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Exploring the potential of non-grid, small-grid, and hybrid solutions

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A research agenda for the future of urban water management: Exploring the potential of non-grid, small-grid, and hybrid solutions

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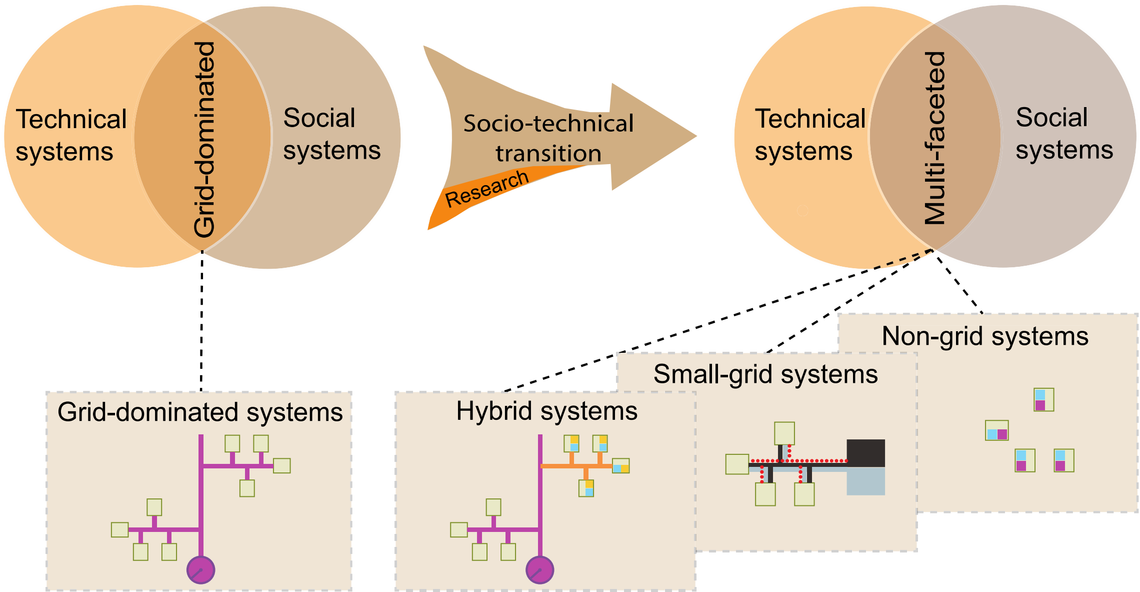
Abstract

Recent developments in high- and middle-income countries have exhibited a shift from conventional urban water systems to alternative solutions that are more diverse in source separation, decentralization, and modularization. These solutions include non-grid, small-grid, and hybrid systems to address such pressing global challenges as climate change, eutrophication, and rapid urbanization. They close loops, recover valuable resources, and adapt quickly to changing boundary conditions such as population size. Moving to such alternative solutions requires both technical and social innovations to co-evolve over time into integrated socio-technical urban water systems. Current implementations of alternative systems in high- and middle-income countries are promising, but they also underline the need for research questions to be addressed from technical, social, and transformative perspectives. Future research should apply a transdisciplinary research approach through socio-technical "lighthouse" projects that apply alternative urban water systems at scale. Such research should leverage experience from lighthouse projects in a range of socio-economic contexts, identify their potentials and limitations from an integrated perspective, and share their successes and failures across the urban water sector.

Keywords

Urban water management, non-grid systems, small-grid systems, hybrid systems, research agenda, transdisciplinary integration

Graphical Abstract



1. Introduction

Cities in high- and middle-income countries generally rely on centralized systems to provide vital water services,[1] including water supply, urban hygiene, urban drainage, and water pollution control.[2] These services are usually provided through networks of buried pipes, termed grids, which connect users to sources of water and sinks for wastewater.[3] Such conventional systems are characterized by strong path dependencies and technological and institutional lock-in effects,[4] which usually undergo incremental changes rather than radical transformations.[5] However, incremental changes are not sufficient to meet such current and future challenges in the urban water sector as rapid urbanization, urban sprawl, eutrophication, climate change, resource scarcity, and aging infrastructure.[6]

Alternative urban water systems have been studied in research,[7-9] discussed in policy,[10-12] and implemented in practice.[13-15] Alternative solutions include potable and non-potable water reuse,[16] source separation, decentralization,[17] and the modularization of treatment systems comprising small-scale, mass-produced, standardized, and automated technology components.[18, 19] These alternatives address pressing urban water challenges by closing loops, recovering valuable resources, and involving infrastructures that can easily adapt to changes in boundary conditions such as population size.

Although promising alternative urban water systems have been developed in recent decades, their market applications remain limited to a few places worldwide.[20] Pilot applications have been implemented in major cities such as San Francisco,[21] Melbourne, Sydney,[22] Hamburg,[23] Beijing,[24, 25] Bangalore,[26] and Zurich.[27] Recent developments in high- and middle-income countries have thus shown an emergent shift from conventional urban water systems to alternative solutions that are more diverse in source separation, decentralization, and modularization.

