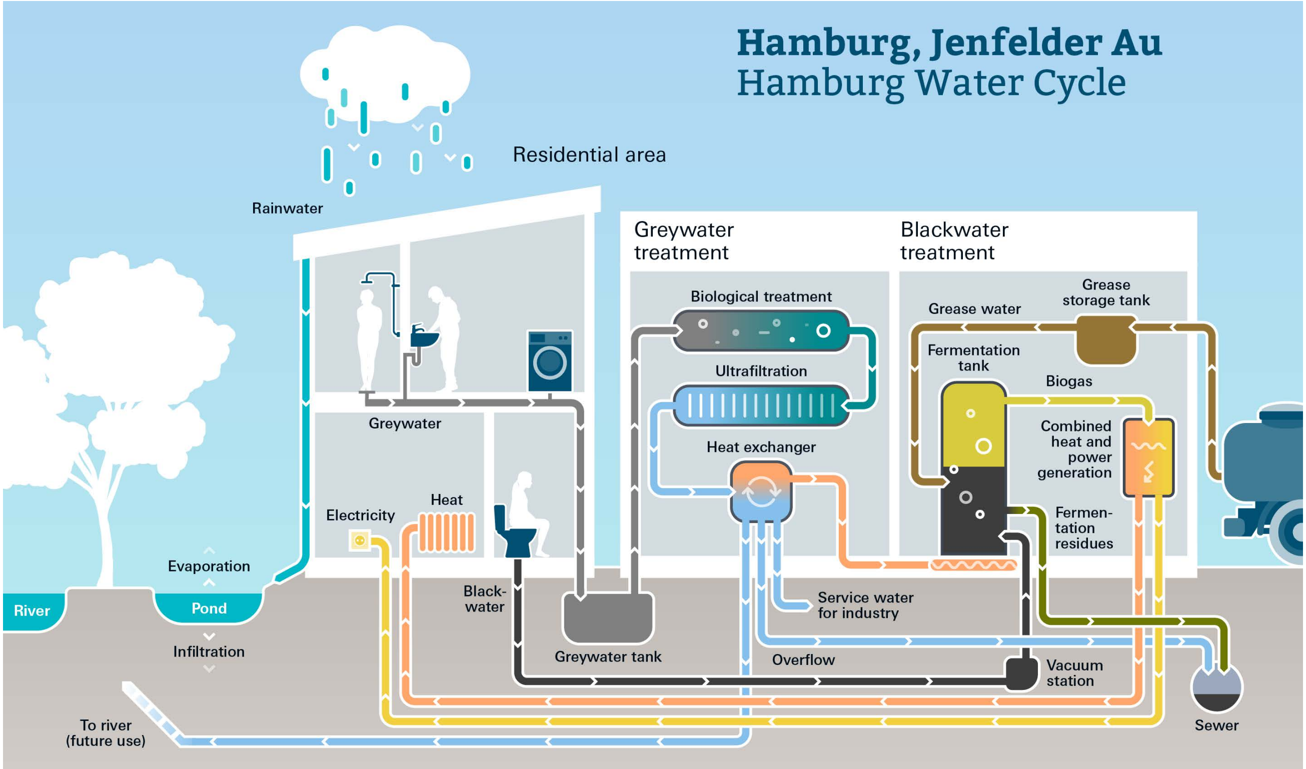

Figure 1: Schematic overview of the wastewater treatment and reuse processes in the Jenfelder Au

The blackwater vacuum network of the HWC consists of the vacuum toilets and pipes in the private area, and the vacuum pipes and network facilities (including shut-off devices, and inspection openings) in the public area. The blackwater accumulating in the neighbourhood is fed via three main lines to the blackwater pumping station in the service yard. There, the vacuum for the entire vacuum network is generated.

Two vacuum tanks collect the blackwater, which is mixed with co-substrate (grease water sourced from restaurants in the neighbouring federal state of Mecklenburg-Vorpommern and reflux from the fermenter), heated and pumped into the fermenter. In the fermenter, the production of biogas takes place. The purified biogas is burnt with air in a combustion engine, which drives a generator that converts the mechanical energy into electricity. The waste heat of the engine, i.e. the thermal energy of the cooling water and the ex-

lenburg-Vorpommern (in contradiction of HWC's core idea to use local 'products').

