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Modular, adaptive, and decentralised water infrastructure: promises and perils for water justice

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Climate change, ageing infrastructure, and funding shortfalls threaten the sustainability of modern, 20th century centralised water systems by increasing drinking water costs and undermining water security, particularly for underserved populations. Modular, adaptive, and decentralised (MAD) water infrastructures can address this by using novel technologies, institutions, and practices to produce, transport, and store clean water in the absence of — or integrated alongside — existing centralised water infrastructure. Examples of MAD water systems include: next-generation ultrafiltration systems, atmospheric water capture systems, mobile water treatment stations, and innovative container-based systems. These decentralised models require a justice-oriented framework to unlock the promise of sustainable access to safe, reliable, affordable water supply for a more mobile, just, and resilient world. We propose a model for advancing justice-oriented MAD water.

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Introduction

For the last century, centralised water supply infrastructure has been the global gold standard for potable water delivery. Yet, 2 billion people globally lack access to safely managed drinking water, with 4 billion facing severe water insecurity at some point each year [1,2]. Climate change presents new challenges for the sustainability of modern water systems, which are often poorly maintained and increasingly approaching the end of their service lives [3]. Ageing pipelines, reliance on outdated treatment and sensor technology, and unprecedented urbanisation alter water demand patterns that cumulatively compromise centralised water systems [4]. Climate-induced infrastructure losses, associated with both chronic (e.g. drought) and acute (e.g. flood) weather events, compound local government financial constraints and further undermine the sustainability of water infrastructure by inhibiting system upgrades and replacement [5,6]. The prospect of costly rebuild-or-relocate decisions in coastal areas, which house over a third of the global population, also undermines funding for badly-needed maintenance and upgrades [7]. Additional global issues, such as replacement of lead service lines, or retrofitting treatment for modern contaminants such as per- and polyfluoroalkyl substances (PFAS), exert additional financial pressure on water systems [8,9].

A large body of literature has analysed the tradeoffs of centralised, decentralised, and hybrid water systems [4,10,11]. Over-reliance on centralised, and centralising, water infrastructure that is increasingly vulnerable to floods, fires, and drought beckons a paradigm shift in this era of managed retreat, climate change, and overall greater human mobility due to socio-environmental disruption [12,13]. Disruptive innovations are already reshaping the energy and waste sectors through decentralised capture and service delivery [14–16]. The water sector is at the cusp of a similar wave of innovation.

This review summarises emerging realities for water insecurity in an era of disruption, and new developments that we call modular, adaptive, and decentralised (MAD) water infrastructure. These technologies can improve system resiliency [17] and may also present a ‘soft path’ to hard-engineered systems for resource-poor communities where climate disruption is minimal [18]. These technologies may also cause unintended consequences that exacerbate water insecurity if they are unaffordable, disproportionately lead to system disconnection by wealthier users, or reduce household water autonomy [19,20].

By bridging the engineering and social sciences, we can expedite the paradigm shift already underway with respect to water delivery while ensuring water justice, security, and sustainability under conditions of climate disruption. We are interested in how physical and social infrastructure can be creatively re-imagined, particularly in low-income and vulnerable communities that already suffer from poor or limited water infrastructure. We present examples of emerging technologies for MAD water supply and summarise MAD water themes that warrant additional consideration for water justice.

Water insecurity in the age of disruption

Water insecurity — the lack of safe, reliable, sufficient, and affordable water for a thriving life [21] — is not restricted to the developing regions. The myth of universal and safe provision in the global north is receiving increasing attention, as many communities have long lacked water coverage [21]. Water insecurity is more common for renters and people living in mobile homes; for disaster migrants and others living in substandard housing; for American Indians, First Nations, and Indigenous people; for Black, Hispanic/Latinx, and other racial/ethnic minority communities; and in informal communities [21]. Fragmented water utilities and ageing water infrastructure are proving ill-equipped to respond to 21st century challenges [22,23]. Climate disruptions compound existing water insecurities by triggering cascading technological failures (or emergencies) that further erode the efficacy of ageing and unequal water infrastructure [24].

There are three main reasons why traditional models of centralised water service development will not work in the climate disaster era. First, disasters across the globe directly destroy water infrastructure: wildfires melt pipes, hurricanes destroy levees, combined sewer overflows pollute waterways, and droughts render storage infrastructure useless [25]. Second, climate disruption contributes to climate migration and climate retreat, and as such, the challenge is to achieve levels of water security for these mobile populations, whether in refugee camps, temporary residences, or new communities [26,27]. Third, water quality deterioration — due to contamination or groundwater salinisation linked to disasters and climate change — makes potable water production increasingly costly [25,28], particularly as water utilities grapple with the costs of removing emerging pollutants such as PFAS and microplastics [29]. Indeed, climate-induced disruptions will speed the decay of public water infrastructure already underway [30], a problem that is even more acute for smaller water systems, whether in high- or low-income regions [31,32].