This shift towards alternative solutions implies far-reaching changes to the urban water sector. Technologies are highly intertwined with institutions[28] and involve mutual interdependence between technical and social structures. Both need to transform and co-evolve over time into new and stable "configurations that work"[29] to continue safe and reliable service provision while tackling emerging challenges.[30] The complexity, ambiguity and uncertainty of such socio-technical transition calls for the "constructive combination or integration"[31] of a wide range of perspectives from research, policy, and practice in ways that are best addressed by transdisciplinary approaches.[32] Such approaches transcend disciplinary boundaries (interdisciplinarity) while spanning research, policy, and practice (transdisciplinarity). They are intended to advance fundamental understanding of current and future challenges to urban water management, to generate promising solutions,[33] and to enable mutual learning between research, policy, and practice.[34]

In this paper, we explore the challenges to and opportunities for a transition to alternative urban water systems in high- and middle-income countries. Recent studies have (i) discussed the need to design, operate, and manage urban water systems in fundamentally different ways,[8, 35] (ii) scrutinized promising alternative solutions,[7, 36] and (iii) analyzed barriers to change in the urban water sector.[28, 37] However, few studies have outlined a transdisciplinary research agenda that discusses key research questions from technical, social, and transformative perspectives, and across interrelated macro, meso, and micro levels. Integrating these perspectives and levels advances our understanding of the complexity of both alternative socio-technical systems and socio-technical transitions in the urban water sector.

We therefore synthesize the discussion from a high-level expert workshop[i] attended by experts from process engineering, environmental engineering, transitions studies, innovation studies, decision analysis, governance studies, environmental studies, social psychology, and transdisciplinary research. The discussion identified key research questions from technical, social and transformative perspectives at three levels: (i) macro, relating to formal and informal rules and regulations and long-term transformations of technological paradigms and societal beliefs; (ii) meso, relating to the spatial organization of technical systems and their governance structures; and (iii) micro, relating to technological components, individual actors, and short-term transformations. We conclude by reflecting critically on the challenges we faced while integrating diverse disciplines and fields in a single research agenda.

2. Recognizing the diversity of technical systems

To discuss technical alternatives to today's conventional systems, we define both the extreme solutions, grid-dominated and non-grid, and the intermediate solutions, small-grid and hybrid. Grids are constituent elements of today's centralized systems, whose capital expenditure on pipes and sewers typically amounts to 70–80%, leading to technological lock-in effects.[38] We define non-grid systems as systems without pipes or sewers between individual buildings, but with piping within buildings and on premises, and small grids as systems with sewers and pipes between a small[ii] number of individual buildings. Both non-grid and small-grid systems are modular structures that can be upscaled and downscaled to meet changing boundary conditions, thus reducing the lock-in effects observed in grid-dominated systems. Hybrid systems integrate non-grid and small-grid solutions into grid-dominated systems, such as non-grid or small-grid treatment of urine within conventional systems (see Figure 1).[2,39]

We discuss the technical systems at the macro, meso, and micro levels. The macro level defines the services that urban water systems are expected to provide, the meso level the spatial organization of alternative systems, and the micro level the individual technologies. All three levels are interrelated. Our discussion excludes the variety of well-established alternative stormwater systems that are flexibly adapted to non-grid, small-grid, and hybrid systems (collectively known as Water Sensitive Urban Design, Low Impact Development, and other terms[40]), as that field has progressed significantly in recent decades.[41,42] This progress has enabled research on stormwater management to shift its focus to maximizing the multiple benefits of stormwater systems with best planning practices[42] and ensuring their compatibility with alternative water and wastewater systems.[43]

