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REVIEW

Emerging solutions to the water challenges of an urbanizing world

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The top priorities for urban water sustainability include the provision of safe drinking water, wastewater handling for public health, and protection against flooding. However, rapidly aging infrastructure, population growth, and increasing urbanization call into question current urban water management strategies, especially in the fast-growing urban areas in Asia and Africa. We review innovative approaches in urban water management with the potential to provide locally adapted, resource-efficient alternative solutions. Promising examples include new concepts for stormwater drainage, increased water productivity, distributed or on-site treatment of wastewater, source separation of human waste, and institutional and organizational reforms. We conclude that there is an urgent need for major transdisciplinary efforts in research, policy, and practice to develop alternatives with implications for cities and aquatic ecosystems alike.

Water has become a challenge of global dimensions (*1*). Many researchers and policy-makers have focused on large water users such as agriculture, the impact of future droughts on food security, and the quality of receiving water, giving little thought to the ability of cities to handle the urban water cycle adequately (*2*). Urban water management (UWM) has recently gained more attention, in part due to the comprehensive Sustainable Development Goal on Water (SDG-6) (*3*). The generally accepted approach to UWM builds on a well-established socio-technical system that, at least in the more affluent part of the world, has solved most of the water and hygiene-related problems afflicting cities at the turn of the 20th century. The core centralized services are the provision of safe drinking water, urban hygiene (for the purpose of public health), and protection against flooding (*4*), complemented by water pollution control.

UWM in high-income countries

The UWM system relies on investment-intensive, usually underground, pipe networks that provide single-quality drinking water and evacuate stormwater and wastewater. In many places, reservoirs and long-distance water conveyance systems compensate for inadequate local water resources. In addition, water and wastewater treatment plants provide an interface to the aquatic environment, treating raw water for drinking-water purposes and wastewater for water pollution control. Indeed, the main components of the UWM system have been considered the most important medical advance since 1840 (*5*) and still serve as the prevailing model for prospering cities worldwide (*6*). An additional important infrastructure—besides water supply and wastewater removal and treatment—is the stormwater drainage system. On a local level, the built environment has a strong influence on the natural hydrological characteristics of a catchment. A substantial part of the global urban area of 658,760 km^2 (*7*) comprises impermeable surfaces. This leads to a higher surface runoff and a faster response time to the rain event (*8*). Without adequate drainage infrastructure, unwanted urban flooding events will occur.

In the process of urban water use, waste is produced in the form of wastewater. However, wastewater also contains important resources, including water, organic matter, heat, and nutrients such as phosphorus and nitrogen (Table 1). For example, the amount of nitrogen passing through the human metabolism on a global scale and therefore potentially ending up in wastewater is on a par with major components of the nitrogen cycle. For a population of 9 billion, nitrogen in wastewater would be of the same order of size as the anthropogenic production of 35 Mt of reactive nitrogen per year (about 25% of the present production) suggested as the upper boundary for a "safe operating space" of humanity (*9*). In view of the large losses of nitrogen in agricultural production (*10*), the world can only be kept within the suggested boundary with a dramatic increase in nitrogen recycling from wastewater.

The current UWM approach has worked so well because it delivers its main services securely at a good quality to a majority of people in a region. Its institutional side is characterized by planning and investment processes traditionally delegated to municipal water authorities. These actors follow well-formulated regulatory codes in their operations and rely primarily on highly specialized technical expertise.

The downsides of the current UWM system are its strong dependence on large quantities of water (Fig. 1), high investment costs, and a need for stable institutions, as well as long planning horizons and inefficient use of resources. Whereas most of these disadvantages have different implications depending on the context, inefficient use of resources is a global issue. Despite the high amounts of energy in wastewater (Table 1), wastewater management is a net consumer of energy, and recycling of nitrogen is only possible to a very

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small degree within the existing system (*11*). Additionally, the substantial investments in infrastructure required to move the large amounts of water in and out of cities and treating the resulting wastewater are of interest beyond the local setting. The most transparent report from the Organization for Economic Cooperation and Development (OECD) (*12*) calculates a global investment need of US$772 billion year^{-1} (or about 1% of gross domestic product) by 2015 for the OECD countries and Brazil, Russia, India, and China. However, other literature estimates are highly variable, from US$190 billion year^{-1} to US$1037 billion year^{-1} (*13*, *14*). Additional US$114 billion year^{-1} [US$71 billion to US$166 billion year^{-1} (*15*)] are required to achieve universal access to safe drinking water and adequate sanitation for all by 2030. Assuming that the investments for water supply and wastewater management are similar in magnitude, the total water infrastructure value for a connected global population of 9 billion people would amount to about US$60 trillion (*16*).

