MAD Water: Integrating Modular, Adaptive, and Decentralized Approaches for Water Security in the Climate Change Era

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Abstract
Centralized water infrastructure has, over the last century, brought safe and reliable drinking water to much of the world. But climate change, combined with aging and underfunded infrastructure, is increasingly testing the limits of—and reversing gains made by—this approach. To address these growing strains and gaps, we must assess and advance alternatives to centralized water provision and sanitation. The water literature is rife with examples of systems that are neither centralized nor networked, yet meet water needs of local communities in important ways, including: informal and hybrid water systems, decentralized water provision, community-based water management, small drinking water systems, point-of-use treatment, small-scale water vendors, and packaged water. Our work builds on these literatures by proposing a convergence approach that can integrate and explore the benefits and challenges of modular, adaptive, and decentralized ("MAD") water provision and sanitation, often foregrounding important advances in engineering technology. We further provide frameworks to evaluate justice, economic feasibility, governance, human health, and environmental sustainability as key parameters of MAD water system performance.

1. Introduction

Centralized water infrastructure has, over the last century, secured safe and reliable drinking water for much of Global North and, to some extent, Global South (Meehan et al. 2021). But extreme weather events, combined with aging and underfunded water infrastructure, are increasingly testing the limits of these large-scale systems connecting pipes and water treatment centers (Stoler et al. 2022, Hasan and Foliente 2015, Baird 2010). Safe drinking water is becoming more expensive to produce (Teodoro 2020, Heyman et al. 2022), while local political constraints and complex processes to access infrastructure funds make it difficult to finance water infrastructure maintenance and the workforce to operate it (Kane and Tomer 2018). Many of those responsible for extending water provision and sanitation to previously underserved populations—both rural and urban—are grappling with the unsustainability of centralized 20th century service models given future climate and financial projections (Vorosmarty et al. 2013; Bogardi et al. 2013; Abel et al. 2019).

In the 19th and 20th centuries enormous gains in water security were made through the expansion of public utilities (Melosi 2008). In many cases these efforts involved the decommissioning of small-scale decentralized systems (*e.g.*, local wells) in favor of centralized piped systems which were, and still are, considered the gold standard of water service delivery (Hardy, 1991, Malin, 2022). Piped, centralized water solutions, implicitly situated at the top of the WHO/UNICEF Joint Monitoring Program (or JMP) drinking water ladder (WHO 2019), are preferred and prioritized as the means of achieving "safely managed water" under the United Nations Sustainable Development Goal SDG 6.1. (WHO 2021). However, it is increasingly obvious that, despite Herculean efforts in monitoring and infrastructure investment, not all of the global population will reach the top of the ladder by 2030 (WHO 2021). Indeed, there will be backsliding in the water provision achievements made in some communities due to underfunding, climate change, and other disruptions (Nunes et al. 2018; Thomson et al., 2019; Spearing and Faust 2020; Odimayomi et al. 2021; Robinne et al. 2021; Hohner et al. 2019; Glazer et al. 2021; Norriss et al. 2021). Hundreds of millions of people—many of them with some connection to piped water and sanitation in both the Global North and Global South—are facing "the end of water," where "Day Zero" is an endemic condition (De Coss-Corzo 2022).

While acknowledging the transformative societal benefits achieved through centralized water systems (Salzman 2017; Troesken et al 2021; Anderson et al 2022, Beach 2022), we must also promote alternatives to centralized water provision and sanitation. The benefits of centralized water systems have been incomplete and uneven, whether for those living on the "last mile," in small towns and remote areas, or in excluded or segregated communities across the globe (Jepson 2014; Jepson and Brown 2014; Cheng 2015; Vandewalle and Jepson 2015; Rodina and Harris 2016; Clark 2018; Deitz and Meehan 2019; Meehan et al. 2020a; Meehan et al. 2020b; Glade and Ray 2022; Wells et al. 2022). These systems have been increasingly prone to failure due to growing climate risks (Vázquez-Rowe et al. 2017). These current gaps and future threats to water systems lead us to rethink our water paradigm; we believe it is imperative to re-examine non-centralized approaches to achieving household water security in the 21st century. Here, we set forth a research agenda that explores the advantages and limits of alternative water provisioning approaches.

New models of modular, adaptive, and decentralized (MAD) water systems are emerging, often with new opportunities for coordination that can expand their reach and scale (Stoler et al. 2022). In many cases, these are made possible by novel technologies, institutions, and practices that produce, transport, store, and treat safe water. Such technological systems can operate in the absence of—or integrated alongside—existing formal, centralized systems of water provision and sanitation (Arora et al. 2015). In other cases, previously overlooked MAD water systems, such as water sharing (Wutich et al. 2018; Brewis et al. 2019; Stoler et al. 2019; Harris et al. 2020; Jepson et al. 2021; Roque et al. 2021; Wutich et al. 2022) or rainwater harvesting (de Melo Bronc et al. 2005; Gomes et al. 2014; Campisano et al. 2017; Soler et al. 2018; Staddon et al. 2018; Crosson et al. 2021; Alim et al. 2020, Doss-Gollin et al. 2015), are receiving new attention from scholars and practitioners. Yet, piped water remains the focus of mainstream policy debates, as exemplified by India's Jal Jeevan Mission to provide every rural household with a tap connection by 2024 (Sarkar and Bharat 2021). As water system performance declines, simpler systems may offer more resilience than the grander schemes preferred by policy makers (Harvey and Drouin 2006; Kleemeier 2000). These MAD water models may help provide access to safe, reliable, affordable water delivery and sanitation in a world of increasing uncertainty: a world characterized by ongoing climate disruption, increased population mobility, and political volatility.

Without a holistic framework to understand these responses and consider the wide-ranging scope and implementation process, there is a serious risk of maladaptation that leads to undesirable, unsustainable, and unjust outcomes (Barnett and O'Neill 2010; Juhola et al 2016; Magnan et al 2016). We argue that a shift to decentralization is already happening, but that the water community at large is doing little to reconceptualize this shift beyond singular technical fixes and mechanistic responses. Without acknowledgement of this shift and a better empirical basis for decision-making, MAD solutions could have inequitable and detrimental implications for water in several water domains: provision, justice, sustainability, governance, and economics. There is thus a fundamental need to integrate existing scholarship across social and engineering sciences into a convergent approach that can mitigate negative outcomes of this nearly-invisible and haphazard socio-technical transition. Our hope is to harness—following successful integrative approaches in interdisciplinary water scholarship (e.g., Ostrom 1990, Pahl-Wostl 2009, Sivipalan et al. 2014, Budds et al. 2014, Jepson 2017)—valuable insights from a wide range of existing perspectives, theories, and cases to form a new integrated field. We suggest a series of frameworks for theorizing a shift to MAD water systems in ways to that can guide the transition productively and avoid reproducing or reinforcing historical WASH inequities.

2. A New MAD Paradigm: Beyond Centralized Piped Water (and Sewer) Systems

The water literature is rife with examples of systems that are neither centralized nor networked, but still meet water needs of local communities in important ways. Examples are documented in literatures including, but not limited to, water and informality (Kooy 2014, Schwartz et al. 2015, Truelove 2019), community-based water management (Cox et al. 2010, Mansuri and Rao 2004, Adams et al. 2020), small-scale water vendors (Whittington et al. 1991, Solo 1999, Kariuki and Schwartz 2005), small drinking water systems (McFarlane and Harris 2018, Klasic et al. 2022), hybrid water systems and regimes (Yates and Harris 2018, Wahby 2021, Storey 2021), decentralized water provision (Arora et al. 2015), green infrastructures for water and wastewater management (Sharma and Malaviya 2021, Green et al. 2021), and packaged water (Wilk 2006, Gleick 2010, Stoler 2012, 2017, Morinville 2017, Pacheco-Vega 2019). Our work builds on this literature by proposing a framework that can bring these contributions into closer, more integrated (and convergent) conversation. As we discuss, this scholarship crucially illustrates the range of innovations in MAD water provision and sanitation, often foregrounding important advances in engineering technology (Dongare et al 2017; Alvarez et al 2018). Yet, we argue the need to equally consider justice, institutional design, and long-term environmental sustainability.

Political-economic dynamics move households and communities to hybrid and decentralized systems in complex ways. For example, on the one hand, there are "shove out" water systems, in which marginalized populations are forced into self-provision or self-management of drinking water (*e.g.*, Vandewalle and Jepson 2015). On the other hand, there are "opt-out" water systems, in which elite or high-income residents disengage and divest from collective water systems (*e.g.*, Lloréns 2021, Workman and Shah 2022). As an example of the rapid rate of growth of such hybrid systems in the absence of formal water policies, personal preferences have created a $20B/year market in point-of-use water treatment devices that are growing at >10% annually; this is over five times larger and faster growing than the global centralized desalination market (Chen et al. 2021). Yet, despite this market success, achieving water security for all remains elusive.