- Figure 1 -

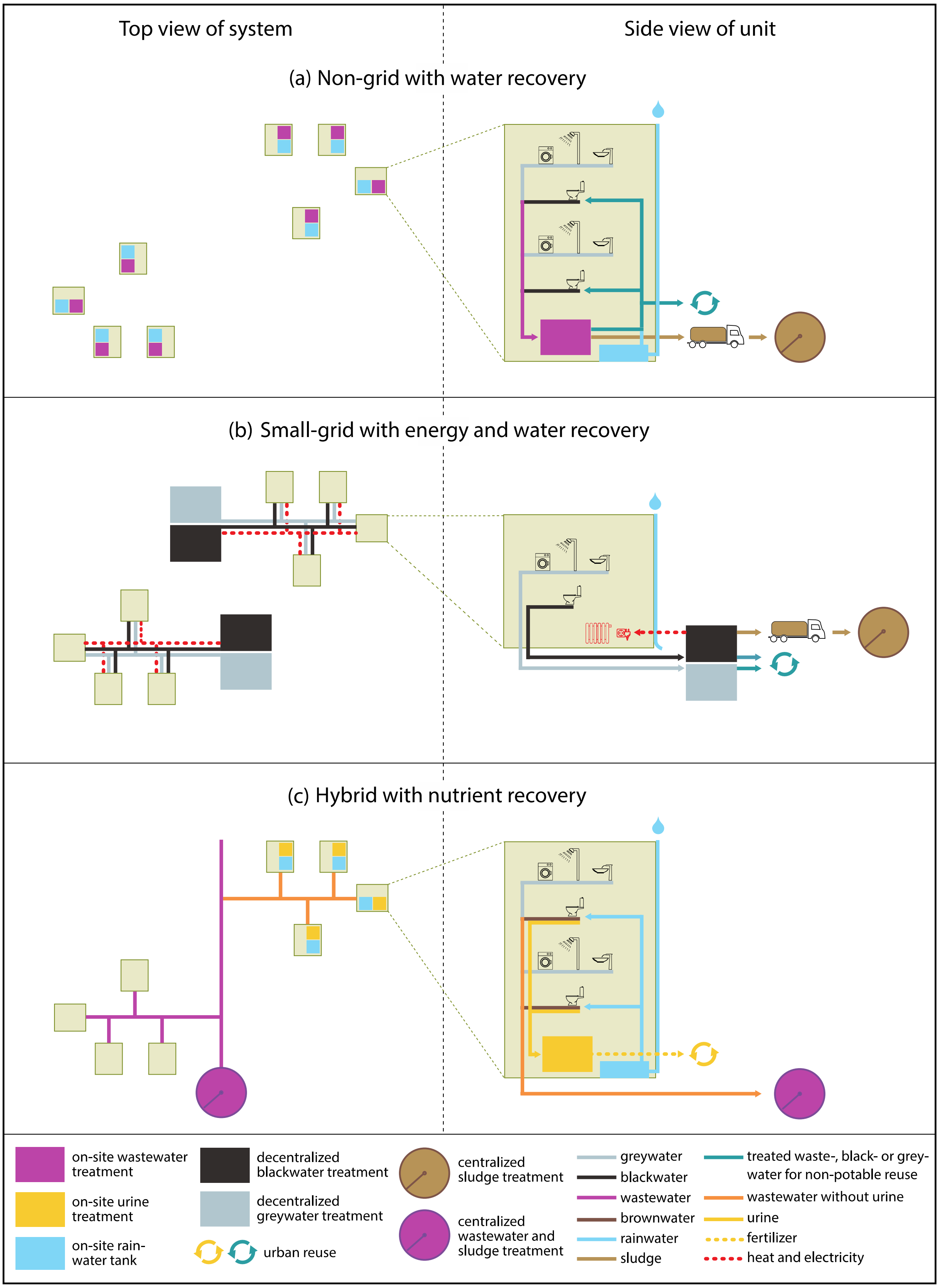

Top view of system
Side view of unit
(a) Non-grid with water recovery
(b) Small-grid with energy and water recovery
(c) Hybrid with nutrient recovery
on-site wastewater treatment
on-site urine treatment
on-site rain-water tank
decentralized blackwater treatment
decentralized greywater treatment
urban reuse
centralized sludge treatment
centralized wastewater and sludge treatment
greywater
blackwater
wastewater
brownwater
rainwater
sludge
treated waste-, black- or grey-water for non-potable reuse
wastewater without urine
urine
fertilizer
heat and electricity

Figure 1. Schematic visualization of (a) non-grid, (b) small-grid, and (c) hybrid urban wastewater systems (left column: top view) and units (right column: side view) based on empirical examples: (a) Beijing, China:[24,25] non-grid systems without sewers between individual buildings but with pipes inside buildings. Blackwater (e.g. from toilet) and greywater (e.g. from sinks, showers, washing machines or dishwashers) is collected in a single wastewater stream and treated on-site for non-potable reuse inside and outside individual buildings (e.g. toilet flushing, irrigation, and/or infiltration for aquifer recharge). Sludge is collected by trucks and treated in centralized sludge treatment plants. Rainwater is harvested and used for toilet flushing. (b) Hamburg, Jenfelder Au, Germany:[23] small-grid systems for groups of individual buildings with different pipes for source-separated wastewater streams. Blackwater and greywater are collected and treated separately in decentralized treatment plants. Treated greywater is reused outside buildings. Energy is recovered from blackwater as heat and electricity and used in buildings. Sludge is collected by trucks and treated in centralized sludge treatment plants. (c) Eawag, Zurich, Switzerland:[27] hybrid systems integrate non-grid and small-grid solutions into a grid-dominated system. Brownwater (e.g. from toilets, but without urine) and greywater is collected in a single wastewater stream and treated in a centralized wastewater treatment plant. Urine is collected through urine-diverting toilets and treated on-site. Urine is transformed into

fertilizer for reuse in urban agriculture[44]. Rainwater is harvested and used for toilet flushing.

Services of urban water management (macro level). The services that urban water systems are expected to provide are generally defined at the macro level.[2] Formal rules of service provision are commonly set by states and nations and are typically informed by international trends. Although in theory no technical decisions are taken at the macro level, it provides the boundaries for the technology choices at the meso and micro levels. In practice, technical decisions are sometimes effectively taken at the macro level due to, for instance, requirements for secondary treatment (e.g., the provisions of the US Clean Water Act).