The HWC in theory also enables non-potable water reuse from greywater treatment and nutrient recovery from the fermentation residues. However, given that strict water quality standards are not (yet) met, greywater is discharged into the main sewer. Fermentation residues could in principle be used to produce fertiliser or a soil amendment. This option was investigated during the 'KREIS' research project, and the findings were inconclusive [12]. KREIS analysed design parameters for the discharge and treatment of the black- and greywater flows and was key for the HWC's technical adaptation. Although it is still intended to utilise the fermentation residues and create nutrient products, there are currently no activities planned or ongoing in this respect.

Institutional Framework Conditions

Legal & Regulatory Conditions

In the last decade, the 'sponge-city' concept has received increased recognition in various German cities (e.g. Berlin, and Hamburg). 'Sponge-cities' focus on rain-/stormwater management and aim to retain as much water as possible through nature-based solutions. DUWTRS are neither prohibited nor explicitly promoted in Germany; however, there are key barriers to implementing DUWTRS due to unclear and/or a lack of regulations [5, 8, 13, 30][2]. It is legal to treat and dispose of wastewater in (semi-)decentralised systems [13] and the municipalities are responsible for public drinking water supply and wastewater disposal under the supervision of the federal states. Responsibilities can be delegated to municipal companies, private companies or public-private partnerships [1]. The federalist reform from 2006 has created a legal and regulative patchwork; it allows federal states to adopt their own regulations in the field of water law [19].

In Hamburg, originally, parts of the HWC were prohibited by law. While decentralised nature-based rainwater management has been allowed in Hamburg's water management guidelines since 1984 [18], the Hamburg Wastewater Act (HmbAbwG) prohibited vacuum-based systems [21][3]. To start initial planning and implementation, the HWC project team, therefore, had to apply for an exemption permit. Long-term operation and eventual follow-up projects required an amendment to the HmbAbwG. Thus, in 2010, the project team from HAMBURG WASSER initiated an amendment process [2, 31, 32], which was successfully concluded in 2018 [2, 30]. Today, §11a Art. 5 of the HmbAbwG contains the term "partial wastewater flows", which allows for separation of black- and greywater, and permits the wastewater disposal authority to set specific requirements for each stream's discharge. According to our interviewees, it helped that the city-owned utility applied for the legal amendment rather than a profit-seeking private company. In addition, in Germany, public drinking water supply and wastewater disposal is regulated at the federal state level. Because Hamburg is a federal city-state and owns the utility, this facilitated the communication between HAMBURG WASSER and the administrative entities necessary to do the HmbAbwG amendment.

Contractual & Financial Arrangements

Existing planning regulations and land ownership structures largely defined the roles and responsibilities of the different stakeholders involved in developing the HWC. The city of Hamburg led the functional planning and marketed and sold the plots through its respective administrative entity (State Department for Real Estate Management and Land Assets (LIG)), while the district of Wandsbek lead the development planning. In addition to the regular planning departments, a dedicated project manager position was created for the real estate development project. A public mandate to provide water and wastewater services to all residents obliged HAMBURG WASSER to establish the HWC up to the property boundaries. A key contractual challenge consisted in mandating that private developers connect to the innovative waste regime, the HWC. Developers – or future owners – could choose, however, to opt out and connect to the centralised system instead. Special contracts were, thus, needed to create a stable arrangement for realising DUWTRS [13]. Because the city was the land owner of the Jenfelder Au, it could mandate that all real estate developers (including all future owners) connect to the HWC. When plots were sold in 2011, the contracts accordingly included a compulsory clause to connect to the HWC.

Concerning costs, the capital expenditures (CAPEX) for installing the HWC were estimated to be 30% higher than a conventional system. The main cost drivers were the installation of additional pipes, the service yard and – based on a precautionary approach since available standards were rare – additional security measures. For example, to date, the emergency solution if the fermenter fails, is direct discharge into the

2 Although in principle legal requirements exist for greywater reuse (e.g. for toilet flushing and irrigation) or energy generation from blackwater [13], it is unclear whether wastewater or waste legislation applies to the recycling of blackwater [30]. In terms of recovered resources (waste/products), currently, secondary raw materials are hardly covered by existing legal regulations [8].