This reconfiguration of waterscapes is happening in both the Global South and Global North, with examples providing a rich foundation for theorizing a coherent framework for assessing the outcomes of these non-centralized, non-piped, and sometimes small-scale water and sewer systems on health and human wellbeing. The ethical and political concerns are significant. "Shove out" MAD water scenarios may create heavy financial and labor burdens for those excluded from centralized piped water systems, or merely shift water provision risks, responsibilities, and costs to vulnerable populations least equipped to manage these (Hope et al. 2020). Scholarship on water insecurity underscores this dynamic. For example, peri-urban neighborhoods on the outskirts of Cochabamba, Bolivia, that were historically denied access to the municipal water utility, were forced to rely on small-scale water vendors (Wutich et al. 2016). Residents in low-income rural subdivisions in South Texas faced a "no-win waterscape," forced to buy expensive water from vending machines as piped water did not provide the quality of service or water to meet all their needs (Jepson 2014; Jepson and Lee 2014). By contrast, high-income Puerto Rico residents built fully independent off-grid water and energy provision in luxury communities after Hurricane María (Lloréns 2021). MAD water systems enabled such an "opt-out" by higher-income and politically powerful populations, allowing them to abandon the costs and responsibilities of participation in solving society-wide water challenges. This emerging, dynamic, socio-technological shift in water infrastructure carries significant implications for water governance, system operation (and more common maintenance), equity, and justice.

MAD water systems are neither inherently good nor inherently bad. Rather, recent trends suggest that communities will increasingly be forced off, or choose to abandon, centralized piped water systems as old models break down under the pressure of under-investment and climate disruptions. We already see the efficacy of the centralized model eroding under the current climatological, demographic, and financial trajectories, as evidenced in the U.S., for example by the aftermath of California's wildfires or the ongoing water quality disaster in Flint, Michigan (Bosscher et al 2019). Such disruptions result in new moves to opt-out of networked water, as well as the formation of communities that are shoved out of centralized systems. As this phenomenon becomes more widespread and common, there is a need for broader, more coordinated research on the benefits and challenges of different configurations of MAD water. In this introduction to MAD water, we lay out key definitions, case examples, and considerations for future research. Our work leverages interdisciplinary contributions from across the social, engineering, finance, and health sciences to describe MAD water systems and understand the future role they have in promoting global just water security. We also outline critical challenges to the environmental, economic, and social sustainability of these new socio-technical configurations. Figure 1 presents a conceptual model of the feedback loop between these components that we believe will be crucial for ensuring that the transition to, and local development of, MAD water systems promotes positive societal and environmental outcomes in a changing world.

INSERT FIGURE 1 (CAPTION BELOW)

Figure 1. Conceptual model outlining examples of economic and governance considerations for successful implementation MAD water systems; measurable benefits to justice, human health, and the environment; and the feedback loop that helps MAD water systems adapt to new contexts.

Given the inherent interdisciplinary nature of MAD water, now is a particularly fruitful time to develop alternatives to dominant water paradigms, given the push toward convergence research (*e.g.*, Westerhoff et al. 2021, Roque et al. 2021, Peek et al. 2020). Convergence research challenges teams from across the sciences to cooperatively develop basic research that can contribute to solving major global problems such as water insecurity and inadequate sanitation. This convergence approach is necessary as we develop this new field of research around MAD water systems, as its success or failure will be decided as much within the realms of justice and environmental sustainability, as in those of hydrology and engineering.

3. MAD Water Systems: Key Definitions

Our work tracks the emergence of new models of MAD water systems. In many cases, these systems are made possible by novel technologies, institutions, and practices that produce, transport, and store safe water – as well as allow for treating and safely reusing water to supplement safe water. These systems include, for example, point-of-use water filtration technologies and onsite wastewater treatment and reuse technologies (Chen et al. 2021; Zodrow et al. 2017). These systems can operate in the absence of—or integrated alongside—existing formal, centralized systems of water or sewer provision. In other cases, previously ignored MAD water systems, such as water sharing (Rosinger et al. 2020) and informal water markets (Garrick et al. 2023), are newly receiving attention from scholars and practitioners. In other cases, we see a hybrid of old practices, such as rainwater harvesting, with new technologies (e.g., Voth-Gaeddert et al. 2022).

Table 1 explains key terms for the MAD water framework. Modularity, adaptability, and decentrality are the key characteristics observed in water systems, and we define these terms in Table 1. In the next section, we provide a series of examples that illustrate how a MAD approach can help us better understand large-scale shifts in the water sector. We do not seek to rigidly define what is or is not MAD; rather, we observe that water systems and their management, exist along gradients of increasing modularity, adaptability, and/or decentrality. Finally, our definition of MAD water involves scalar implications. MAD water systems range in connectivity and operational scale, from systems that include an array of household technologies and relations that are fully decentralized to more distributed systems within smaller, localized networks. Following Stoler and colleagues (2022), we conceptualize MAD water across five key dimensions of water security: harvesting, treating, distributing, monitoring, and governing. Table 2 lists some examples of the application of the MAD water framework for a range of water systems. Several of these examples, including lower-tech ones, are described in the following case studies.

<Table 1. Key Terms, Definitions & Examples for MAD (Modular, Adaptive, or Decentralized) Water Approaches>

4. MAD Water Case Studies

4.1 MAD Example: Sand Scoops in Ephemeral Rivers

Sand scoops represent one of the oldest and simplest technological forms that fits within, and illustrates, the MAD water framework. Water can be collected from ephemeral streams when dry by digging scoop holes into the sand of a dry riverbed to form a shallow well. Even when the river is not flowing, rivers can hold substantial volumes of water near the surface of the riverbed. Water just below the riverbed can be easily accessed using a simple hand tool, or even one's hands. This water can be conveyed to where it needs to be by a person carrying a gourd, by donkey, or by motor vehicle. When one scoop hole is dry or no longer usable, a similar scoop can be made elsewhere in the same river or river system or replicated nearby if demand is higher. Informal governance systems may dictate how close an existing scoop a new one can be dug. While this can—in principle—yield good quality water, it is often contaminated (Quinn et al. 2018). As with the method of conveyance, treatment can vary from low-tech, such as filtering through a piece of fabric, to high tech such as an advanced filtration membrane or bio-sand filter. The latter example illustrates how within a MAD water system at different stages in the chain can have starkly different technology levels, but how these can combine to produce potable water for final users.

4.2 MAD Example: Point-of-Use Drinking Water Systems

One example of a technology that can contribute to MAD water systems is engineered point-of-use (POU) drinking water treatment, where a treatment unit is used at individual locations in a household. POU treatment can take many forms, including media filtration (*e.g.*, granular activated carbon block filtration in a pitcher or biosand filtration), membrane filtration (*e.g.*, reverse osmosis), or disinfection (*e.g.*, ultraviolet light, chlorination, boiling) (Pooi and Ng 2018). Many systems implement more than one of these technologies (Oyanedel-Craver and Smith 2008). POU treatment embodies the idea that not all water used within a household needs to be treated to drinking water standards (Wolff and Gleick 2002; Zodrow et al. 2017). Many POU treatment units are modular, and water treatment capacity (e.g., liters per day) can be increased with additional units. These units may be purchased (*e.g.*, under-sink filters) or constructed using locally available materials (*e.g.*, ceramic filters or biosand filters). POU drinking water treatment is used around the world, either as a primary form of treatment, to improve water aesthetics, or to remove the most recent class of emerging organic contaminants such as per- and poly-fluoroalkyl substances (PFAS) (Patterson et al., 2019). Lower cost water quality monitoring using colorimetric and microfluidic technology (Phuangsaijai et al., 2021; Jaywant & Arif, 2019) may empower community or households to independently test their water quality. When combined with real-time water quality monitoring using information and communication technology and sensors in micro-networked households, POU treatment could substantially improve water quality (Stoler et al. 2021). However, effective maintenance and monitoring of POU devices and sensors can pose a challenge to poor communities—if the burden of operation and maintenance are placed on poor communities rather than the centralized system—and may occur as a "shove out" technology that could subvert longer-term efficacy of water provision (Vandewalle and Jepson 2015). A recent survey in the USA found that lower income households spend more of their income on POU devices and bottled water, compared with higher income households, suggesting a potential need for public funding of POU devices (Kidd et al. 2020).

4.3 MAD Example: Handpumps

Handpumps are used across the world to access shallow groundwater, most commonly in the Global South (Foster et al. 2019). They are used both in rural areas that may be hundreds of km from the nearest piped water system, and in informal urban settlements where household or even standpipe connection to the nearby centralized water system is blocked for institutional or politically reasons, the aforementioned "shove out" communities. The pumps themselves are off-the-shelf modular items, often bought in bulk by governments or development agencies (MacArthur 2015). Wells can be drilled or dug where needed and replicated if demand is high or an initial well fails; in this way, they can be adaptive. Finally, they are off-grid and, depending on the distance between them and aquifer properties, hydrologically decentralized as well. They are situated technologically between shallow wells accessed by buckets, and boreholes with motorized pumps, the latter also being a technology of choice for high-income "opt out" communities (Fox et al., 2016; Hynds et al., 2013). Conceptualizing handpumps and their management and monitoring as MAD water systems (Thomson et al., 2012; Thomson and Koehler, 2016; Koehler et al., 2018) may serve us better—and the households that use them—than viewing them as an interim step between untreated surface water and piped, treated connection to the home.

4.4 MAD Example: Onsite Systems for Wastewater Management

The concept of clean sanitation originally started at a small, decentralized scale, focusing mainly on disposal of human waste using systems such as privies. During the 19th and 20th Centuries, with the advent of piped water systems, the focus shifted to treatment of wastewater from densely populated areas, prior to discharge into local surface, through large scale centralized treatment. While decentralized systems may have become less common in the Global North, at least in urban areas, they remain ubiquitous in the Global South: only 7% of people in Sub-Saharan, and 13% of people in Central and Southern Asia have a sewer connection, compared with 83% in Europe and North America (World Health Organization & UNICEF, 2017).