In the 19th century, decision-makers identified urban hygiene as the main service to be delivered, leading to the installation of sewers, with unintended detrimental effects on water quality. In the 20th century, water pollution control was added, resulting in the construction of wastewater treatment plants.[45] Towards the end of the 20th century, authors started to discuss the sustainability of urban water management.[2,46] In the 21st century, the focus on sustainability appears to be contributing to a shift towards incorporating urban water management into the evolving circular economy.[47-50] The circular economy involves resource recovery from wastewater, primarily water, energy, and nutrients, as an additional service while balancing service goals and overall resource efficiency, such as energy demand for alternative technologies.[2] Water reuse opportunities are usually found at household and industry level as substitution of other water sources,[51] at city level for recreational and ecological purposes and cooling,[52] and at landscape level for streamflow augmentation[53] and agricultural irrigation.[51] Energy reuse is typically relevant in households in the recovery of heat and treatment facilities in the recovery of chemical energy from sludge as heat or electricity.[54] Nutrient reuse can be found at all levels from gardens to large-scale agriculture. The wider the variety of services that urban water systems are expected to provide, the more challenging service provision becomes. The complexity of ensuring hygiene in on-site water provision from greywater exemplifies this challenge well.[55]

Spatial organization of urban water management (meso level). The spatial organization of urban water services, including system type, system size, and mixing of water flows are all defined at the meso level. The integration of such services with other sectors and their services, such as energy supply and food supply, is also determined at this level. The meso level provides some of the most obvious arguments for alternative urban water systems: conventional grid-dominated systems require sufficient financial capital, long planning horizons, stable institutions, and sufficient water resources.[7] In many low- and middle-income countries, few or none of these conditions prevail, and even in high income countries, sufficient financial capital and water resources are not always available.[56]

However, even where such conditions are met, new demands for resource recovery services increase the demand for alternative solutions. It is often advantageous to recover resources from less diluted sources (e.g. nutrients from urine) or less contaminated ones (e.g. water from greywater). This may result in greater demand for source separation (see Figure 1),[7,57] which can best be realized by means of non-grid or small-grid systems. Similarly, streamflow augmentation of small water courses with treated wastewater may lead to more widely distributed treatment systems.[53] Progress in such digital technologies as wireless communication, automation, and remote sensing, monitoring, and controlling support radically different approaches to urban water management[58] and allow distributed non-grid or small-grid systems to be operated remotely and semi-automatically.[59]

However, the technological lock-in effects of legacy infrastructure, make it likely that, in the short term, non-grid and small-grid solutions will be implemented in new development areas or integrated into existing grid-dominated systems, resulting in increasing system hybridization.[3] In the long term, alternative systems have the potential to disrupt the urban water sector, resulting in deeper sectoral transformation, discussed further below.

Single technologies (micro level). Most research on and development of alternative urban water systems take place at the micro level, mainly as on-site or small-scale technologies for treating combined or source-separated domestic wastewater. Source separation requires different treatment technologies for greywater, blackwater, urine, and feces[17]. Such technologies face specific challenges, such as robustness and ease of maintenance, and may rely on new types of interfaces, such as urine-separating toilets.

Hybridizing existing technologies for multiple purposes both creates economic incentives and furthers system flexibility. Much can be learnt from research on alternative stormwater systems,[41, 43] including the adaptability of existing nature-based systems for wastewater and greywater treatment (e.g. subsurface constructed wetlands[60] and dual-mode biofilters[61]) to provide additional local amenity benefits. The integration of treatment or resource recovery in single household devices, such as recycling showers[62] offer an alternative to intra-household grids. However, they require close collaboration between research and industry to meet the increasing complexity of designing, installing, and operating these systems.

3. Acknowledging the key role of social contexts

Strong lock-in effects occur also at the social level.[28] Moving from grid-dominated systems to non-grid, small-grid, and hybrid solutions implies far-reaching changes in social contexts. These contexts involve two distinct elements: actors and institutions. Actors comprise the firms, utilities, universities, policy makers, users, and non-government organizations involved in designing, operating, managing, regulating, and using urban water systems. Institutions set the "rules of the game" that shape actors' behaviors and thus condition the opportunities for and barriers to innovation.[63] Institutions come in numerous forms, ranging from formal regulations, such as laws and water quality standards, to more intangible rules, such as cultural norms on how to properly use a toilet, and cognitive frames, such as "ways of doing things" in a wastewater utility.[63] These institutional characteristics interact and reinforce each other and thus maintain overall stability. Consequently, alternative urban water management approaches challenge widely held and deeply embedded societal norms, regulations, and beliefs.

Developing, diffusing, and adopting alternative urban water systems requires a series of institutional changes at various levels. These include adapting existing laws, regulations, and health standards at national and international levels, urban planners and architects rethinking urban design, utility staff and treatment equipment suppliers embracing new business models, and users adjusting their behavior to new technologies and interfaces. The scale and diversity of these reconfigurations highlight the multi-dimensional, interconnected, and context-specific character of the transitions required. This implies that even if public and private stakeholders agree to transform urban water management, they will be confronted with considerable path dependencies and unintended consequences at all levels, similar to those of the technical systems discussed above.