Society and technology are slowly coming to grips with the limits of 20th century 'modern water' [33]. Such a revolution is already underway to address other forms of resource insecurity. The most progress has been made in decentralising energy security through the widespread adoption of solar panels, wind turbines, and other low-carbon alternatives to centralised energy systems. These strategies allow modern households to contribute to, or disconnect from, the energy grid [15,16], with justice principles ensuring affordable electricity pricing [34] despite significant implications for energy governance [35]. Similarly, entrepreneurs are using decentralised approaches to reduce sanitation insecurity in low-resource settings through innovations such as dry toilets and container-based sanitation, which convert and monetise waste into useful products [36]. The same principle is in operation in high-income settings through anaerobic digestion systems that turn organic waste (faecal sludge, food and garden wastes) into biogas [37]. We now discuss how MAD water infrastructure can serve 21st-century water needs in just and sustainable ways.

Examples of modular, adaptive, and decentralised water infrastructure

Early generations of decentralised approaches to safe drinking water, such as point-of-use chemical and solar disinfection, rainwater harvesting, and safe water storage have been around for decades [38,39]. Creating the right quality water at the right time and place can save energy but requires a new generation of decentralised water treatment technologies [40]. There are several promising new MAD water technologies, and we present examples framed around five critical dimensions of water security: harvesting, treating, distributing, monitoring, and governing.

Harvesting

In addition to using low-technology harvesting techniques such as rainwater collection, dug wells, and fog catchers, MAD systems can also harvest moisture from the air to produce useful quantities of clean drinking water [41–43]. Passive systems, which take advantage of diurnal humidity and temperature variations, are likely to be of limited use in areas of higher population density, and those with very low humidity. While active systems, requiring artificially cooled collected surfaces, are relatively energy intensive [44] and still constrained by fundamental thermodynamics [43], nevertheless lend themselves to being solar powered and thus independent of centralised water and energy systems. The water produced is still at risk of contamination from airborne pollutants [45] and so may require significant treatment, with attendant costs and management issues. Although there are limited examples of these systems operating at scale, the local autonomy they offer is compatible with MAD water principles.

Treating

The use of high-performance small-sized modular treatment systems enables decentralised water systems to provide *fit-for-purpose* water quality. This avoids over-treating water that subsequently degrades during distribution or is used in applications which do not require high-quality water (e.g. toilets or irrigation). Modular treatment systems can be rapidly deployed in private, commercial, and government buildings to treat relatively small quantities of water to a very high quality, and have been especially useful during emergencies when centralised water systems fail. Modular systems can potentially be mass produced, certified by third-party validation centres, and readily installed by homeowners or non-specialised plumbers [46]. Many modular treatment technologies, such as carbon block, nanofiltration, graphene or reverse osmosis filtration, or UV disinfection, are already commercially available or very near to market. Ultrafiltration (UF) modules have long been deployed in low-resource settings where reliable chemical disinfection is not guaranteed or locally accepted, or is over-reliant on transport and storage of hazardous chemicals such as chlorine [46]. Newer gravity-driven membrane filtration systems, which feature composite membrane and biofilm ultrafiltration, offer household-scale solutions with annual costs as low as US$5.71 per household [47,48], with hydrothermal solutions to backwash the membrane and increase sustainability [49].

Distributing

MAD infrastructures have also been used by tribal communities in the US. During the COVID-19 pandemic, rapid relief programs combining water quality testing, delivery, and a mobile water filtration system in a converted school bus, have helped address local water pollution issues faced by the Hopi Tribe [50]. Elsewhere a decentralised, 100% automatic, off-grid water filtration system, can be installed at any groundwater well site to provide safe drinking water. This *Water Box* system has been successfully tested in the Navajo Nation for over 5 years [50] and can produce around 4000 litres of potable water per day. Portable MAD systems have also demonstrated their effectiveness in the production of drinking water in emergency situations. These systems can be used as a pre-treatment for RO, MF, or UF treatments and can be adapted to meet the water treatment requirements for the duration of the emergency. MAD systems can improve health through improved water quality at the point of consumption, and have the potential to provide sustainable fit-for-purpose water to communities.