In addition to higher tech systems such as the Gates Foundation toilet (Hiolski, 2019) and containerized sanitation (Ferguson et al., 2022), there is revived interest in composting systems (Mariwah et al., 2022; Anand & Apul, 2014) as a means of safely managing fecal waste. These systems, by which we mean both the technology (Li et al., 2023; Geetha Varma et al., 2022) and the management models and institutional environment in which they sit, can be considered as MAD systems. These decentralized systems may not always be modular—artisanal/bespoke septic tanks are common—but the management of fecal sludge is inherently adaptive, with the conceptualization and monetization of fecal sludge as a resource opening up new business models (Wichelns et al., 2015; Shukla et al., 2023).

In the Global North, septic systems were considered a temporary solution for wastewater management, but millions in less dense rural areas in the Global North still use them. The mass use of septic tanks has long been known to have detrimental effects on groundwater in some regions (e.g., Bloetscher & Van Cott 1999). In late 1990, US EPA reported to Congress (US EPA 832-97-001b) that not all the areas in the US are going to be sewered and some type of onsite/decentralized systems will be used on a permanent basis. Moreover, advances in technologies for onsite treatment, disposal and reuse have attracted attention of the centralized municipalities as a means to improve climate resilience and water security for their customers (Water Environment Research Foundation 2010). The innovations in decentralized sanitation and fecal sludge management developed in the Global South may be increasingly seen in the Global North as well.

4.5 MAD Example: Rainwater Cisterns

For over a decade, the Brazilian government and NGOs executed several programs to construct cisterns for domestic water, livestock, and crops in support of rural communities across the semi-arid Northeast region (Água Para Todos; Projeto São José; One Million Cisterns Program; Program One Piece of Land and Two Types of Water) (Gomes et al. 2012; Gomes et al. 2014; Gnadlinger et al. 2020; Cirilo, 2008; Enéas da Silva et al., 2013). Rainwater cistern programs in Brazil sought to increase water access for many rural households in the drought-prone semi-arid zone (Gomes et al. 2012). The first version of the program involved cement cisterns for individual households, where the government partnered with civil society to distribute raw materials to rural residents via community associations. Community members worked together to construct the cisterns for individual households—these were harvesting and distribution systems with decentralized governance and service—and included programs for gender empowerment (Morais and Rocha 2013). The materials were standardized and easily replicable, making them modular forms of harvesting and distribution. Later versions of the program involved plastic cisterns that are also replicable and more quickly distributed—meaning that they were adaptive. Treatment and monitoring, if performed, is at the household level (Silva et al. 2020). Rainwater cisterns can be vulnerable to extended drought (Doss-Gollin et al. 2015), and water quality is highly variable, with *E. coli* detected in many cisterns (Da Silva et al. 2020).

4.6 MAD Example: Rural Water Management in Brazil

Many rural communities in the Brazilian state of Ceará participate in a non-governmental program called System for Rural Sanitation (*Sistema de Saneamento Rural* – SISAR) that functions as a network of community associations (Meleg et al. 2012; Dos Santos Rocha and Salvetti 2017). Similar programs exist in other Brazilian states and other countries as well (Grillos et al 2021; Dupuits 2019). SISAR has eight regional offices that facilitate self-management of water distribution systems for approximately 100-300 rural communities in their region. SISAR operates in communities that are not connected to the primary municipal piped water system, and it does not fund investment in new water system infrastructure. Rural communities that participate in SISAR primarily harvest water through a pre-existing community-scale well or local reservoir connected to a small, piped water network serving 30-100 households. The SISAR regional office provides technical assistance and trains community operators to treat water and maintain community-scale water distribution systems. SISAR trains operators to monitor the status of the distribution system and household water use, though operators do not monitor the status of the water resource such as water level in the well (Cooperman et al. 2020). The SISAR regional office oversees household billing and provides social support for localized governance through community associations. Each of these features of the water system uses a similar model across all communities and can be modified to adapt to changes in local conditions, making them modular and adaptive.

4.7 MAD Example: Packaged Water: Sachets, Bottles, and Bags

We further acknowledge that increasing the MAD characteristics of a water service sometimes presents important tradeoffs. For example, the many forms of vended and delivered water around the world include packaged water, most commonly bottled and bagged (or "sachet") water (Vedachalam et al. 2017). In high-income settings, bottled water tends to be an optional luxury good, but in low-income settings—particularly water scarce communities—bottled or sachet water can effectively serve as a virtual extension of existing water infrastructure, whether centralized and decentralized (Stoler 2017). Packaged water harvesting, treatment, and distribution are all remarkably MAD as entrepreneurs can set up filling machines wherever there is a reliable groundwater or municipal water source, and nimbly supply communities who lack centralized water infrastructure. In many West African countries, for example, sachet water has become the *de facto* drinking water supply in communities not connected to municipal water grids. While federal governments have centralized monitoring and governance schemes for packaged water, the most effective governance has been decentralized, self-administered industry quality control as market forces shape leading producers' desire to burnish their product's reputation. Yet, while packaged water has temporarily bailed out many governments from their duty to provide constituents with safe water, ever growing streams of plastic waste and the lack of price controls to stabilize household drinking water expenses highlight the downsides and unsustainability of this form of MAD water (Stoler 2012, Pacheco-Vega 2019).

<TABLE 2>

5. Assessing MAD Water Systems: Considerations for Future Research

From our perspective, the concept of household water security is defined by the lived and relational experiences that contribute to human flourishing and well-being (Jepson et al., 2017; 2018). That is, access to safe water is necessary but not sufficient to achieve water security. The water and sanitation systems we have described above—to varying degrees—provide some level of household water security. Technical solutions alone will not create water security. Other critical dimensions, such as affordability, adequacy, and reliability for all water needs also should be part of a holistic understanding of water security achieved by MAD water (Bakker and Morinville 2013; Jepson, 2014; Jepson et al. 2017).

More than meeting basic needs, we also consider water security to be relational in the sense of enhancing the socio-cultural, economic, and governance capabilities of communities and households (Jepson et al. 2019; Sultana and Loftus 2019; Meehan et al. 2023)—as well as long-term environmental sustainability. Our view of MAD water is thus framed not only in terms of water as a material good to be distributed, but water as part of a larger set of social relations (Budds et al. 2014, Linton and Budds 2014) that has implications on many dimensions of social life. In this way, we recognize the profound relational shifts MAD water systems will have on hydro-social relations. Therefore, hydro-social relations—including cultural and psychosocial dimensions—must necessarily constitute water security, and thus, be part of how we conceptualize and assess MAD water systems moving forward.

Modern water systems attempt to convey treated water to as close to households as possible, ideally with access inside the household or compound. Such conveyance efforts therefore aim to minimize or eliminate fetching distance and time and create some degree of household autonomy through access to water using a private tap. Water governance structures generally aim to ensure that the water remains affordable for users, and to ensure ongoing financial viability of the system. One of the biggest challenges of MAD water systems is to make them easy for households to use in order to ensure user acceptance (Contzen, Killmann, and Mosler 2023), while allowing for appropriate levels of local engagement for system governance and the protection of human and environmental health. Here, we position justice as a primary goal and highlight issues in the key domains of economics, governance, human health, and environmental sustainability that must be approached differently under the MAD water paradigm.

5.1 MAD Water & Justice

Adaptive, decentralized systems allow for variation in how they are conceptualized, managed, and used. By their nature they can be outside the established, albeit imperfect and contested, paradigm of centralized water provision. As much as being an advantage, this also poses risks, such as elite capture, predatory pricing, or neglect. Therefore, our approach to MAD water and the efficacy of this paradigm to support water security necessarily includes a fundamental consideration of water justice (Sultana and Loftus 2019, Boelens et al. 2018, Wade 2018, Zeitoun et al. 2016).

We draw on the expansive scholarship on environmental justice to illustrate how the MAD water paradigm intersects with considerations of water justice (Table 3). As mentioned earlier, water security refers to access, affordability, adequacy, and reliability for all water needs, including physical, cultural, social, and economic. These needs are broadly defined and directly align with distributive definitions of water justice.

A challenge for MAD water is to ensure that these benefits of water security are experienced equitably. A goal we propose is to assess MAD water's efficacy as a paradigm to facilitate equitably distributed current and future water provision. Within *distributive justice* frameworks, one also needs to consider "the community of justice" (who are the recipients of these benefits?). For MAD water, we consider benefits to be accrued across individuals, households, and communities whose risks may be differently determined by race/ethnicity, indigeneity, class, gender and sexuality (Brewis et al. in revision, Leonard et al. 2023, Meehan et al. 2020). These dimensions are often difficult to balance, and in tension, but they do need to be considered. Indeed, *interpersonal justice* (or interactional justice) operates within the distributive paradigm in that as people navigate the waterscape, individuals, regardless of social category, should experience equitable treatment and respect (Wutich et al. 2016).

We also recognize the critical importance of *procedural justice*, understood in terms of fair participatory processes and rules for decision making, for MAD water systems. This also draws from the definition of water security, as referring to securing "the ability of individuals, households, and communities to navigate hydro-social relations and secure safe and affordable water particularly in ways that support the sustained development of human capabilities and wellbeing in their full breadth and scope" (Jepson et al. 2017, 3). This is a central dimension of justice, navigating hydro-social relations as necessarily participatory, but it is often missing in transitions that are driven by technological change. Our argument is that MAD water systems need to incorporate regulatory governance systems to ensure inclusion, informed consent, and participatory efficacy, and to avoid elite capture (as described in Brewis et al. 2021). There are several principles of participatory governance, from shared decision-making to access to information, and considering the diversity of MAD water, and these principles will vary; however, inclusion of participatory approaches are critical for achieving just water security. We note a promising trend toward developing participatory convergence research to ensure that MAD Water interventions are co-designed (Hargrove and Heyman 2020, Hargrove et al. 2020, Roque et al. 2021, 2024) by communities and researchers, to make certain the community's needs and desires are centered in the design of MAD Water systems.