Changing widely-held societal norms, regulations and beliefs (macro level). Widely-held cultural norms, regulations and beliefs need to be identified that influence the success or failure of alternative systems. The urban water sector depends on a particularly strong set of 'taken-for-granted' technological paradigms and societal beliefs that stabilize the currently prevalent system.[45] Scholars have long called for unpacking macro-level institutional black boxes, such as global industry structures dominated by large firms and donors, the "yuck factor" most cultures associate with water reuse, and the globally standardized curricula for civil engineers, which strongly prioritize conventional grid-dominated systems. To date, few studies have examined whether, where, and how such macro structures exert their influence and how innovative actors may circumvent institutional barriers when pursuing alternative solutions. A key challenge in this respect is the socio-technical complexity and spatial diversity of alternative systems, which blur traditional operational scales, boundaries, and actors' roles and responsibilities.[64]

To date, research in this field has focused on defining institutional design principles,[65, 66] benchmarking change processes,[1] mapping legitimation processes,[21] and assessing institutional capacity for change.[67] Overall, this body of work is scattered and has overlooked some core research areas, particularly in global water governance structures, interactions between actors, institutions, and technologies,[68] and policy mixes that may support the diffusion of alternative solutions in various socio-economic settings. For instance, case studies examining the success or failure of the systems in Beijing, Hamburg, and Zurich emphasize context-specific institutional barriers while downplaying path dependencies that looked similar across all cases.[45] Future research should generate deeper understandings of the macro-level dynamics that shape and enforce the formal rules governing who, how, and how well urban water systems are managed.

Reforming organizations, industry, and governance structures (meso level). Moving to alternative systems also implies changes within and across organizations, industry, and economic incentive structures. Firms providing conventional systems reportedly struggle with radically novel business models and service structures for alternative systems.[69] As these systems mature, start-ups and spin-offs may increasingly disrupt the incumbents' income streams while maintaining or even improving the overall service level for end users.[70, 71] While considerable spatial variety exists, adapting the internal organization, innovation structures, and income streams of traditional firms and utilities to alternative solutions is far from straightforward.[37]

Consequently, the economic feasibility and social impacts of alternative solutions need to be better understood. Their multi-dimensional costs and benefits have strong implications for finding the optimal degree of decentralization in diverse spatial and socio-economic contexts.[72] Likewise, policy makers will have to rebalance the allocation of public and private costs and benefits in the urban water sector.[22] Important policy questions about the environmental impact and social equity of different socio-technical system designs arise here,[73] in particular whether and how alternative solutions can contribute to guaranteeing equitable access to urban water services.

Another open question concerns how to effectively organize the operation and maintenance of alternative solutions. Several promising niche experiments have implemented alternative systems at scale in San Francisco,[21] Beijing,[24,25] Bangalore,[26] and various European[23,27,] and Australian cities.[9,69] The results of these early initiatives are mixed, but they highlight the lack of any systematic evaluation and categorization of the organizational challenges that they face or of governance structures and regulative frameworks that are conducive to innovation while protecting public health and vulnerable societal groups.

Changing behaviors and routines (micro level). Moving away from conventional grid-dominated systems requires that a broader range of stakeholders engage in ensuring that alternative solutions are accepted, adopted, and safely managed. While some alternative systems may operate in a fully automated way, in most cases individuals, households, utility practitioners, private businesses, and regulators will have to become more involved in using and managing such systems. Part of the challenge thus involves encouraging and empowering a shift in key stakeholders' daily routines and practices. For instance, how can users be motivated to become more involved in investing, installing, adopting, operating, and managing the systems and changing their behaviors and routines? To answer this question, a nuanced understanding of (i) contextual expectations about the role of government, (ii) contemporary societal norms and values related to conventional urban water management, and (iii) users' perceptions and understandings of alternative systems is required. Such insights provide detailed insights into the variety of psychological drivers, objectives, and motives for adopting and maintaining new technologies. Such understanding assists in designing suitable, context-specific interventions that encourage the acceptance and safe management of alternative solutions.[74] For instance, public commitment may enhance people's use of alternative solutions.[75]

A key challenge for research in this area is that relatively few non-grid, small-grid, and hybrid systems have been implemented to date. Therefore, previous research has mostly focused on community acceptance and emotional responses,[76, 77] but studies associated with (i) defining and allocating rights and responsibilities related to alternative systems and (ii) using and maintaining such systems in the long term are scarce from either user or utility perspectives. Future research will benefit from experimental studies on implemented pilot systems by acquiring knowledge of the long-term use and maintenance[78] and the rights and responsibilities associated with them. For example, a psychological analysis of why urine-separating toilets were accepted at the Eawag headquarters in Switzerland but were not in similar buildings in Germany would be a highly interesting research endeavor.

4. Managing socio-technical transitions: An integrative and dynamic perspective

As argued in the preceding sections, the future pervasiveness of alternative solutions will depend not only on the availability of new technical configurations and suitable institutional arrangements but also on their alignment. Thus, the timing and co-management of innovation processes becomes crucial. The challenge is to inquire into conditions for transitioning the entire socio-technical system towards a more multi-faceted urban water sector.[29] Maintaining existing services while enabling radical shifts in the way urban water services are provided requires the formulation of long-term visions[2, 79] and context-sensitive implementation of alternative systems.