3 Sewage transport was legally limited to gravity flow sewers and pressure sewers, but not "negative pressure" (= vacuum).

city's wastewater sewer. Because no special public funds could be provided to develop the HWC, given existing regulations[4] [1],, the HWC team tapped EU and national research funds to cover the 30% CAPEX increase. HAMBURG WASSER covered 'the regular' costs, i.e. connecting to the existing centralised system. The EU funds covered the additional equipment costs and national funds (BMBF, BMWi) covered research and development activities. According to interviewees, these grants were indispensable for the project's realisation. Additional infrastructure costs within the buildings had to be paid by the developers/owners (reportedly ca. 1% increase in the total building costs). Concerning human resources for project management, HAMBURG WASSER's innovation department was financed with regular funds. The Wandsbek district administration used internal funds and applied for external grant money to fund the dedicated project manager position. The HWC's operational costs (OPEX) are covered without any special tariffs or financial incentives. The neighbourhood's residents pay regular water and wastewater tariffs, as in other parts of the city. The reduced water consumption of households connected to the HWC (mostly caused by the water-saving vacuum toilets) mean that a four member household saves around €170/year (prices from 2017)[5] compared to households connected to centralised infrastructure [14].

Industry & Market Structures

Given the federalist reform from 2006 [19], Germany lacks uniform regulations for innovative water systems, such as the HWC. The regulative patchwork results in a lack of standardised (and compatible) treatment technologies, products, planners and suppliers [8]. When planning and implementing the HWC, specialised planners and equipment suppliers were, thus, missing and the existing standards and technical guidelines could not provide detailed guidance. For example, while there is a DIN-standard for vacuum piping in buildings, it is tailored to conventional wastewater systems, not to the low-flush blackwater systems used in the HWC [6]. Likewise, standards for greywater treatment and reuse were not available in the project planning stage. For instance, DIN did not publish minimum quality requirements for greywater reuse until 2021 [7]. This lack of industry standards challenged the vetting process done by the relevant authorities [21].

Many technical solutions and contextual adaptations had to be identified through research (see below). For example, the HWC project team in the KREIS research project evaluated potential vacuum toilet models from three available suppliers (Roediger, VacuSaTec and Jets) [3] and their noise levels. In the end, most of the buildings were equipped with toilets from Roediger. The required system's ertise to plan, operate and maintain vacuum-based systems. Given this shortage, HAMBURG WASSER during the construction supported the vacuum specialists and trained them together with Roediger. This guaranteed proper installation of system components within the buildings, which is essential for the system's functionality, and to guarantee acceptable sound volumes when flushing vacuum toilets. Furthermore, Roediger invested more time and money than contractually required because of the chance it had to gain a competitive advantage in an emerging niche market.

Overall, there are very few suppliers of vacuum-based systems, such as the HWC, and they still operate mostly in niche markets.[6] However, because heat/energy recovery from biogas is well-regulated and mature suppliers and market structures exist in Germany, technical suppliers for this part of the HWC were readily available (GETEC AG as the contractor).

4 Financial arrangements must follow the principles of public financial conduct [1].

5 As of 2017: water price 1.85€/m³ and wastewater fee 2.11€/m³.

6 Regarding greywater: while technically greywater treatment is doable and effluent standards can be reached using membranes, it is not economically viable since drinking water is simply too cheap. Regarding sludge application: currently, in Germany, treated sewage sludge can be used as fertiliser on agricultural soils or in landscaping measures, provided they meet the standards (low pollutant loads). However, today, in practice, the vast majority of the sludge dry matter is incinerated. While in 2012 more than 45 % of sewage sludge was applied, in 2016 it was about 35 %, and in 2019 around 20%. This can be attributed to, among other things, increasing quality requirements and spreading restrictions (fertiliser legislation).

Knowledge, Skills & Capacity

The knowledge, skills and capacities on how to plan, construct, connect, operate and maintain the HWC system were mostly established through learning-by-doing. Initial practical insights on source-separation and vacuum-based systems were collected through exchanges with other pilot projects, particularly Flintenbreite (Lübeck, Germany), which became the initial reference point. In Flintenbreite, a small-scale source-separation concept (rain-, black- and greywater) using a vacuum-based system was implemented in 1999 [20]. Analysis of a similar project in Sneek (Netherlands, since 2005) showed that adequate technology choices and management are conducive to user-acceptance [12]. To increase its understanding and collect practical experience on stakeholder management, in 2011, the HWC team established a demonstration plant close to the Jenfelder Au (Gut Karlshöhe) [3], where various research activities were undertaken from 2011 to 2017. The lessons learnt from such projects as Flintenbreite supported technology selection and the fine-tuning of system components [3, 11, 12, 21]. The evaluations carried out at the demonstration plant during the KREIS research project (2011-2015) [12] were also vital to define the final technical system set-up. Activities at the demonstration plant and exchanges with other projects also helped the establishment of a common vision and mutual trust among all the involved stakeholders, and the movement from the conceptual to the detailed planning stage.