Water justice incorporates another critical dimension that is salient for experiences with water provision and use: *recognition as justice*. The dominant paradigm of water provision considers modern water as an economic good that is commodified and transferable. Yet, that is only one water world view. Recently scholars have challenged the universality of water with different world views and values (Leonard et al. 2023, Yates et al. 2017, Wilson and Inkster 2018). The implications for calls to incorporate other water worlds and values hold wide-ranging consequences for MAD water systems. From a water justice perspective, MAD water systems should be co-designed in ways that accommodate cultural values in ways that are respected.

Finally, and perhaps most powerfully, is the potential for MAD Water to address the need for *transformative justice* (Morris 2000), an approach similar to restorative justice (Nocella and Anthony 2011). Transformative justice seeks to redress past harms by addressing root causes of oppression, centering victims' need for justice, and reintegrating communities. Transformative and restorative justice are nascent fields in water research (Neal et al. 2014, Nikolakis and Quentin Grafton 2014, Corral-Verdugo and Frías-Armenta 2006), but research led by Indigenous scholars indicates that such approaches have the potential to powerfully reshape water systems and knowledge (Leonard et al. 2023, Wilson et al. 2021). The potential role of MAD water systems to contribute to transformative justice is currently unknown, but an important potential area for future research.

<Table 3. Defining justice for MAD water approaches>

5.2 Political Economy of MAD Water: Economics & Governance

Economies of scale tend to favor larger, centralized systems. This may be changing, even for large municipalities in the Global North, due to the cost challenges of maintaining or expanding aging infrastructure to meet capacity and sustainability goals of communities (Garrido-Baserba et al. 2022). The move to MAD systems may be driven by financial pressures in these cases, but it is an open question what the financial logic of MAD solutions may be across countries and contexts. On one hand, the development and maintenance of smaller scale systems may increase total spending on water systems in the short term, adding financial pressure to governments and households. Yet, MAD solutions may represent an investment in employment and skill transfer to currently underserved populations and more efficient water and energy use, leading to more sustainable long-term benefits. Safety, financing, affordability, and education and training are key. Table 4 lists economic considerations for factors and examples of how MAD water and conventional water systems (Table 4) fit into those factors.

The high fixed costs, low variable costs, and scale of centralized systems allow for high levels of subsidy and cross-subsidy. These can be progressive, such as lifeline tariffs or legal restrictions on cut-offs, or they can be regressive (Fuente et al., 2016; Morales-Novelo et al., 2018), such as in the United States where poor, urban communities must address deteriorating infrastructure after White flight to suburbs. Other examples of regressive costs include high connection fees or bulk discounts when the system is functioning correctly, or—when it is not—cutting off poorer and more marginalized communities or neighborhoods when underinvestment reduces system reach or performance ("shove out"). Those remaining on the system continue to receive water at a cost that is lower than the long-term cost of production. In either case, these subsidies are often hidden or implicit.

As they capitalized on economies of scale, centralized public utilities created institutional structures that, along with policies, enabled progressive contributions and cross-subsidy that led to more equitable access for users of the public system. The move to MAD systems will change this. Being decentralized, the costs of supplying water using MAD water systems could be more closely linked to the local cost of supply, making cost differences overt and subsidies explicit. The regulatory and policy environment for water supply has been built around the natural monopoly of centralized water systems. These governance structures, and the discourse around subsidies, will have to adapt to the different economic characteristics of MAD systems to ensure that water remains affordable, and outcomes are sustainable and equitable. An important line of inquiry in the shift from centralized systems to MAD approaches will be the economic implications in terms of affordability and progressive (or regressive) distribution. The need to address this at both national and local levels is not the only political consideration associated with MAD water. Table 5 lists factors associated with water governance and example application of these factors to MAD water.

The development of large, centralized public utilities also reshaped political landscapes, with public good and natural monopoly arguments combining to create mandates for government involvement in water and sanitation services. Yet, the political challenges created by these centralized approaches have undermined their ability to deliver on promises of universal access and financial efficiency. As governments managed public utilities, either as direct service providers or as principals overseeing contracts with private providers, many could not overlook the opportunities for corruption and patronage (Herrera 2017). Achieving good governance of centralized systems entails a complex approach of creating avenues for participation and representation while also insulating utilities from special interests and parallels the principle of participatory justice outlined above. The political pressure to keep tariffs low can undermine the ability of managers to maintain and expand infrastructure, leaving an uneven patchwork of service and reifying the inequities centralized approaches aimed to address. Those being left out of the maintenance are usually the same groups that are excluded from politics and are economically vulnerable.

MAD water holds the potential to address these challenges, but this shift can have divergent impacts on political representation, accountability, and equity (Table 5). Water systems are managed at different scales with complex networks of overlapping jurisdictions, including utilities, regulatory agencies, watershed or river basin management, and specialized water districts. It is hard for citizens to know which actor to hold accountable for service failures, and coordination across these actors is very challenging (Mullin 2009). In addition, small scale community systems, especially privately-owned ones, may not be well integrated into larger scale planning efforts, increasing risks during drought for already vulnerable communities (Mullin 2020). "Temporary" shifts to MAD solutions, such as bottled water distribution during contamination and natural hazards or POU water treatment for household wells or hauled water, can overcome dangerous drinking water quality or quantity conditions. MAD solutions provide flexibility in the timing and scale of emergency response since different systems can be introduced at different times as local needs shift (e.g., Roque et al. 2021). However, they have high costs and place financial burdens and monitoring challenges on already marginalized communities (Jepson and Brown 2014). Emergency relief is also vulnerable to political pressures and electoral cycles (Cooperman 2022), and short-term shifts to MAD systems can reduce the urgency of public investment and let officials off the hook for fulfilling mandates to provide secure, reliable drinking water or sanitation services (*e.g.*, Vandewalle and Jepson 2015). Over time, MAD approaches may disincentivize public officials from expanding piped water and sanitation systems, leaving residents in an indefinite precarious situation. MAD approaches often require local collective action, and communities that are more likely to successfully engage in collective action, often due to long-time relationships of trust and reciprocity, are better able to harness the gains of MAD systems. Those communities that lack the political connections for adequate distribution and maintenance are left even farther behind, leading to increased inequality between groups (Cooperman 2019, Dobbin and Lubell 2021).

<Table 4. Economic Considerations for MAD Water >

<Table 5. Governance Considerations for MAD Water >

5.3 Human & Environmental Health

MAD water systems have the potential to improve human health and broader environmental health. The human health implications are broad, spanning communicable and non-communicable diseases, injuries, and mental health disorders (see Table 6). Improvements to water quantity and quality have long been associated with preventing a wide range of waterborne, water-washed, water-related, and water-based communicable diseases originally organized by the Bradley-Feachem classification (Bartram and Hunter 2015). Reducing water fetching and the need to store drinking water by having a nearby, reliable system will drive down these communicable disease risks. The non-linear relationship between water quality and diarrheal disease (Thomson et al., 2022) by which even short periods of drinking contaminated water have disproportionate health impacts (Hunter, Zmirou-Navier and Hartemann, 2009; Brown and Clasen 2012) makes addressing water-related health risks all the more important. Minimizing fetching needs and increasing autonomy is also theorized to reduce other non-communicable health risks including dehydration and carriage-associated injuries (Geere et al. 2018; Rosinger & Young 2020). Finally, more recent scholarship has shown that further health gains associated with improving water services provision are related to improved mental health

(Wutich et al. 2020). All of these can be addressed through *properly designed, implemented, and managed* MAD water systems.

Water quality improvements also reduce non-communicable disease risk factors associated with natural and anthropogenic water pollutants ranging from arsenic to old industrial pollutants like benzene or lead and emerging organic chemical pollutants like PFAS and phthalates (Wutich et al. 2021). MAD water systems are particularly well-positioned to help with emerging contaminants because they can be tailored to local water needs. However, the monitoring, management, and disposal of difficult toxicants such as PFAS or disinfection by-products, and pathogens such as *Cryptosporidium*, may challenge MAD water systems. MAD water systems may be able to respond more quickly than large, centralized systems to changing water quality and treatment needs. For example, products like PFAS can be readily absorbed, and removed from, water on activated carbon blocks or separated from water by reverse osmosis in commercially available POU systems (Herkert et al. 2020). However, these updates can be narrow, including only the users with the knowledge, salience, and resources, or short-lived compared to upgrading treatment at centralized facilities. Moreover, MAD system managers may not be well-suited to properly dispose of the forever chemicals.

MAD water approaches should also prioritize environmental sustainability and ideally promote ecosystem services, sustainability, and resilience for local communities (Table 7). For example, wastewater reuse systems can discharge water into appropriate green infrastructure, providing benefits to the community and the environment. MAD water systems can also be compatible with ecosystem services, such as locating rainwater collection infrastructure in a drainage basin that already needs to absorb floodwaters. At the very least, MAD water systems must not undermine ecosystem services provided by wildlife or natural landscapes. MAD water systems should be sustainable and not impose any downstream burdens, such as new waste streams, which are likely to affect water supplies or compromise ecosystem services elsewhere. This implies the adoption of recyclable treatment media, protocols for safely handling any dangerous waste products that accumulate during treatment and filtration or using sustainably sourced or renewable consumables.