Today, UWM is incurring increasing economic, social, and environmental costs, even in countries with a long tradition of successful practices. This is a consequence of aging built infrastructures, increasing urbanization, emerging contaminants, competitive water uses, and measures to mitigate the effects of climate change (e.g., water-saving measures). Furthermore, public utilities have often missed out on charging full-cost tariffs and are increasingly confronted with a backlog of investments (*13*). These recent developments question whether and in what form the existing UWM system can still be the best solution for the world as it has been since the beginning of the 20th century (*13*).

Limitations for the global diffusion of centralized UWM

Whereas the need for reform in industrialized countries might still be a matter of debate, the proliferation of current UWM practices to the rest of the world is certainly riddled with major problems. Although reliable information on sewers (Fig. 2A) and treatment plants is scarce for Africa and Asia, there is general agreement that connection rates remain very low [an estimated connection rate of 14% for Africa and 18% for Asia in 2000 (*17*)], and the overall treatment of the collected wastewater remains highly insufficient, even in capital cities (*18*). For Latin America, connection rates are higher, but only 15% of municipal wastewaters are treated (*19*).

This backlog is compounded with the current unprecedented global population growth rate. A major part of this growth is projected to take place in the cities of Africa and Asia, including many countries with a low human development index (HDI) as well as pronounced and increasing water scarcity (Fig. 2B). Small and medium-sized towns will bear the brunt of this future urbanization growth (*20*), notably in the provision of access to safe drinking water (Fig. 2C) and sewers (Fig. 2A). High urban growth rates lead to high planning uncertainty, especially in areas with a low HDI and low institutional reliability (*21*). In combination with high discount rates, indicating a strong preference for spending money on immediate benefits rather than on long-term investments (*22*), there is little willingness and ability to embark on large-scale infrastructure projects. A modeling study based on past investment patterns (*17*) estimated that even on the most optimistic assumptions, only 36% of the African population and 44% of the Asian population will be connected to a sewer network by 2050. The implementation of well-functioning, nutrient-eliminating wastewater treatment plants depends on the previous construction of sewers and often involves substantial delays. A case in point illustrating the enormous resources and sector investments needed has become apparent with the Swachh Bharat national campaign by the government of India to achieve a turnaround in India's poorly served cities and towns (*23*).

Apart from the lack of capital, there are also other, more general reasons why conventional UWM is not the best solution for rapidly growing

Table 1. Resources in wastewater. For nutrients and water, global averages are given. No global information is available concerning warm water and organic matter in wastewater. Local loads depend inter alia on nutritional status, household devices, water availability, and habits.

Water (liters person^{-1} day^{-1})		
Domestic	184	Global average (*69*)
Industrial	300	Industrial global average (*69*)
Energy (MJ person^{-1} year^{-1})		
Heat contained in warm water	2800	Typical European country (*11*)
Chemical energy contained in organic matter	540	Typical European country (*11*)
Chemical energy "embedded" in N and P	180	Global average, year 2000 (*11*, *17*)
Nutrients from human metabolism (g person^{-1} day^{-1})		
Nitrogen (N)	10	Global average, year 2000 (*17*)
Phosphorus (P)	2	Global average (*17*)