These kinds of transitions have to be analyzed at two levels: (i) In the short term, new solutions have to be implemented in protected niches[80] that enable testing of and learning from alternative systems under current technical and institutional conditions; (ii) in the longer run, lessons learned from such experience need to be mainstreamed. During this transition, different types of learning by utilities, technology providers, governments and users will be essential. First-order learning about facts ("Are we doing things right?") is required for improving the efficiency of the new systems under otherwise unchanged technical and institutional conditions. Second-order learning about "taken-for-granted" beliefs ("Are we doing the right things?") is necessary for expanding the field of alternatives. Third-order learning about underlying assumptions, theories, paradigms, and principles ("How do we decide what is right?") is essential for enabling deep shifts in policy priorities and institutional frames,[81] as is underway in the renewable electricity sector. First-order and second-order learning will be more prominent in short-term transformation, while in the longer term, third order learning will become increasingly prevalent.[82]

Implementing multi-faceted urban water systems under current sectoral conditions. In the short term, research has to focus on whether and how current utilities, regulators, consultancies, and users are able to implement alternative solutions. New ways of participatory planning and experimental implementation of alternative solutions have to be developed alongside the prevailing grid-dominated systems. Often, the implementation of alternative solutions will depend on protected spaces that shield actors from the path dependencies of the centralized system. In Beijing[24, 25] and Bangalore,[26] such protection stemmed from city and state regulations, in San Francisco[21] and Hamburg[23] from utilities that pro-actively promoted experimental approaches. The alternatives developing in such protected niche contexts directly challenge the competencies, routines, and organizational structures of existing water utilities, regulators, and users.[69] Widespread implementation will require first-order and second-order learning for many actors across different organizations and decision levels. Research should deal with how innovation management can be improved within the water sector, such as by creating protected spaces. It should also focus on how the water sector can tap into synergies with other sectors, such as energy and waste, to overcome the silo effect.[83]

Insights from the energy and waste sectors' past experiences and responses to similar challenges could be highly instructive for urban water management.[20] In particular, contextual studies are required to characterize change processes that have enabled or hindered innovations alongside prescriptive methods that induce or facilitate these change processes. Approaches already exist in various areas of political and organization science[84-86] and in decision and management science[87-91] to describe, analyze, plan, and evaluate various transition pathways from the existing centralized systems to more multi-faceted urban water systems. These approaches include models for assessing spatial infrastructure systems, for instance by integrating geographical data, methods for reliably eliciting decision-makers' priorities,[92] and tools for analyzing and comparing system alternatives.[93] Moreover, research accompanying niche experiments is critical to tracking learning processes and identifying key conditions for upscaling and mainstreaming alternative solutions. The research should focus on how different aspects of socio-technical systems, including innovation management, business models, regulation, pricing models, and user behaviors, can be developed in a balanced way.

Supporting the mainstreaming of multi-faceted urban water systems. The co-evolution of technical and social systems into socio-technical "configurations that work"[29] is complex. This complexity requires the capacity to revisit and revise fundamental assumptions: third-order learning.[82] Here, the role of researchers is to anticipate and evaluate emergent trends among diverse sectoral stakeholders.[94] We can expect that as alternative systems mature, prices for modular technologies will drop as a result of mass manufacturing ("economies of numbers"),[18] utilities and firms will establish robust business models and operational procedures, technical standards will be codified, and regulators will learn how to deal with more widely distributed systems. Based on insights from the transition literature[6] and recent experiences with the energy transition, we can expect that these transformations will occur very rapidly once sufficient momentum has accumulated.

A key research challenge in this area is to specify longer-run needs and opportunities. This relates mostly to leveraging current and assessing longer-term transformation pressures that will act on the sector, including climate change, shifts in demand patterns and societal values, and rapid urbanization and socio-economic change. Futures methods, such as scenario analysis, are useful in addressing uncertainties related to such pressures.[90, 91, 95] Several key research questions emerge from this challenge: How can visions and long-term transition strategies for municipalities, regions, and entire countries be identified and formulated? What kind of political power struggles will emerge once the sector's income and actor structures are deeply transformed? How can funding priorities of urban, national, and international governments and donors be adapted in favor of alternative solutions? How can incremental change induce the transition from one system state to another, and how can this transition be steered? And, finally, what can be learned from experience around the globe in transforming urban water systems?

5. Towards an integrative research agenda

Considering the technical, institutional, and transition challenges and opportunities outlined above, we summarize the path forward for future research on urban water management as key research questions (see Table 1).

A key insight from our discussion is that experimentation in isolated pilot projects is not enough to mainstream alternative urban water systems. Future research should use a transdisciplinary approach to generating evidence through socio-technical "lighthouse" projects that apply alternative urban water systems at scale, such as across a whole city district, and thus engage research, policy, and practice in joint learning processes. Such research should highlight drivers of and barriers to innovation and demonstrate the potentials and limitations of alternative systems from an integrated socio-technical system perspective. It should also leverage experience from lighthouse projects in diverse socio-economic contexts, document this experience, and share successes and failures in research, policy, and practice across the urban water sector.

To our knowledge, many potential "lighthouse" projects are emerging in cities as diverse as San Francisco, Bangalore, and Hamburg with highly context-sensitive drivers and niche actors. However, system knowledge remains scattered and tacit and is not systematically compared. Yet, such cross-contextual knowledge exchange and mutual learning is of crucial importance to spurring global innovations within the water sector and to accelerating the evolution, diffusion, and general validation[21] of alternative urban water systems. We thus encourage international non-government organizations, city networks, and donors to engage in increased strategic networking and in facilitating cross-contextual knowledge exchange and mutual learning about the most relevant successes and failures, for instance through IWA Specialist Groups, C40 Cities Networks, and capacity building programs from such development partners as the World Bank.