In the construction phase, detailed design and construction guidelines were established to ease knowledge transfer among the involved actors [22, 23]. The construction process was accompanied by advising building owners on the installation of vacuum technology in buildings. In addition, together with Roediger, the HWC team offered trainings for maintenance companies. When people moved in, the HWC development team of HAMBURG WASSER welcomed the new residents and distributed a FAQ-infosheet on the HWC, including do's and don'ts [14].

Despite the above, there are still several knowledge- and capability-related challenges. For example, existing institutional norms jeopardise effective operation. Since the HWC is a closed system, smooth operation requires a dedicated supervisor/operator. After the internal handover from HAMBURG WASSER, the 'Netzbetriebe' manages the pipe network and the 'Klärwerke' the treatment plant, creating the challenge of seamless coordination and knowledge transfer between the two entities. Another difficulty is the requirement that an on-site caretaker be responsible for operation and recurring and on-demand maintenance. However, for HAMBURG WASSER, the HWC is small, not high on its priority list, and seen as a burden by the utility's operational staff. Finally, the lack of follow-up projects within Hamburg and Germany means that the unique knowledge, skills and capacity acquired during HWC's development might be lost again. Without further diffusion, it will be difficult for planners, technology experts, firms and service personnel to specialise in these kinds of systems. This could also diminish user acceptability, if adequate support for end users gets increasingly expensive and/or not timely available.

Recognition & Legitimacy

To foster recognition and legitimacy among the relevant stakeholder groups, the HWC team early on systematically identified and addressed key actors and developed a strategic communication concept [12]. The overriding goal was to establish a positive image by marketing the HWC as a sustainable, high-quality infrastructure solution [12]. The communication dealt with the HWC's technical, ecological and social benefits (e.g. low noise, odour and costs). In addition, the HWC demonstration plant had a dual legitimising function. Through interdisciplinary research, vital technology and system knowledge was generated, which increased trust within the utility and among city officials that the HWC could really work. Simultaneously, it served as a 'proof of concept', and, thus, as a legitimising object for the general public, future developers, owners and residents. Likewise, from 2013 to 2017, the 'Jenfelder Au Urban Neighbourhood' exhibition took place [27]. Trained guides provided tours through the demonstration plant, answered questions and collected feedback [28]. During the construction stage, from 2016 on, a client consultation was organised at 'Gut Karlshöhe' to explain the concept to real estate developers and future owners so as to reduce stakeholders' concerns [29]. Finally, the legal amendment process (HmbAbwG §11a Art. 5) and the development of targeted outreach materials for different stakeholder groups, including design and construction guidelines [22, 23] and a FAQ-infosheet on the HWC [14], served additionally to foster legitimacy.

Key Interventions & Lessons Learnt

The interplay of multiple favourable conditions and constructive interventions by the actors involved were key to the HWC's successful implementation and in qualifying the Jenfelder Au as a "lighthouse case" for DUWTRS at neighbourhood scale. Four key interventions stand out.

First, the strong lead of HAMBURG WASSER and stable political support were key conditions. The main impetus for the development project was the political decision to change the Jenfeld district's social structure [17]. HAMBURG WASSER's proposal to integrate the HWC into the district's development plan fell on fruitful ground as the HWC was perceived as a key selling point to attract higher-income residents. It complemented state-level climate change mitigation and adaptation strategies, as well as the project's ambitions, in serving as a role model for an energy-efficient and future-oriented urban development [9]. A wide range of local stakeholders supported this vision and there was hardly any opposition during the planning and implementation stages.

Second, several research and outreach activities were key in coordinating the implementation of the innovative technological approach and establishing favourable institutional conditions and public acceptability. This consisted largely of pro-active and expansive networking, as well as knowledge acquisition and targeted dissemination. Learning from other projects and research activities, including the establishment of a demonstration plant, were key to developing and contextualising the HWC's final design. Furthermore, the knowledge and capacity gaps of stakeholders were strategically identified and addressed. Targeted activities and materials were developed, respectively, for planners, architects, developers, builders, service companies, researchers, practitioners and residents [10, 12, 14, 21-23]. To analyse user acceptability, HAMBURG WASSER conducted surveys with residents in 2018 and 2019 [15]. It plans to conduct the survey on a recurring basis over a period of 5 years, the next in 2024.

Third, amending the HmbAbwG was key. HAMBURG WASSER took the lead on this and the result is an amendment to the Hamburg Wastewater Act in 2018, which now includes 'partial wastewater flows', thus, explicitly allowing for DUWTRS [30].