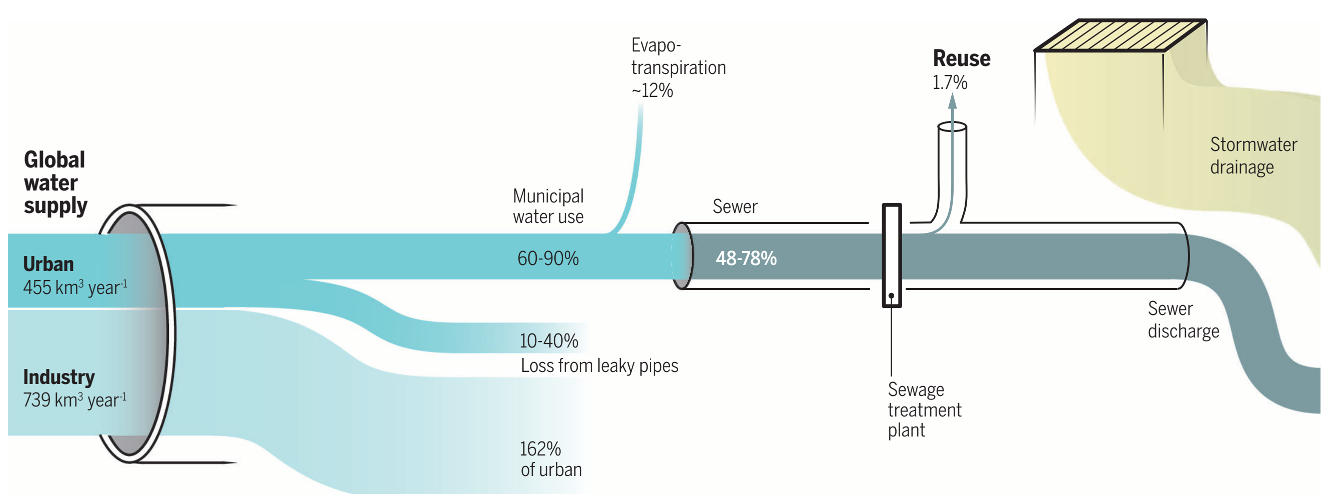


Fig. 1. The global urban water cycle. According to country-specific data from FAO (*69*), the global municipal water withdrawal is estimated to be 454.8 × 10^9 m^3 year^{-1} (184 liters person^{-1} day^{-1}), and 738.8 × 10^9 m^3 year^{-1} (300 liters person^{-1} day^{-1}) for industrial use. This corresponds to 12% and 19%, respectively, of the total global water withdrawal. Shiklomanov (*74*) estimates global urban evapotranspiration to be around 12%. Typical water "losses" due to leaky supply systems are between 10 and 40% (*69*, *75*). Globally, around 1.7% [7.7 × 10^9 m^3 year^{-1}; from (*36*)] of the municipal water supply is reused in this way—mostly for irrigation.

cities. Network-based infrastructures are designed and built for "final design performance." High growth rates therefore impose large idle capacities during the early life of the infrastructure, with correspondingly high per-user costs (*22*). Furthermore, high planning uncertainty also increases the risk of sunk costs if the expectations of city growth are not fulfilled or if not enough water is available for the correct functioning of the sewers. The lack of stable energy supplies, spare parts, and know-how for reliable operation are additional factors that limit the expansion of centralized systems (*24*). As a special case, the improvement of sanitation conditions in informal settlements in low- and middle-income countries has proved difficult because of disabling institutional environments, a lack of secure tenure and rule of law, which often prevent private or public investments in infrastructure (*25*, *26*). In view of the expected increase in the populations of such informal settlements from today's 1 billion to 2 billion in 2030 (*27*), this is a quantitatively important situation with dramatic consequences not only for the inhabitants themselves, but also for the urban and natural environment.

On the basis of those facts, we conclude that for the areas with the highest rate of urbanization, there is an urgent need to develop more cost-effective and resource-efficient systems that deliver the desired water services of UWM without the prohibiting constraints of the conventional centralized system.

Alternative solutions to conventional UWM

As the currently dominant conventional approach to UWM is unlikely to meet the challenges of an increasingly globalizing world [see also (*28*–*30*)], a shift toward a "new paradigm" is required (*31*). Three of the more salient candidates for new water paradigms that substantially depart from the present strategy are integrated water resources management (IWRM), adaptive management (AM), and ecosystem-based approaches (EBAs) (*31*). A shared feature of these reform agendas is that they give primacy to organizational and institutional reforms in order to orient water management toward providing sustainable water services rather than merely delivering quantities of water. These approaches have gained traction in science and policy-making in recent years (*31*). In particular, they have inspired new policy approaches such as the European Framework Directive, or kindred approaches in countries like Australia, South Africa, and China. However, the impacts on real water systems have been limited (*30*, *31*). One reason is that the routines and practices of water professionals are not directly determined by planning discourses or governmental mission statements. Rather, they are oriented to technical expertise and the professional cultures that have developed over decades in line with the dominant UWM systems.