Table 1. Summary of open research questions to be addressed in future research on alternative urban water systems

	Macro level	Meso level	Micro level
Technical perspective	How can urban water services be defined to reflect the specific challenges of the 21st century? How can these new defined services be translated into ideal combinations of non-grid, small-grid, hybrid, and grid-dominated systems at the meso level and new technical developments at the micro level?	How can ideal combinations of non-grid, small-grid, hybrid, and grid-dominated systems be determined for given contexts? Which degree of source separation, decentralization and modularization is optimal? How can different systems be integrated into a coherent system of systems? How can digital technologies support remote and semi-automatic operation of a large number of distributed treatment systems?	How can on-site and small-scale technologies fulfill the goals set at the macro level? How can these technologies be integrated into households without creating new lock-in effects, for instance, in the form of intra-household grids? How can small-grid systems be designed without creating new lock-in effects?
Social perspective	How do existing laws, norms, and beliefs influence the adoption of alternative urban water systems? What institutional arrangements are optimal for the safe operation and maintenance of non-grid,	What new business models, market structures and firm strategies can potentially transform the conventional urban water system? What economic and financial incentives can support non-grid, small-grid, and hybrid	How do users understand and perceive non-grid, small-grid, and hybrid systems? Which motives and drivers predict stakeholders' acceptance, adoption, and maintenance of alternative systems?

	small-grid, and hybrid systems in various contexts? What context-sensitive legitimation strategies can support the diffusion of non-grid, small-grid, and hybrid systems?	systems in a fair and inclusive way? How can a large number of distributed systems be effectively operated, maintained, regulated, and controlled?	Which interventions can promote the adoption, use, and maintenance of alternative systems? How can different stakeholders shape institutions in favor of alternative urban water systems?
	Short term	Long term	
Transformative perspective	How can experimental implementation of alternative systems be established and developed at scale? How can consideration of and learning about alternative systems be achieved and sustained as standard processes?	How can visions and transition strategies for municipalities, regions, and entire countries be formulated, integrated, and supported within the water sector and across interdependent sectors? How can social and technical innovation processes be coordinated over the course of several decades without disrupting services along the way or creating stranded investments and still break with established path dependencies?	

6. Epilogue - Reflections on integrating multiple perspectives

In this paper, we integrate a range of disciplinary perspectives and fields to outline an integrative research agenda for the future of urban water management. Although we propose a transdisciplinary approach for future research, we are fully aware of the difficulties posed by such an approach.[96] Our challenge in integrating these different perspectives and fields within this paper provides insights into the issues that transdisciplinary teams will have to address. We found it crucial to establish the intrinsic purpose of our integration effort, weigh the contributions of the various perspectives and fields, combine these contributions, and remain critical of the emerging conclusions. As in any team effort, we faced the challenge of balancing the various and sometimes competing expectations, interests, and needs of all co-authors and the often underestimated challenge of appreciating and honoring the specific contributions of each co-author.[97] Writing this paper was a highly iterative and dynamic two-year process. The result can be regarded both as a "system of thought in reflective equilibrium" and as a work in progress that is subject to continuous revision.[98]