Monitoring

Because MAD water systems are less centralised and less hierarchical, they require similarly distributed monitoring to optimise operational performance and ensure water safety. Low-cost internet-of-things technology will play an important role. Examples include groundwater handpumps outfitted with GSM transmitters contributing to dramatically reduced pump downtimes in rural Kenya by sending messages to local mechanics when there is a mechanical failure [51], QR-codes as currently linked to distributed sanitation systems [52], and low-cost Arduino-based sensors for monitoring water levels and quality in rainwater harvesting systems. To ensure the desired just outcomes of a MAD approach these monitoring systems must be well-integrated into participatory governance systems, and not just technological add-ons [51] that increase management or maintenance burdens for households or communities.

Governing

Modular infrastructures are promising and versatile technologies to supplement centralised urban water infrastructures, provide continuous water to rural communities, and serve as emergency solutions [18]. Emergency deployment of MAD systems is usually governed by command-and-control protocols, with costs often of lesser concern than speed and technocratic effectiveness. Sustainable and just use on a longer-term basis, including the ability to, for example, regulate demand management during a drought, requires integration with local governance systems. MAD systems can be low-cost, simple to operate, and low-maintenance, and in many cases independent of grid energy. Consequently, MAD infrastructures play an increasingly pivotal role in the water sector due to the need for more flexible and adaptive solutions in urban and rural communities in the context of climate change and sustainability [17,23,53]. Embracing decentralisation risks fragmentation without coordination or systemic integration. The degree of fragmentation in decentralised water systems is greatest in low- and middle-income nations where there is unreliable or no local supply and households often use multiple water sources (e.g., rainfall collection, local wells, delivery services) to improve household water security [54]. Decentralisation is also often a reactive adaptation to governance failings in centralised systems and requires greater coordination to achieve social justice and sustainability goals.

In summary, innovative MAD water treatment technologies will be critical tools for ensuring water security and sustainability in the age of disruption, given their versatility in various socio-cultural and political-economic contexts. But MAD approaches also require a justice-oriented framework in order to prevent the reproduction of historic inequalities in water supply provision. Visionary thinking is necessary to drive the technologies, institutions, and practices necessary to harvest, treat, distribute, monitor, and govern MAD water alongside, or in lieu of, centralised water infrastructure.

Modular, adaptive, and decentralised systems for sustainability and water justice

Serious questions remain as to how MAD water can advance progress toward achieving universal drinking water that is accessible, available, and free from key contaminants in a system that is sustainable, equitable, and just. To achieve 'just sustainabilities' — with twin goals of long-term environmental and social wellbeing — the mere technocratic provision of accessible, affordable, and safe water is insufficient, and in many cases, ineffective or even harmful [55,56]. Justice-informed approaches to MAD water systems recognise how socio-technical shifts in the waterscape reforumulate hydro-social relations, lived experiences and everyday embodiment, and social power [33]; and by extension, the conditions necessary to achieve water justice [57]. Drawing on the water-capabilities approach, securing water is "the ability to engage with and benefit from the sustained hydro-social processes that support water flows, water quality, and water services in support of human capabilities and wellbeing" [58]. So *how* can MAD water systems go beyond SDG benchmarks and be designed, implemented, and maintained to enhance water justice and equity in real-world conditions?

Ongoing research into social infrastructure is the first place to look for suitable approaches. Social infrastructure encompasses formal and informal institutions (e.g. norms about water), social networks, and cultural values [59] that can potentially regulate and maintain physical systems. For example, centuries-old approaches to water allocation such as the *acequias* and similar long-standing systems elsewhere around the world were resilient in the face of challenge precisely because of their flexible, trusted and decentralised decision-making systems [60]. Such pre-existing social infrastructure offers an entry point to reimagine sustainable MAD water systems that add new technical functions or capabilities.

Social dimensions of water provision are a critical part of the deployment ecosystem that fosters engaged and meaningful participation in water services [61]. By recognising and building on social infrastructure, MAD water systems can better align with local cultural values, institutions, and priorities. They can also co-create pathways for new water norms, practices, and collectivities [62].

There is some evidence that MAD water system design and implementation can advance water justice in terms of promoting collective participation and recognition and steer actors away from the individualisation, commodification, and self-isolating provisioning that often further entrenches water insecurity for others [60,63]. Leveraging social infrastructure and designing MAD water requires productive and generative *partnerships with* local water and environmental authorities. The conventional (and centralising) provisioning role of local water authorities in MAD water systems may evolve into more of a supportive role that simultaneously distributes risk and increases local autonomy for self-supplied or decentralised communities. This increased autonomy will not eliminate managerial responsibilities, but rather redistribute these powers across a broader range of local water actors [55,57,59], with explicit care to not increase burdens on households. The need for consumers or communities to purchase water services, either directly or through local tariffs, from a single large state or private entity may be replaced by the need to contract out maintenance services. Institutional support is essential to ensure that a shift made in the name of subsidiarity does not result in passive elite capture [64] or risk merely being transferred from those most able to manage it to those least able to afford and mitigate it [65].