This debate tells us that it is not enough to hope for technological breakthroughs or to believe in the wisdom of more inclusive governance arrangements alone. Rather, the joint development of new institutional conditions and technological designs is needed to ensure fundamental improvements [so-called transitions in socio-technical regimes (*32*)]. What is at stake, therefore, is a mainstreaming of novel system alternatives in the UWM sector that would respond to the challenges noted above. A number of technological and institutional approaches look promising. They represent potential foci of future innovation efforts. However, they are nonexclusive, and there are many overlaps and potential synergies between them.

Stormwater drainage

Urbanization means that not only the population but also the area in need of drainage increases. Estimates for 2000 to 2030 indicate an enlargement

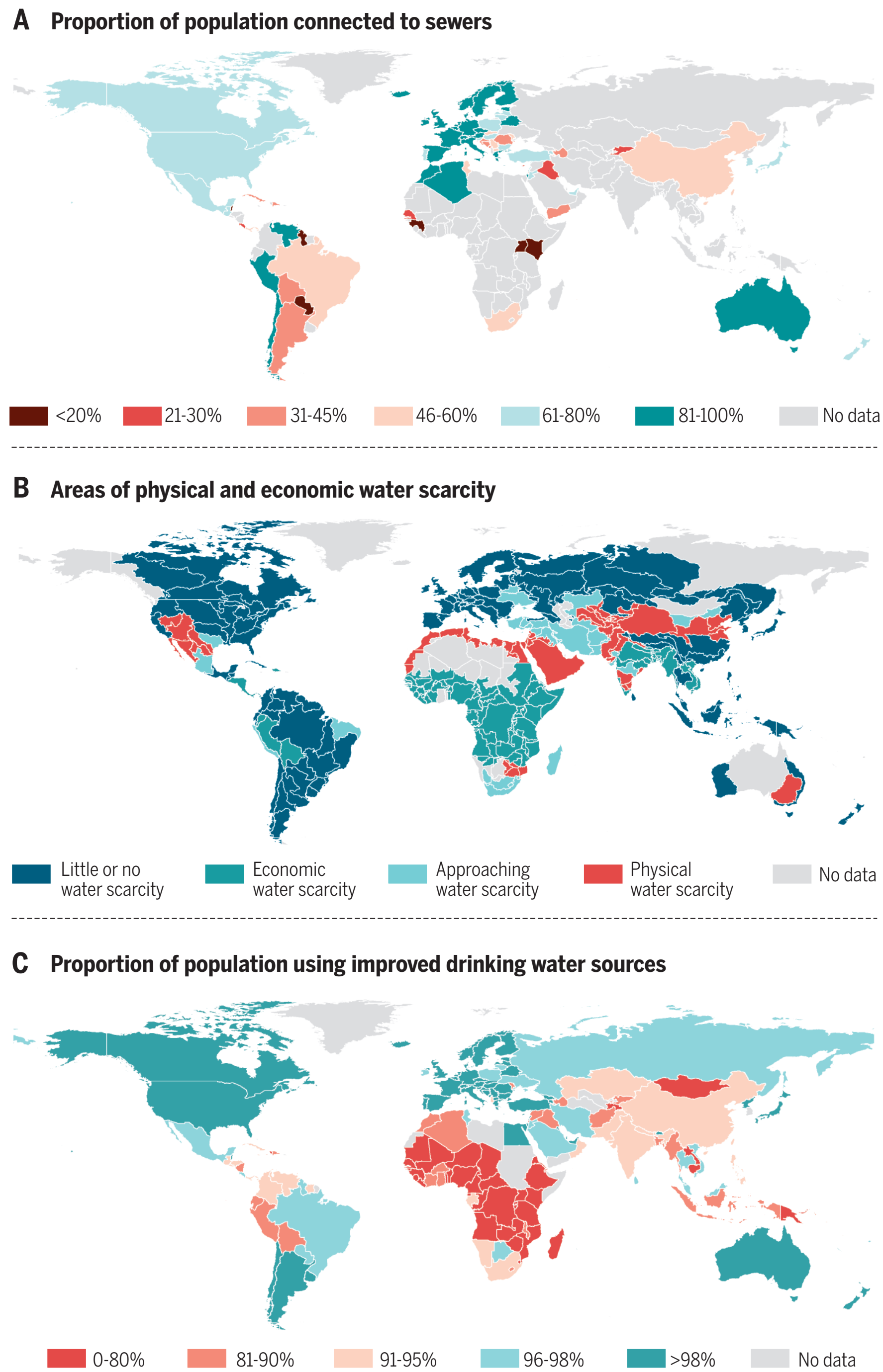


Fig. 2. Important global challenges of UWM. (**A**) Proportion of population connected to sewers (*76*). (**B**) Areas of physical and economic water scarcity [data from International Water Management Institute (IWMI); updated in 2015; map reproduced with permission from IWMI (*77*)]. (**C**) Proportion of population using improved drinking-water sources (*78*).

of the global urban areas by an additional 60 to 200% (*33*). It is therefore no surprise that the limits of the conventional UWM approach were first recognized in stormwater drainage. Concepts such as sustainable urban drainage systems (SUDS), low-impact urban design and development (LIUDD), water-sensitive urban design (WSUD), and green infrastructures (GI) appeared in the scientific literature toward the end of the 20th century (*34*). The primary goal of these concepts is to maintain or reintroduce a more natural state of the urban hydrological catchment, to reduce the impact of stormwater drainage on the aquatic environment, and to reduce flood risk. All these concepts introduce a strong element of decentralized measures and emphasize the importance of long-term planning.