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Notes

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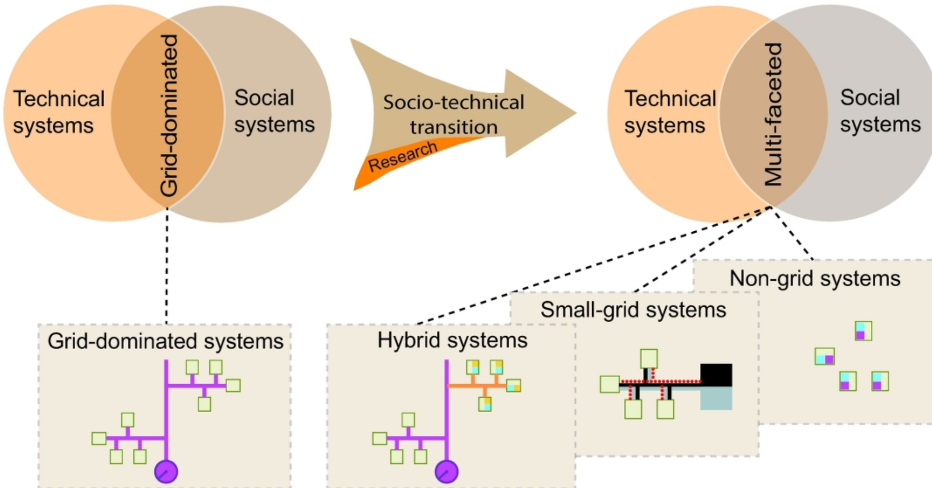
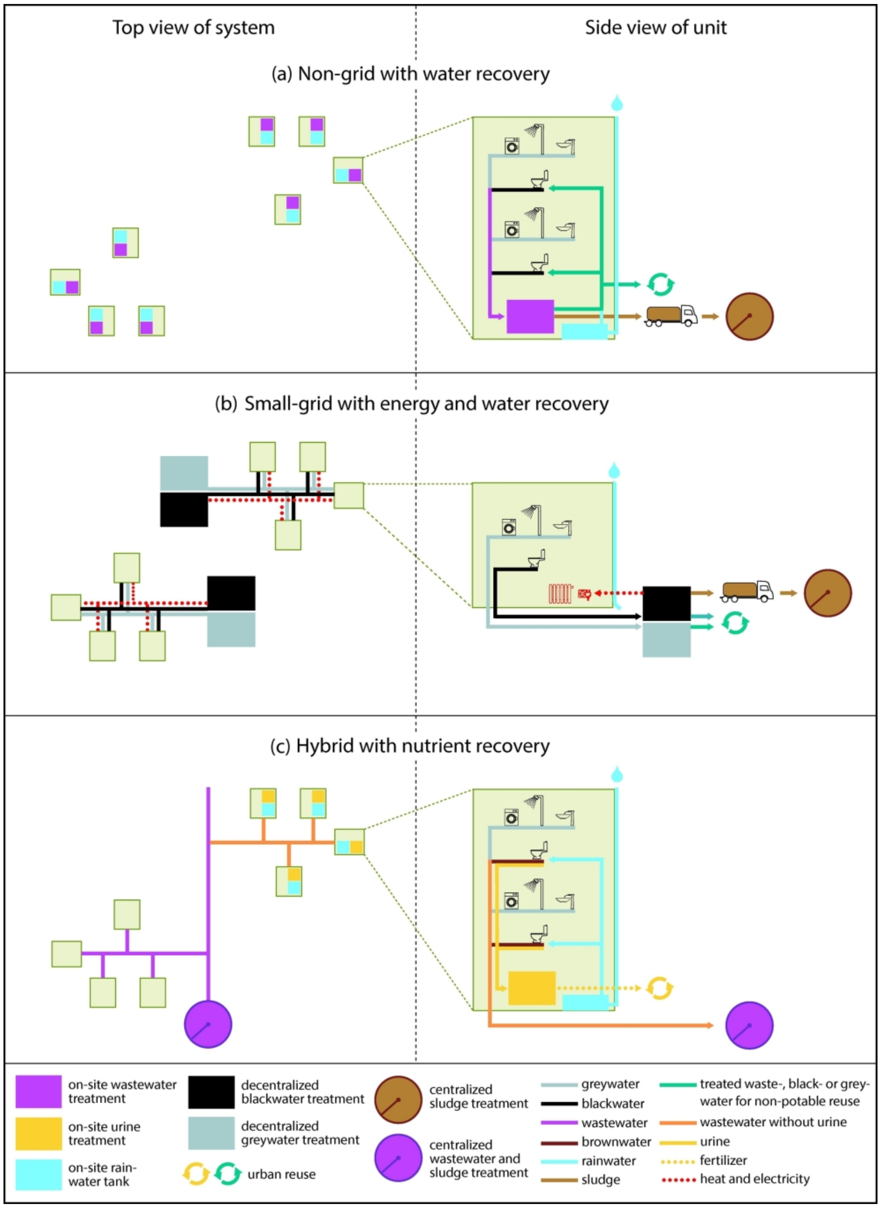
[i] An international group of 35 researchers and practitioners from 21 organisations, including the co-authors of this article, gathered in March 2018 at Monte Verità (Switzerland) to discuss the outlooks for a socio-technical transition in the urban water sector.

[ii] The definition of "small" is relative to context and varies from, for example, tens of houses in a rural or peri-urban setting to several thousand residential and commercial units in a highly urbanized setting.



Graphical Abstract

190x98mm (300 x 300 DPI)



Schematic visualization of (a) non-grid, (b) small-grid, and (c) hybrid urban wastewater systems (left column: top view) and units (right column: side view) based on empirical examples: (a) Beijing, China:24, 25 non-grid systems without sewers between individual buildings but with pipes inside buildings. Blackwater (e.g. from toilet) and greywater (e.g. from sinks, showers, washing machines or dishwashers) is collected in a single wastewater stream and treated on-site for non-potable reuse inside and outside individual buildings (e.g. toilet flushing, irrigation, and/or infiltration for aquifer recharge). Sludge is collected by trucks and treated in centralized sludge treatment plants. Rainwater is harvested and used for toilet flushing. (b) Hamburg, Jenfelder Au, Germany:23 small-grid systems for groups of individual buildings with different pipes for source-separated wastewater streams. Blackwater and greywater are collected and treated separately in decentralized treatment plants. Treated greywater is reused outside buildings. Energy is recovered from blackwater as heat and electricity and used in buildings. Sludge is collected by trucks and treated in centralized sludge treatment plants. (c) Eawag, Zurich, Switzerland:27 hybrid systems integrate non-grid and small-grid solutions into a grid-dominated system. Brownwater (e.g. from toilets, but without urine) and greywater is collected in a single wastewater stream and treated in a centralized wastewater treatment plant. Urine is collected through urine-diverting toilets and treated on-site. Urine is transformed into fertilizer for reuse in urban agriculture44. Rainwater is harvested and used for toilet flushing.

179x245mm (300 x 300 DPI)