Finally, MAD water systems could enhance community abilities to recover and thrive from extreme events such as floods and droughts, rapid socio-demographic changes such as a mass migration event, or economic shocks such as a depression or sudden currency devaluation. In such high-risk contexts, MAD water infrastructure should ideally be quickly scalable to a sudden increase in usage, potentially physically mobile to help relocate away from danger, and require maintenance sustained through reliable supply chains that are relatively insulated from global institutions and politics. However, small water systems often struggle to provide water security during drought shocks due to economic, infrastructural, planning, and enforcement challenges (Mullin 2020). A shift toward MAD water systems could enhance human and ecosystem resilience, depending on the political, economic, and justice perspectives described above.

<Table 6. Human Health Outcomes for MAD Water >

<Table 7. Environmental Sustainability for MAD Water >

6. **Conclusions and Next Steps**

MAD water systems may have the capacity to provide better water and sanitation services for communities and households currently relying on poor water supplies, and for whom piped water to the home is a pipe dream rather than a realistic policy goal. It will be important for MAD water to be built, as a field, on empirical assessments of how specific MAD configurations perform in terms of key outcomes like justice, environmental sustainability, human health, governance, and economic wellbeing. We suggest a simple framework (Figure 1) as a place to start. We invite scholars to join us in this effort. Many scholars are already working on crucial components of this research agenda, but not yet in conversation with each other as part of an integrated field. Others are beginning convergence efforts, working with interdisciplinary teams to solve intractable water or sanitation problems. Still others are developing ways to work ethically, equitably, and respectfully with water-insecure communities, contributing new methods for research, communication, and collaboration. And many practitioners have important practical insights that are not yet well-understood in the academic literature. All of these perspectives will be crucial as we move beyond the 20th century water provision paradigm. MAD water systems are poised to make substantial contributions to confronting the global challenges of climate change, population displacement, and financial upheaval expected later this century.

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TABLES

Table 1. Key Terms, Definitions & Examples for MAD (Modular, Adaptive, or Decentralized) Water Approaches

Term	**Definition**	**MAD Water Example(s)**	**Counter-Example(s): NOT MAD**
Modular	Fit-for-purpose, easily replicable, can be expanded or reduced according to need, and are often mobile or portable, i.e., do not rely on fixed, permanent infrastructure (Mobile systems that can be easily deployed as populations move & resettle are by nature modular and included in our definition.)	Point-of-use water filtration systems: can be expanded to process more water Onsite/Decentralized wastewater treatment and reuse system that can be expanded modularly to meet demand. Water vending trucks that move water from source to customers Mobile desalination or treatment systems for disaster response.	Conventional water & wastewater treatment plants designed for specific capacity (e.g., due to both site and permitting constraints)
Adaptive	Can be quickly and responsively modified to meet immediate needs	Household water sharing: norms-based system can be modified to encompass different water needs and relationships	Systems governed by Federal water legislation are often not adaptive because the change process is long and slow
Decentralized	Dispersed, distributed, and localized. Lack of central coordination in water distribution	Rainwater harvesting: Individual households collect & allocate water independently Onsite wastewater treatment and reuse to amend rainwater harvesting.	Municipal water & sewer utilities typically have centralized infrastructure & decision-making

Table 2. Examples with modular, adaptive, or decentralized characteristics for water harvesting, treatment, distribution, monitoring, or governing.

Example	Harvesting			Treating			Distributing			Monitoring			Governing			Citation
	M	A	D	M	A	D	M	A	D	M	A	D	M	A	D	
Sand scoops in ephemeral rivers	✓	✓	✓	✓	✓	✓	✓	✓	✓					✓	✓	Quinn et al. 2019
Water truck vending in Bolivia	✓						✓	✓	✓				✓	✓	✓	Wutich et al. 2016
Remotely-monitored handpumps in Kenya	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓		✓	✓	Thomson 2021
Rainwater harvesting in Brazil, Uganda, Mexico	✓	✓	✓				✓	✓	✓							Staddon et al 2018; Lindoso et al 2018; Adrich and Page-Tan 2020
Water sharing after Hurricane Maria, Caribbean							✓	✓	✓				✓	✓	✓	Roque et al. 2021
Sistema de Saneamento Rural (SISAR) communities in Brazil				✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Cooperman 2019; Dos Santos Rocha and Salvetti; Meleg 2012
Packaged water in West Africa	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓				Stoler 2017
Hauled water in U.S. colonias							✓	✓	✓							Garcia et al. 2016
Bottled water among unhoused people in London, U.K.	✓	✓	✓				✓	✓	✓							Meehan et al. 2022

In-home water treatment systems in Kathmandu Valley, Nepal				✓	✓	✓										Shrestha et al. 2018
Water kiosks in Delhi, India				✓	✓	✓	✓	✓	✓							Sarkar & Choudhary 2020
Water ATMs in Delhi, India				✓	✓	✓	✓	✓	✓							Sarkar 2019
"Luxury Techno-Libertarians" in Puerto Rico	✓	✓	✓	✓	✓	✓										Lloréns 2021

Table 3. Defining justice for MAD water approaches

Forms of Justice	**Brief Description**	**Example**
Distributive	Access to resources and outcomes are fair and equitable across social groups and classes (e.g. gender, sexuality, class, race/ethnicity, indigeneity)	No disparities in water quality between genders or racial-majority and racial-minority water users
Interpersonal	Individuals are treated fairly and equitably, no matter who they are	Low-income and high-income people are treated equally when buying water from private vendors
Procedural	Rules, norms, and decision-making processes are fair and equitable	All genders are equally represented in decision-making to change to water rules
Recognition	Different worldviews and values are fairly and equitably represented	Indigenous conceptions of the value of water are equally considered when determining water allocations and definitions of “use”
Transformative (or restorative)	Root causes of oppression in water systems are collaboratively addressed and communities are peacefully reconstructed	The root causes of oppressive water systems are identified and corrected in ways that address victims’ needs, rehabilitate offenders, and reintegrate society

Table 4. Economic Considerations for MAD Water

Economic Factors	**Brief definition**	**Example**
Financing	Capital investment and O&M of systems must be paid for.	✓ Potentially lower up-front costs relative to replacing aging centralized infrastructure.

		× Unclear the extent to which decentralized systems can generate economies of scale.
Affordability	Costs of water access do not place an undue burden on users relative to their household income	✓ Users no longer pay high connection costs to large piped systems across large distances that are prone to high water leakage and corruption. × Previously hidden cross-subsidies no longer possible, leading to higher prices for marginalized.
Workforce and business development	MAD systems provide opportunities for local skills development and employment.	✓ Brazilian programs to implement rainwater harvesting targeted gender empowerment and training in cistern construction (De Moreas 2013) × Proprietary treatment systems lock in the need for external support.

Table 5. Governance Considerations for MAD Water

Governance Factors	**Brief definition**	**Example**
Representation	Users participate and/or have their interests present in local government / higher level decision making	✓ Users can more easily serve on decentralized water boards. × Decentralized rural systems may cause governments to ignore rural constituents

Accountability	Service providers (utility/NGO/other) are accountable to users (depending on who/where service providers are)	✓ Local providers are closer to users and better able to respond to requests; users can more easily communicate and protest × Central governments may no longer respond to concerns or requests related to other public services from decentralized water system users who no longer rely on or pay into centralized water systems
Equity	Users have equal access to reliable, secure water sources	✓ Users previously unserved or underserved by centralized systems have better access × Wealthy residents are better able to self-provide off-grid solutions that poor residents cannot afford

Table 6. Human Health Outcomes for MAD Water

Human Health Outcomes	**Brief definition**	**Example**
Water-related diseases	MAD water systems reduce disease morbidity and reduce the overall burden of waterborne diseases.	✓ Reliable supplies close to home reduce use of unsafe sources. × Small scale treatment struggle with tricky contaminants.
Physical wellbeing	Physical burden, risk of injury and threat associated with water fetching is minimized.	✓ Supplies close to home reduce risk of exposure to physical violence when collecting water. × Non-piped systems necessitate water fetching.

Mental health	The transition to MAD water systems reduces or eliminates mental health impacts associated with water insecurity.	✓ Reliable supplies close to home reduce worry. × Responsibility for O&M by non-professionals increases mental stress.

Table 7. Environmental Sustainability for MAD Water

Environmental Sustainability Components	**Brief definition**	**Example**
Ecosystems Services	System(s) or feature(s) that are compatible with existing services, or otherwise do not interfere with their function.	✓ Integration of high-tech MAD treatment systems with natural or constructed wetlands. × Modular systems not designed for specific local environmental conditions.
Sustainability	System(s) or feature(s) that do not generate downstream ecosystem burdens or tradeoffs, such as creating problematic waste products, or reducing ecosystem services.	✓ Lower carbon footprint from initial construction. × Difficulties with handling and disposal of brine or chemical waste accumulated during treatment.
Resilience	System(s) or feature(s) that enhance a community's ability to recover from extreme weather or other shocks.	✓ Infrastructure that is portable and can be rapidly expanded/scaled during an emergency. Supply chains for infrastructure parts is buffered from global financial risks, etc. × Decentralized systems have less redundancy and may be more vulnerable to shocks such as operator errors and cyber-attacks.