Increasing water productivity

This practice helps to reduce net water consumption and utilize the available water more efficiently. Three main strategies designed to increase water productivity are reducing water waste, down-cycling or reuse of lower-quality water, and regenerating high-quality water from used water (*35*). In the last two strategies, the collected wastewater is in most cases treated in wastewater treatment plants to the desired quality, making it fit for reuse. Globally, around 1.7% [7.7×10^9 m^3 $year^{-1}$; from (*36*)] of the municipal water supply is reused in this way—mostly for irrigation (Fig. 1). In California, 61% of the reused 0.8×10^9 m^3 $year^{-1}$ of water is applied for irrigation, and the rest is mainly used for recharging the groundwater and for the targeted alimentation of surface water (*36*). There are comparatively few large-scale direct potable reuse schemes, and these compete in terms of energy consumption and costs with desalination technology. The advantage of this approach is its compatibility with conventional network-based UWM. However, it requires additional infrastructure for treatment and redistribution, thus increasing the energetic, financial, and institutional burden. More innovative solutions are found in Table 2.

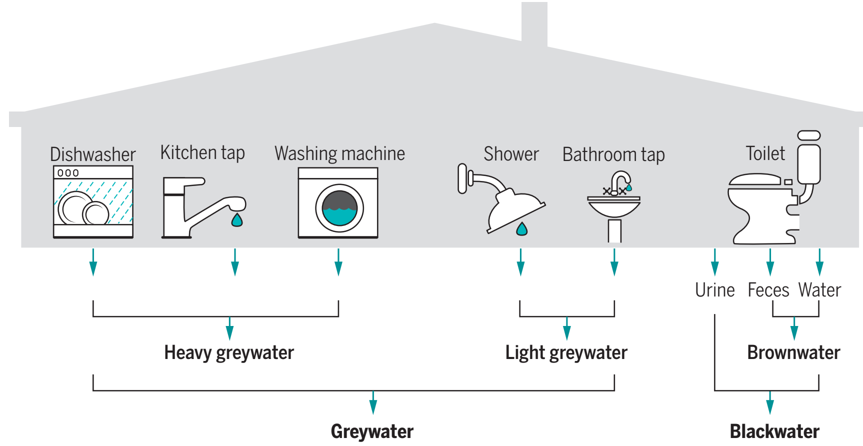


Fig. 3. With source separation of wastewater in the household, new types of wastewater can be constructed for optimal treatment. It is even possible to include treatment and recycling processes in a single device. This offers totally new perspectives for mass-produced, consumer-friendly wastewater treatment technology (for examples, see Table 2).