Fourth, continuous networking created a collaborative and cooperative culture around the HWC. Collaboration took place between various public departments, the utility, research institutes and the private sector. The district of Wandsbek created a dedicated project management position, which was key to consistent development planning. This dedicated position increased the district planning department's capacity to coordinate and participate in stakeholder meetings related to the HWC. At HAMBURG WASSER, individuals who were strongly committed and identified with the project were involved across the entire process. This was conducive to knowledge exchange with the private sector, especially with the main technical supplier (Roediger). It also helped to create a collaborative and cooperative atmosphere, which was considered by the interviewees as one of the critical success.

About the Lighthouse Project

Resource-oriented decentralised urban water management systems improve the flexibility, resilience and sustainability of water and sanitation infrastructure and are, thus, key in sustainability transitions. The Lighthouse Project assesses some of the most prominent examples.

Why? – Project Goals

Resource-oriented onsite/decentralised urban water management systems (DUWTRS) will play a key role in enabling sustainability transitions in the water and sanitation sector. DUWTRS close loops, recover valuable resources, produce marketable products, reduce the energy and water demand and can quickly be adapted to changing conditions. Despite increasing evidence of their potential benefits in improving the flexibility, resilience and sustainability of water and sanitation infrastructure, only a few cities worldwide have successfully implemented "lighthouse initiatives" (LHs) at scale. Systematic evidence of critical success factors and how to best implement LHs in cities in developed and emerging economies are lacking.

The Lighthouse Project conceptualised what are LHs and selected representative projects to analyse. The objectives were: 1), to identify the distinctive characteristics of LHs, 2) to identify cities and neighbourhoods that have established LHs and assess technological and institutional best practices, and 3) to synthesise the results and produce templates for the diffusion of DUWTRS in cities in developed and emerging contexts.

What? – Lighthouse Initiatives Key Characteristics

Comprehensive arrangement: Integrating new technologies into a matching socio-economic and institutional context
Long-term perspective (project length and available funding): Stable incentives that enable 'adaptive learning'
Broad-scale adoption: Fully developed value chain at neighbourhood/city district level comparable to centralised approach
Visibility and impact beyond immediate context: Examples that can inspire/guide initiatives to replicate core features

How? – Research Logic & Methods

We adopted a cross-comparative case study approach that synthesised results from prior Eawag projects (4S and BARRIERS) and amended them with additional secondary data and targeted expert interviews. In doing so, we generated practice-oriented lessons on how to best implement LHs and derived new theoretical knowledge on the generic conditions of their success to highlight sustainability transitions within the urban water and sanitation sector.

Now? – Recommendations

Long-term vision and strategy.
Establishing national/local strategies and programmes that define binding climate change mitigation targets are essential. Ideally, they explicitly express DUWTRS' potential contributions. Explicit references (and e.g. subsidies) to DUWTRS prevent 'one-off projects'. Follow-up projects are vital to diffuse acquired knowledge, skills and capacity and to guarantee an adequate supply of planners, technology experts, firms and specialised service personnel with the requisite knowledge.

Political and utility support/lead.
Political support and the lead (or participation) of the utility/ies are key to securing the resources and long-term O&M required. The continued endorsement of people in key positions (e.g. mayor, utility CEOs, and relevant city departments) helps to (politically) legitimise DUWTRS, to locate potential synergies and create strategic guidance. Sustained networking and creating a collaborative and cooperative atmosphere is key to strategically involve/address the city administration, utilities, planners, architects, developers, builders, service companies, researchers, practitioners and residents.

Incentivise transition.
It is necessary to ease the issuing of exemption permits to foster lighthouse initiatives, and to update the legal framework to explicitly include DUWTRS. Abandoning the polluters-pay principle and/or the provision of subsidies could incentivise resource-recovery concepts. To facilitate reuse, clarifying end-of-waste regulations for wastewater 'products' could foster the creation of (niche) markets.

Adequate project management.
Eight offices/institutions/decision-making bodies were involved in the Jenfelder Au, but there was no overarching 'supervising' authority. Establishing a dedicated project manager position would create a clear leader who could work on continued stakeholder coordination and collaboration. Installing a dedicated 'operational' project management, complemented with a 'strategic' steering group, including people in key positions (e.g. mayor, and utility CEOs), can facilitate project success. Key positions should not undergo personnel changes.

Payoff for users and investors.
The system must pay off in the long-term. Property owners and residents chose Jenfelder Au because they were looking for a place to live, not for the HWC.

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