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Title: MAD Water: Integrating Modular, Adaptive, and Decentralized Approaches for Water Security in the Climate Change Era

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Abstract

Centralized water infrastructure has, over the last century, brought safe and reliable drinking water to much of the world. But climate change, combined with aging and underfunded infrastructure~~ing~~, is increasingly testing the limits of—and reversing gains made by—~~these large-scale water systems~~this approach. To address these growing strains and gaps, we must assess and advance alternatives to centralized water provision and sanitation. The water literature is rife with examples of systems that are neither centralized nor networked, ~~but~~ yet ~~still~~ meet water needs of local communities in important ways, including: informal and hybrid water systems, decentralized water provision, community-based water management, small drinking water systems, point-of-use treatment, small-scale water vendors, and packaged water. Our work builds on these literatures by proposing a convergence approach that can integrate and explore the benefits and challenges of modular, adaptive, and decentralized ("MAD") water provision and sanitation, often foregrounding important advances in engineering technology. We further provide frameworks to evaluate justice, economic feasibility, governance, human health, and environmental sustainability as key parameters of MAD water system performance.

1. Introduction

Centralized water infrastructure has, over the last century, secured safe and reliable drinking water for much of Global North and, to some extent, Global South (Meehan et al. 2021). But extreme weather events, combined with aging and underfunded water infrastructure, are increasingly testing the limits of these large-scale systems connecting pipes and water treatment centers (Stoler et al. 2022, Hasan and Foliente 2015, Baird 2010). Safe drinking water is becoming more expensive to produce (Teodoro 2020, Heyman et al. 2022), while local political constraints and complex processes to access infrastructure funds make it difficult to finance water infrastructure maintenance and the workforce to operate it (Kane and Tomer 2018). Many of those responsible for extending water provision and sanitation to previously underserved populations—both rural and urban—are grappling with the unsustainability of centralized 20th century service models given future climate and financial projections (Vorosmarty et al. 2013; Bogardi et al. 2013; Abel et al. 2019).

In the 19th and 20th centuries enormous gains in water security were made through the expansion of public utilities (Melosi 2008). In many cases these efforts involved the decommissioning of small-scale decentralized systems (*e.g.*, local wells) in favor of centralized piped systems which were, and still are, considered the gold standard of water service delivery (Hardy, 1991, Malin, 2022). Piped, centralized water solutions, implicitly situated at the top of the WHO/UNICEF Joint Monitoring Program (or JMP) drinking water ladder (WHO 2019), are preferred and prioritized as the means of achieving "safely managed water" under the United Nations Sustainable Development Goal SDG 6.1. (WHO 2021). However, it is increasingly obvious that, despite Herculean efforts in monitoring and infrastructure investment, not all of the global population will reach the top of the ladder by 2030 (WHO 2021). Indeed, there will be backsliding in the water provision achievements made in some communities due to underfunding, climate change, and other disruptions (Nunes et al. 2018; Thomson et al., 2019; Spearing and Faust 2020; Odimayomi et al. 2021; Robinne et al. 2021; Hohner et al. 2019; Glazer et al. 2021; Norriss et al. 2021). Hundreds of millions of people——

many of them with some connection to piped water and sanitation in both the Global North and Global South—are facing "the end of water," where "Day Zero" is an endemic condition (De Coss-Corzo 2022).

While acknowledging the transformative societal benefits achieved through centralized water systems (Salzman 2017; Troesken et al 2021; Anderson et al 2022, Beach 2022), we must also promote alternatives to centralized water provision and sanitation. The benefits of centralized water systems have been incomplete and uneven, whether for those living on the "last mile," in small towns and remote areas, or in excluded or segregated communities across the globe (Jepson 2014; Jepson and Brown 2014; Cheng 2015; Vandewalle and Jepson 2015; Rodina and Harris 2016; Clark 2018; Deitz and Meehan 2019; Meehan et al. 2020a; Meehan et al. 2020b; Glade and Ray 2022; Wells et al. 2022). These systems have been increasingly prone to failure due to ~~increasing~~growing climate risks (Vázquez-Rowe et al. 2017). These current gaps and future threats to water systems lead us to rethink our water paradigm; we believe it is imperative to re-examine non-centralized approaches to achieving household water security in the 21st century. Here, we set forth a research agenda that explores the advantages and limits of alternative water provisioning approaches.

New models of modular, adaptive, and decentralized (MAD) water systems are emerging, often with new opportunities for coordination that can expand their reach and scale (Stoler et al. 2022). In many cases, these are made possible by novel technologies, institutions, and practices that produce, transport, store, and treat safe water. Such technological systems can operate in the absence of—or integrated alongside—existing formal, centralized systems of water provision and sanitation (Arora et al. 2015). In other cases, previously overlooked

MAD water systems, such as water sharing (Wutich et al. 2018; Brewis et al. 2019; Stoler et al. 2019; Harris et al. 2020; Jepson et al. 2021; Roque et al. 2021; Wutich et al. 2022) or rainwater harvesting (de Melo Bronc et al. 2005; Gomes et al. 2014; Campisano et al. 2017; Soler et al. 2018; Staddon et al. 2018; Crosson et al. 2021; Alim et al. 2020, Doss-Gollin et al. 2015), are receiving new attention from scholars and practitioners. Yet, piped water remains the focus of mainstream policy debates, as exemplified by India's Jal Jeevan Mission to provide every rural household with a tap connection by 2024 (Sarkar and Bharat 2021). As water system performance declines, simpler systems may offer more resilience than the grander schemes preferred by policy makers (Harvey and Drouin 2006; Kleemeier 2000). These MAD water models may help provide access to safe, reliable, affordable water delivery and sanitation~~supplies~~ in a world of increasing uncertainty: a world characterized by ongoing climate disruption, increased population mobility, and political volatility.

Without a holistic framework to understand these responses and consider the wide-ranging scope and implementation process, there is a serious risk of maladaptation that leads to undesirable, unsustainable, and unjust outcomes (Barnett and O'Neill 2010; Juhola et al 2016; Magnan et al 2016). We argue that ~~theis~~a shift to decentralization is already happening, but that the water community at large is doing little to reconceptualize this shift beyond singular technical fixes and mechanistic responses. Without acknowledgement of this shift and a better empirical basis for decision-making, MAD solutions could have inequitable and detrimental implications for water in several water domains: provision, justice, sustainability, governance, and economics. There is thus a fundamental need to integrate existing scholarship across social and engineering sciences into a convergent approach that can mitigate negative outcomes of this nearly-invisible and haphazard socio-technical transition. Our hope is to harness—following successful integrative approaches in interdisciplinary water scholarship (e.g., Ostrom 1990, Pahl-Wostl 2009, Sivipalan et al. 2014, Budds et al. 2014, Jepson 2017)—valuable insights from a wide range of existing perspectives, theories, and cases to form a new integrated field. We suggest a series of frameworks for theorizing a shift to MAD water systems in ways to that can guide the transition productively and avoid reproducing or reinforcing historical WASH inequities.

2. A New MAD Paradigm: Beyond Centralized Piped Water (and Sewer) Systems

The water literature is rife with examples of systems that are neither centralized nor networked, but still meet water needs of local communities in important ways. Examples are documented in literatures including, but not limited to, water and informality (Kooy 2014, Schwartz et al. 2015, Truelove 2019), community-based water management (Cox et al. 2010, Mansuri and Rao 2004, Adams et al. 2020), small-scale water vendors (Whittington et al. 1991, Solo 1999, Kariuki and Schwartz 2005), small drinking water systems (McFarlane and Harris 2018, Klasic et al. 2022), hybrid water systems and regimes (Yates and Harris 2018, Wahby 2021, Storey 2021), decentralized water provision (Arora et al. 2015), green infrastructures for water and wastewater management (Sharma and Malaviya 2021, Green et al. 2021), and packaged water (Wilk 2006, Gleick 2010, Stoler 2012, 2017, Morinville 2017, Pacheco-Vega 2019). Our work builds on this literature by proposing a framework that can bring these contributions into closer, more integrated (and convergent) conversation. As we discuss, this scholarship crucially illustrates the range of innovations in MAD water provision and sanitation, often foregrounding important advances in engineering technology (Dongare et al 2017; Alvarez et al 2018). Yet, we argue the need to equally consider justice, institutional design, and long-term environmental sustainability.

Political-economic dynamics move households and communities to hybrid and decentralized systems in complex ways. For example, on the one hand, there are "shove out" water systems, in which marginalized populations are forced into self-provision or self-management of drinking water (*e.g.*, Vandewalle and Jepson ~~2016~~2015). On the other hand, there are "opt-out" water systems, in which elite or high-income residents disengage and divest from collective water systems (*e.g.*, Lloréns 2021, Workman and Shah 2022). As an example of the rapid rate of growth of such hybrid systems in the absence of formal water policies, personal preferences have created a $20B/year market in point-of-use water treatment devices that are growing at >10% annually; this is over five times larger and faster growing than the global centralized desalination market (Chen et al. 2021). Yet, despite this market success, achieving~~ement of~~ water security for all remains elusive.