Source separation of waste

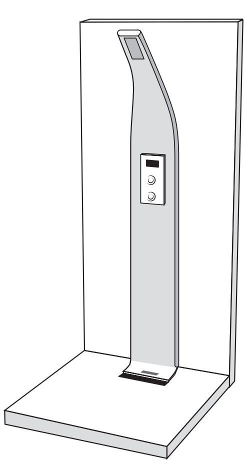
Separating wastewater streams as early as possible alleviates resource recovery and/or facilitates the treatment process. This can take place at the household level, but also at the level of a single household device (Fig. 3). In particular, the separation of greywater promises new ways of reusing water. Compared with wastewater reuse, greywater recovery involves smaller hygienic concerns, has a reduced "yuck" factor, and demands less treatment effort. Especially in arid

Table 2. Examples of emerging solutions to UWM challenges.

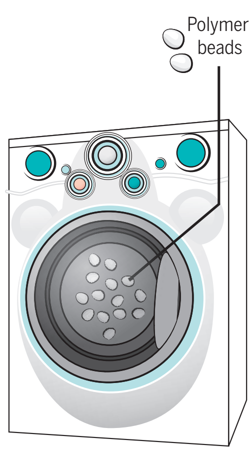
Increasing water productivity — Reuse | Substitution

Distributed treatment

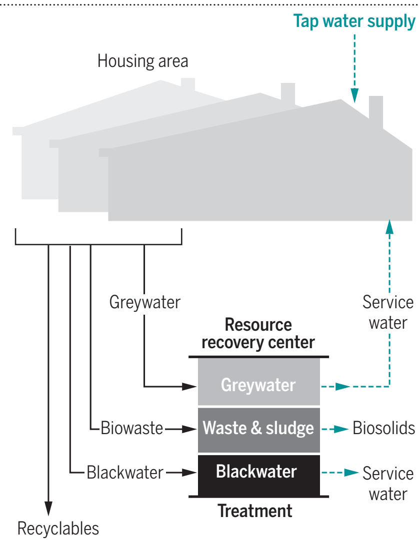
Source separation of waste



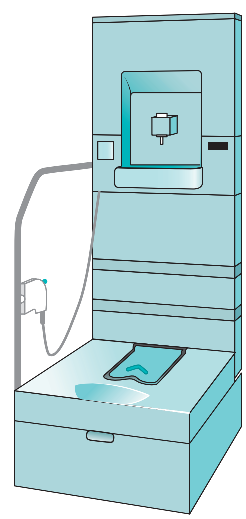
Recycling shower (*70*)



Waterless washing machine (*71*)



Distributed treatment of waste at district level (*72*)



Blue Diversion Toilet (*73*)