Meso-scale institutions can act as brokers of technical information about system design, construction and maintenance; help lower-income users to access necessary credit; create new value chains; or provide maintenance services [66,67]. By incorporating these factors into the research design, MAD water systems can be co-designed to be sustainable, socially acceptable, and institutionally supported [68]. To advance further development of MAD water socio-technical systems, we propose a justice-oriented framework using the same five dimensions of water security introduced earlier: harvesting, treating, distributing, monitoring, and governing (Table 1). These themes require focused scientific and technological advances in order to scale MAD water systems into viable, sustainable alternatives. These themes are also consistent with the lifecycle stages of other goods — material extraction, production, use, and end-of-life disposal — but present tradeoffs in the context of water technology innovation. For example, households harvesting water from multiple sources may improve their water security and disaster resilience, but could complicate water treatment with each additional source, and governance may differ by source. Such tradeoffs present obstacles to efficient and equitable technology transitions.

Decentralisation may also undermine funding models for equitable distribution and monitoring if it allows wealthier consumers to disconnect from infrastructure relied upon by poorer consumers [69]. The kind of infrastructural (social and material) transformation we are

Table 1

Foundations for a justice-oriented framework for MAD water systems.

Theme	Description	Water Justice Concerns
Harvesting	Acknowledges a diversity of water sources and recognises the potential benefits to wellness and resilience gained by using multiple concurrent sources, as is already the case in many low- and middle-income settings.	Ensuring equal access to the desired mix of water sources for the advancement of human capabilities.
Treating	Implements variable treatment processes for acceptable drinking, household, agricultural, or industrial water. MAD water infrastructure requires use-specific treatment regimens that consider traditional and emerging contaminants.	Fit-for-purpose water, not fit-for-whom water.
Distributing	Recognises a range of techniques for re-distributing water that is fit for purpose, including water sharing agreements at community (e.g. upstream/downstream) and household (e.g. between neighbours) levels, and informal water vending or transport systems. Here the small-scale integration of social and physical infrastructure can be transformative.	Ensuring equal access to conveyance infrastructure, including subsidisation of start-up or connection fees for lowest-income households.
Monitoring	Supports data collection and analysis to help manage water infrastructure. We have barely scratched the surface of the potential benefits gained from information and communication technology (ICT) and sensor advances, such as real-time water quality monitoring (micro-networked households), that can help us harvest, clean, and convey water.	Deploying ICT to promote transparency and equity in water management and safety, rather than further water commodification.
Governing	Provides oversight to ensure equity, justice, and sustainability of a water supply. Communities may benefit from new hybrid, multiscalar modes of governance that may not be compatible with outdated models of centralised infrastructure governance.	Reconciling community governance and maintenance roles with those of centralised systems without increasing burdens on community members or leaders.

proposing with MAD water requires attention to how these shifts alter embodied water labour, alter infrastructural temporalities of decay and repair, and articulate different configurations of citizenship [70,71]. These new sociotechnological configurations cascade and reshape not only social power but the terrain of water justice.

Conclusion

Communities, researchers, and policymakers should recognize the evolution of MAD water systems and advance a new vision that is safe, secure, and socially equitable. In this new age of disruption, decentralised approaches should be part of a formal strategy to ensure water security in the face of climate uncertainty and weather shocks. We must anticipate the ongoing wave of technological innovation in MAD water systems and develop new justice-oriented institutional arrangements and governance systems that can be tailored to local needs and ensure safe water for all. There is still much to learn, particularly about strategies for transitioning from centralised to decentralised water provision systems [72,73], user perceptions of off-grid systems [74], and institutional barriers and needs [75]. Nonetheless, decentralised systems are poised to address existing challenges and anticipated future socio-environmental disruptions around the world. For many regions, a justice-oriented MAD approach may be the most viable path toward achieving Sustainable Development Goal 6 for global safe water, and sustaining those gains throughout the 21st century.

CRediT authorship contribution statement

Justin Stoler: Conceptualization, Writing – original draft, Writing – review & editing. **Wendy Jepson**: Conceptualization, Writing – original draft, Writing – review & editing. **Amber Wutich**: Conceptualization, Writing – original draft, Writing – review & editing. **Carmen Velasco**: Writing – original draft, Writing – review & editing. **Patrick Thomson**: Writing – original draft, Writing – review & editing. **Chad Staddon**: Writing – review & editing. **Paul Westerhoff**: Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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