This reconfiguration of waterscapes is happening in both the Global South and Global North, with examples providing a rich foundation for theorizing a coherent framework for assessing the outcomes of these non-centralized, non-piped, and sometimes small-scale water and sewer systems on health and human wellbeing. The ethical and political concerns are significant. "Shove out" MAD water scenarios may create heavy financial and labor burdens for those excluded from centralized piped water systems, or merely shift water provision risks, responsibilities, and costs to vulnerable populations least equipped to manage these (Hope et al. 2020). Scholarship on water insecurity underscores this dynamic. For example, peri-urban neighborhoods on the outskirts of Cochabamba, Bolivia, that were historically denied access to the municipal water utility, were forced to rely on small-scale water vendors (Wutich et al. 2016). Residents in low-income rural subdivisions in South Texas faced a "no-win waterscape," forced to buy expensive water from vending machines as piped water did not provide the quality of service or water to meet all their needs (Jepson 2014; Jepson and Lee 2014). By contrast, high-income Puerto Rico residents built fully independent off-grid water and energy provision in luxury communities after Hurricane María (Lloréns 2021). MAD water systems enabled such an "opt-out" by higher-income and politically powerful populations, allowing them to abandon the costs and responsibilities of participation in solving society-wide water challenges. This emerging, dynamic, socio-technological shift in water infrastructure carries significant implications for water governance, system operation (and more common maintenance), equity, and justice.

MAD water systems are neither inherently good nor inherently bad. Rather, recent trends suggest that communities will increasingly be forced off, or choose to abandon, centralized piped water systems as old models break down under the pressure of under-investment and climate disruptions. We already see the efficacy of the centralized model eroding under the current climatological, demographic, and financial trajectories, as evidenced in the U.S., for example by the aftermath of California's wildfires or the ongoing water quality disaster in Flint, Michigan (Bosscher et al 2019). Such disruptions result in new moves to opt-out of networked water, as well as the formation of communities that are shoved out of centralized systems. As this phenomenon becomes more widespread and common, there is a need for broader, more coordinated research on the benefits and challenges of different configurations of MAD water. In this introduction to MAD water, we lay out key definitions, case examples, and considerations for future research. Our work leverages interdisciplinary contributions from across the social, engineering, finance, and health sciences to describe MAD water systems and understand the future role they have in promoting global just water security. We also outline critical challenges to the environmental, economic, and social sustainability of these new socio-technical configurations. Figure 1 presents a conceptual model of the feedback loop between these components that we believe will be crucial for ensuring that the transition to, and local development of, MAD water systems promotes positive societal and environmental outcomes in a changing world.

INSERT FIGURE 1 (CAPTION BELOW)

Figure 1. Conceptual model outlining examples of economic and governance considerations for successful implementation MAD water systems; measurable benefits to justice, human health, and the environment that can be used to demonstrate return on investment (ROI); and the feedback loop that helps MAD water systems adapt to new contexts.

Given the inherent interdisciplinary nature of MAD water, now is a particularly fruitful time to develop alternatives to dominant water paradigms, given the push toward convergence research (*e.g.*, Westerhoff et al. 2021, Roque et al. 2021, Peek et al. 2020). Convergence research challenges teams from across the sciences to cooperatively develop basic research that can contribute to solving major global problems such as water insecurity and inadequate sanitation. This convergence approach is necessary as we develop this new field of research around MAD water systems, as its success or failure will be decided as much within the realms of justice and environmental sustainability, as in those of hydrology and engineering.

3. MAD Water Systems: Key Definitions

Our work tracks the emergence of new models of modular, adaptive, decentralized (MAD) water systems. In many cases, these systems are made possible by novel technologies, institutions, and practices that produce, transport, and store safe water – as well as allow for treating and safely reusing water to supplement safe water. These systems include, for example, point-of-use water filtration technologies and onsite wastewater treatment and reuse technologies (Chen et al. 2021; Zodrow et al. 2017). These systems can operate in the absence of—or integrated alongside—existing formal, centralized systems of water or sewer provision. In other cases, previously ignored MAD water systems, such as water sharing (Rosinger et al. 2020) and informal water markets (Garrick et al. 2023), are newly receiving attention from scholars and practitioners. In other cases, we see a hybrid of old practices, such as rainwater harvesting, with new technologies (e.g., Voth-Gaeddert et al. 2022).

Table 1 explains key terms for the MAD water framework. Modularity, adaptability, and decentrality are the key characteristics observed in water systems, and we define these terms in Table 1. In the next section, we provide a series of examples that illustrate how a MAD approach can help us better understand large-scale shifts in the water sector. We do not seek to rigidly define what is or is not MAD; rather, we observe that water systems and their management, exist along gradients of increasing modularity, adaptability, and/or decentrality. Finally, our definition of MAD water involves scalar implications. MAD water systems range in connectivity and operational scale, from systems that include an array of household technologies and relations that are fully decentralized to more distributed systems within smaller, localized networks. Following Stoler and colleagues (2022), we conceptualize MAD water across five key dimensions of water security: harvesting, treating, distributing, monitoring, and governing. Table 2 lists some examples of the application of the MAD water framework for a range of water systems. Several of these examples, including lower-tech ones, are described in the following case studies.

<Table 1. Key Terms, Definitions & Examples for MAD (Modular, Adaptive, or Decentralized) Water Approaches>

4. MAD Water Case Studies

4.1 MAD Example: Sand Scoops in Ephemeral Rivers

Sand scoops represent one of the oldest and simplest technologytechnological forms that fits within, and illustrates, the MAD water framework. Water can be collected from ephemeral streams when drywhen dry by digging scoop holes into the sand of a dry riverbed to form a shallow well. Even when the river is not flowing, rivers can hold substantial volumes of water near the surface of the riverbed. Water just below the riverbed can be easily accessed using a simple hand tool, or even one's hands. This water can be conveyed to where it needs to be by a person carrying a gourd, by donkey, or by motor vehicle. When one scoop hole is dry or no longer usable, a similar scoop can be made elsewhere in the same river or river system or replicated nearby if demand is higher. Informal governance systems may dictate how close an existing scoop a new one can be dug. While this can—in principle—yield good quality water, it is often contaminated (Quinn et al. 2018). As with the method of conveyance, treatment can vary from low-tech, such as ~~basic~~ filtering through a piece of fabric, to high tech such as an advanced filtration membrane or bio-sand filter. The latter example illustrates how within a MAD water system at different stages in the chain can have starkly different technology levels, but how these can combine to produce potable water for final users.

4.2 MAD Example: Point-of-Use Drinking Water Systems

One example of a technology that can contribute to MAD water systems is engineered point-of-use (POU) drinking water treatment, where a treatment unit is used at individual locations in a household. POU treatment can take many forms, including media filtration (*e.g.*, granular activated carbon block filtration in a pitcher or biosand filtration), membrane filtration (*e.g.*, ~~under-sink~~ reverse osmosis), or disinfection (*e.g.*, ultraviolet light, chlorination, boiling) (Pooi and Ng 2018). Many systems implement more than one of these technologies (Oyanedel-Craver and Smith 2008). POU treatment embodies the idea that not all water used within a household needs to be treated to drinking water standards (Wolff and Gleick 2002; Zodrow et al. 2017). Many POU treatment units are modular, and water treatment capacity (e.g., liters per day) can be increased with additional units. These units may be purchased (*e.g.*, under-sink filters) or constructed using locally available materials (*e.g.*, ceramic filters or biosand filters). POU drinking water treatment is used around the world, either as a primary form of treatment, to improve water aesthetics, or to remove the most recent class of emerging organic contaminants such as per- and poly-fluoroalkyl substances (PFAS) (Patterson et al., 2019). Lower cost water quality monitoring using colorimetric and microfluidic technology (Phuangsaijai et al., 2021; Jaywant & Arif, 2019) may ~~enable~~empower community or households ~~level~~to independently test their water quality.~~ing.~~ When combined with real-time water quality monitoring using information and communication technology ~~(ICT)~~ and sensors in micro-networked households, POU treatment could~~an~~ ~~powerfully~~substantially improve water quality (Stoler et al. 2021). However, ~~Effective~~ effective maintenance and monitoring of POU devices and sensors can pose a challenge to poor communities—if the burden of operation and maintenance are placed on poor communities rather than the centralized system—and may occur as a "shove out" technology that could subvert longer-term efficacy of water provision (Vandewalle and Jepson ~~2016~~2015). A recent survey in the USA found that lower income households spend more of their income on POU devices and bottled water, compared with higher income households, suggesting a potential need for public funding of POU devices (Kidd et al. 2020).

4.3 MAD Example: Handpumps

Handpumps are used across the world to access shallow groundwater, most commonly in the Global South (Foster et al. 2019). They are used both in rural areas that may be hundreds of km from the nearest piped water system, and in informal urban settlements where household or even standpipe connection to the nearby centralized water system is blocked for institutional or politically reasons, the aforementioned "shove out" communities. The pumps themselves are off-the-shelf modular items, often bought in bulk by governments or development agencies (MacArthur 2015). Wells can be drilled or dug where needed and replicated if demand is high or an initial well fails; in this way, they can be adaptive. Finally, they are off-grid and, depending on the distance between them and aquifer properties, hydrologically decentralized as well. They are situated technologically between shallow wells accessed by buckets, and boreholes with motorized pumps, the latter also being a technology of choice for high-income "opt out" communities (Fox et al., 2016; Hynds et al., 2013). Conceptualizing handpumps and their management and monitoring as MAD water systems (Thomson et al., 2012; Thomson and Koehler, 2016; Koehler et al., 2018) may serve us better—and the households that use them—than viewing them as an interim step between untreated surface water and piped, treated connection to the home.