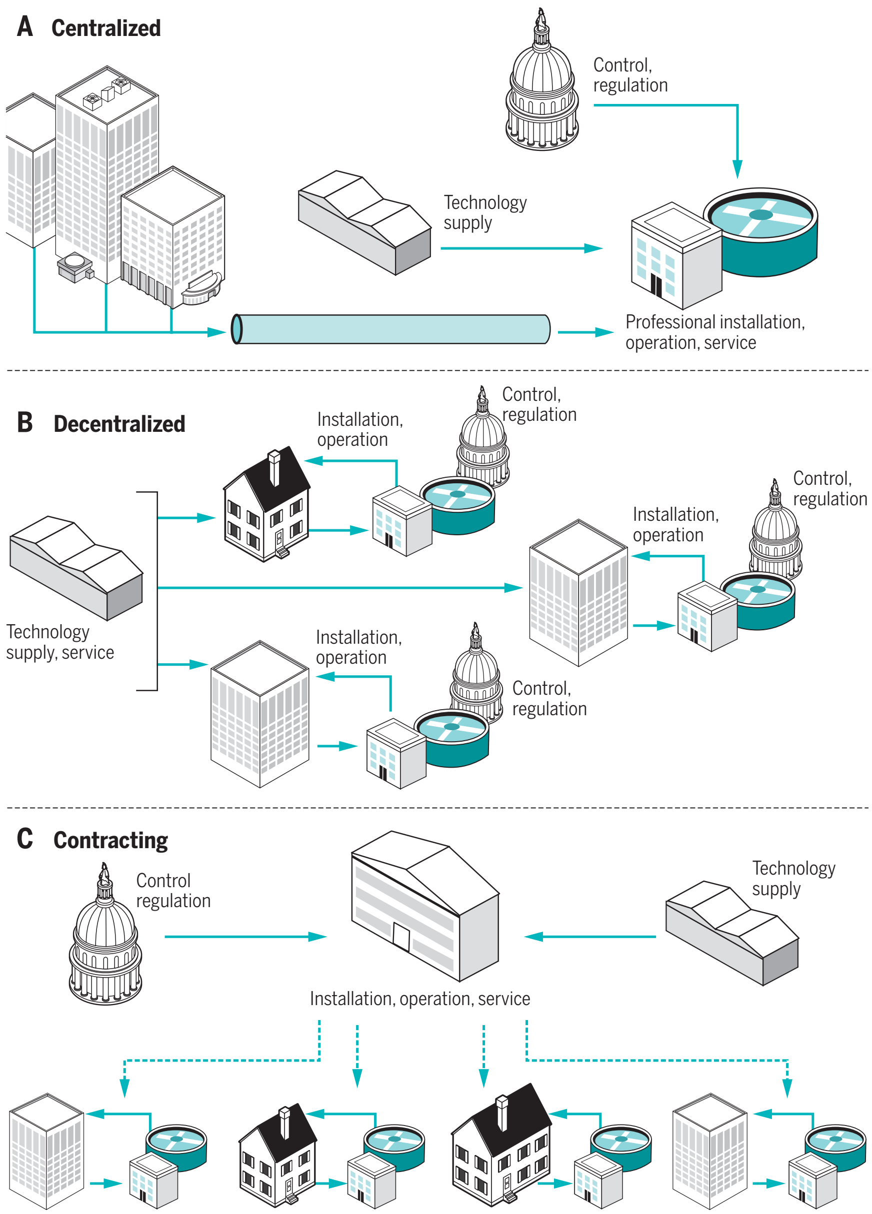


Fig. 4. Alternatives for management of centralized and decentralized wastewater treatment plants. (**A**) Fully centralized, (**B**) fully decentralized, and (**C**) contracting scheme for decentralized technology with centralized operation.

regions, greywater provides greater potential potable water savings than local stormwater capture because it provides a steady source of water during periods with little or no rainfall (*36*, *37*). Not only water, but also energy and nutrients are more easily recovered from source-separated wastewater: energy from hot water (*38*) and from feces (*39*) as well as nutrients from urine (*40*). Some well-documented examples of source separation include the 40 million domestic biogas reactors in China (*41*) or the almost 100,000 urine-diverting dry toilets in peri-urban areas of eThekwini, South Africa (*42*). Although most examples of source separation are still found in areas without existing sewers, there are good reasons to apply this concept more broadly in order to render UWM more resource efficient (*43*).

Distributed or on-site treatments

Decentralized systems have the advantage that they can be installed in the short term when needed, thereby reducing the requirement for large-scale investment in sewers and centralized wastewater treatment plants. Moreover, they allow the local reuse of water and therefore increase water productivity (Table 2). Also, the argument of lower costs of centralized systems due to economies of scale at the treatment plant has become much less persuasive in recent years (*44*). Over the last few decades, large numbers of decentralized wastewater treatment plants have been installed worldwide (*45*). Their performance has been judged as mediocre at best, with some authors stating that their failures are not primarily due to immature technology but rather to weak or unsuitable organizational models and institutional setups (*37*). Whereas this may be partially true (see next section), many small-scale technologies are little more than scaled-down conventional treatment plants, originally developed with a very different set of requirements than we would imagine for small-scale technology.

Institutional and organizational reforms

Multiple efforts on this front have been advocated in the sector since the late 1980s (*46*). Great hopes were originally placed in a stronger involvement by private actors in service delivery and infrastructure investment. However, evidence about the success of these reforms is mixed (*47–50*). Research has shown that public and private organizations can be equally effective and efficient in strategic planning (*51*), and that success of reforms depends on how well competences of utilities and institutional context conditions are aligned with the technological characteristics of the sector (*52*, *53*). For the case of distributed systems, this means that innovation in organizational and regulatory models is badly needed. The centralized management approach, combined with centralized treatment technology, has been considered the most cost-efficient organizational and regulatory mode for most of the 20th century (*44*) (Fig. 4A). This is especially true when it is compared to a fully decentralized approach, where end users are responsible for operating their treatment plants and regulators have to oversee innumerable individual installments (Fig. 4B). Recent advances in sensor and communication technology, however, enable new contracting schemes (Fig. 4C) where central operators can monitor large fleets of individual appliances and thereby guarantee very good performance in terms of effluent quality and convenience for the end user (*54*).

Ways forward for policy and research

Overall, any promising approach to solving the urban water challenges requires innovation and development processes in almost all technical, organizational, and institutional dimensions. However, the UWM sector seems to be very poorly prepared to deal with innovations (*55*, *56*). The legacy of the network logic, slow renewal cycles, and high long-term investments lead to risk aversion with respect to novel technologies. Little competence in innovation management has consequently been built up in most water utilities (*53*). Policy-makers and end users have also been reluctant to accept disruptive changes, so that increased efforts are necessary to mainstream innovations [compare direct potable reuse (*57*)]. Furthermore, a major international research and policy effort is needed in the field of sustainable water futures (*1*). This represents a policy challenge on par with other processes of global change.

On-site treatment and source separation, especially in combination, open up the potential for locally adapted water services and the recovery and reuse of valuable resources. A good example is the "Reinvent the Toilet Challenge" of the Bill & Melinda Gates Foundation, calling for the next generation of on-site wastewater treatment technology. This call aimed to stimulate the academic community to develop an innovative toilet for the urban poor with no requirement for conventional network infrastructures (water pipes, sewers, electricity networks), while simultaneously promoting maximal resource recovery and zero emissions (*58*). By concentrating on the toilet alone, this initiative essentially broke with the convention of treating domestic wastewater as a single stream and suggested that source separation in on-site settings is an attractive way forward (Table 2). The Blue Diversion Toilet, a urine-diverting dry toilet with a separate water cycle developed within this program, exemplifies the high potential of source separation and resource recovery in a single household device (Fig. 3). By separating human waste from the water cycle, energy-efficient on-site treatment and recycling of the water become possible (*59*), and the separate collection of urine and feces allows for a large number of processes to recover nutrients and energy (*60*). Even on-site treatment of urine and feces may be conceivable, opening the market for these technologies beyond urban slums (*61*). This is, however, still in the development stage only.

The aim of such efforts is not only to solve technical problems, and it must involve more parties than scientists and engineers alone. The complexity, ambiguity, and uncertainty of such radical innovation processes require a approach that transcends the boundaries between different disciplines and bridges knowledge generated by research, policy, and practice (*62*). Longer-term industrial transformation policy programs must be envisaged to meet the challenges of UWM, especially as the sector is characterized by large and long-lived infrastructure. We can learn here from recent experiences in sectors such as agriculture, defense, health, or energy (*63*). First, successful transitions need long-term support for basic research on a broad variety of alternative solutions. For UWM, this means that we should not aim for one single superior alternative to replace the established technological paradigm. Second, public policies should complement and support innovations made by private actors but without curtailing competition between alternative solutions. UWM can learn much from how this complementarity played out in the field of renewable energy (*64*, *65*). Finally, technologies should be tested in a broad variety of experimental settings to ensure robustness, cost-effectiveness, social acceptance, and the wide applicability of alternative solutions.

The present rapid urbanization in areas with water scarcity and/or missing or aging urban water infrastructure is an immense challenge, as well as a formidable chance for developing next-generation technologies and management structures. In Australia, increasing water scarcity has led to large-scale academic efforts to develop the alternative resource of stormwater (*66*), whereas the aging infrastructure of the United States has led to similar efforts in the area of infrastructure management (*67*). Singapore pursues centralized recovery of wastewater to reduce dependence on Malaysian water resources (*36*), and in China, small-scale membrane bioreactors are proliferating to provide enough water for its growing cities (*68*). There will be no one-size-fits-all solution, but with the immense challenges for UWM ahead of us, it will be important to accelerate research efforts and to profit from the lessons learned about successful innovations in other sectors.

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