4.4 MAD Example: Onsite Systems for Wastewater Management

The concept of clean sanitation originally started at a small, decentralized scale, focusing mainly on disposal of human waste using systems such as privies. During the 19th and 20th ~~-~~ C~~c~~enturies~~y~~, with the advent of piped water systems, the focus shifted to treatment of wastewater from densely populated areas, prior to discharge into local surface, through ~~using~~ large scale centralized treatment. ~~and surface water discharge systems in densely populated areas~~ While decentralized systems may have become less common in the Global North, at least in urban areas, they remain ubiquitous in the Global South: only 7% of people in Sub-Saharan, and 13% of people in Central and Southern Asia have a sewer connection, compared with 83% in Europe and North America (World Health Organization & UNICEF, 2017).

~~As well as~~In addition to higher tech systems such as the Gates Foundation toilet (Hiolski, 2019) and containerized sanitation (Ferguson et al., 2022), there is revived interest in composting systems (Mariwah et al., 2022; Anand & Apul, 2014) as a means of safely managing fecal waste. These systems, by which we mean both the technology (Li et al., 2023; Geetha Varma et al., 2022) and the management models and institutional environment in which they sit, can be considered as MAD systems. These decentralized systems may not always be modular—artisanal/bespoke septic tanks are common—but the management of fecal sludge is inherently adaptive, with the conceptualization and monetization of fecal sludge as a resource opening up new business models (Wichelns et al., 2015; Shukla et al., 2023).

~~, with millions of septic systems in less dense rural areas~~In the Global North, ~~. Use of~~ septic systems ~~in an unsewered area was~~were considered a temporary solution for wastewater management, but millions in less dense rural areas in the Global North still use them. The ~~, at least in Global North. But in late 1990, US EPA in its report to Congress (US EPA 832-97-001b) recognized that not all the areas in the US are going to be sewered and some type of onsite/decentralized systems will be used on a permanent basis. There have been unintended consequences, as the~~ mass use of septic tanks has long been known to have detrimental effects on groundwater in some regions (e.g., Bloetscher & Van Cott 1999). I~~But~~ ~~in~~ late 1990, US EPA ~~in its report~~reported to Congress (US EPA 832-97-001b) ~~recognized~~ that not all the areas in the US are going to be sewered and some type of onsite/decentralized systems will be used on a permanent basis. Moreover, advances in technologies for onsite treatment, disposal and reuse have attracted attention of the centralized municipalities as a means to improve climate resilience and water security for their customers (Water Environment Research Foundation 2010). ~~.~~The innovations in decentralized sanitation and fecal sludge management developed in the Global South may be increasingly seen in the Global North as well.

~~But an onsite system when installed properly and managed professionally can offer a cost-effective means to manage wastewater on a permanent basis in unsewered areas worldwide. Advances in technologies for onsite treatment and disposal or reuse have also attracted attention of the centralized municipalities to methodically integrate use of these technologies to improve climate resilience and water security for their customers (Water Environment Research Foundation 2010).~~

4.5 MAD Example: Rainwater Cisterns

For over a decade, the Brazilian government and NGOs executed several programs to construct cisterns for domestic water, livestock, and crops in support of rural communities across the semi-arid Northeast region (~~Agua~~ Água Para Todos; Projeto São José; One Million Cisterns Program; Program One Piece of Land and Two Types of Water) (Gomes et al. 2012; Gomes et al. 2014; Gnadlinger et al. 2020; Cirilo, 2008; Enéas da Silva et al., 2013). Rainwater cistern programs in Brazil sought to increase water access for many rural households in the drought-prone semi-arid zone (Gomes et al. 2012). The first version of the program involved cement cisterns for individual households, where the government partnered with civil society to distribute raw materials to rural residents via community associations. Community members worked together to construct the cisterns for individual households—these were harvesting and distribution systems with decentralized governance and service—and included programs for gender empowerment (Morais and Rocha 2013). The materials were standardized and easily replicable, making them modular forms of harvesting and distribution. Later versions of the program involved plastic cisterns that are also replicable and more quickly distributed—meaning that they were adaptive. Treatment and monitoring, if performed, is at the household level (Silva et al. 2020). Rainwater cisterns can be vulnerable to extended drought (Doss-Gollin et al. 2015), and water quality is highly variable, with *E. coli* detected in many cisterns (Da Silva et al. 2020).

4.6 MAD Example: Rural Water Management in Brazil

Many rural communities in the Brazilian state of Ceará participate in a non-governmental program called System for Rural Sanitation (*Sistema de Saneamento Rural* – SISAR) that functions as a network of community associations (Meleg et al. 2012; Dos Santos Rocha and Salvetti 2017). Similar programs exist in other Brazilian states and other countries as well (Grillos et al 2021; Dupuits 2019). SISAR has eight regional offices that facilitate self-management of water distribution systems for approximately 100-300 rural communities in their region. SISAR operates in communities that are not connected to the primary municipal piped water system, and it does not fund investment in new water system infrastructure. Rural communities that participate in SISAR primarily harvest water through a pre-existing community-scale well or local reservoir connected to a small, piped water network serving 30-100 households. The SISAR regional office provides technical assistance and trains community operators to treat water and maintain community-scale water distribution systems. SISAR trains operators to monitor the status of the distribution system and household water use, though operators do not monitor the status of the water resource such as water level in the well (Cooperman et al. 2020). The SISAR regional office oversees household billing and provides social support for localized governance through community associations. Each of these features of the water system uses a similar model across all communities and can be ~~tweaked~~ modified to adapt to changes in local conditions, making them modular and adaptive.

4.7 MAD Example: Packaged Water: Sachets, Bottles, and Bags

We further acknowledge that increasing the ~~modular, adaptive, or decentralized (~~MAD~~)~~ characteristics of a water service sometimes presents important tradeoffs. For example, the many forms of vended and delivered water around the world include packaged water, most commonly bottled and bagged (or "sachet") water (Vedachalam et al. 2017). In high-income settings, bottled water tends to be an optional luxury good, but in low-income settings—particularly water scarce communities—bottled or sachet water can effectively serve as a virtual extension of existing water infrastructure, whether centralized and decentralized (Stoler 2017). Packaged water harvesting, treatment, and distribution are all remarkably MAD as entrepreneurs can set up filling machines wherever there is a reliable groundwater or municipal water source, and nimbly supply communities who lack centralized water infrastructure. In many West African countries, for example, sachet water has become the *de facto* drinking water supply in communities not connected to municipal water grids. While federal governments have centralized monitoring and governance schemes for packaged water, the most effective governance has been decentralized, self-administered industry quality control as market forces shape leading producers' desire to burnish their product's reputation. Yet, while packaged water has temporarily bailed out many governments from their duty to provide constituents with safe water, ever growing streams of plastic waste and the lack of price controls to stabilize household drinking water expenses highlight the downsides and unsustainability of this form of MAD water (Stoler 2012, Pacheco-Vega 2019).

<TABLE 2>

5. Assessing MAD Water Systems: Considerations for Future Research

From our perspective, the concept of household water security is defined by the lived and relational experiences that contribute to human flourishing and well-being (Jepson et al., 2017; 2018). That is, access to safe water is necessary but not sufficient to achieve water security. The water and sanitation systems we have described above—to varying degrees—provide some level of household water security. Technical solutions alone will not create water security. Other critical dimensions, such as affordability, adequacy, and reliability for all water needs also should be part of a holistic understanding of water security achieved by MAD water (Bakker and Morinville 2013; Jepson, 2014; Jepson et al. 2017).

More than meeting basic needs, we also consider water security to be relational in the sense of enhancing the socio-cultural, economic, and governance capabilities of communities and households (Jepson et al. 2019; Sultana and Loftus 2019; Meehan et al. 2023)—as well as long-term environmental sustainability. Our view of MAD water is thus framed not only in terms of water as a material good to be distributed, but water as part of a larger set of social relations (Budds et al. 2014, Linton and Budds 2014) that has implications on many dimensions of social life. In this way, we recognize the profound relational shifts MAD water systems will have on hydro-social relations. Therefore, hydro-social relations—including cultural and psychosocial dimensions—must necessarily constitute water security, and thus, be part of how we conceptualize and assess MAD water systems moving forward.

Modern water systems attempt to convey treated water to as close to households as possible, ideally with access inside the household or compound. Such conveyance efforts therefore aim to minimize or eliminate fetching distance and time and create some degree of household autonomy through access to water using a private tap. Water governance structures generally aim to ensure that the water remains affordable for users, and to ensure ongoing financial viability of the system. One of the biggest challenges of MAD water systems is to make them easy for households to use in order to ensure user acceptance (Contzen, Killmann, and Mosler 2023), while allowing for appropriate levels of local engagement for system governance and the protection of human and environmental health. Here, we position justice as a primary goal and highlight issues in the key domains of economics, governance, human health, and environmental sustainability that must be approached differently under the MAD water paradigm. ~~Figure 1 presents a conceptual model of the feedback loop between these components that we believe will be crucial for ensuring that the transition to, and local development of, MAD water systems promotes positive societal and environmental outcomes in a changing world.~~

~~**INSERT FIGURE 1**~~

~~Figure 1. Conceptual model outlining examples of economic and governance considerations for successful implementation MAD water systems; measurable benefits to justice, human health, and the environment that can be used to demonstrate return on investment (ROI); and the feedback loop that helps MAD water systems adapt to new contexts.~~

5.1 MAD Water & Justice

Adaptive, decentralized systems allow for variation in how they are conceptualized, managed, and used. By their nature they can be outside the established, albeit imperfect and contested, paradigm of centralized water provision. As much as being an advantage, this also poses risks, such as elite capture, predatory pricing, or neglect. Therefore, our approach to MAD water and the efficacy of this paradigm to support water security necessarily includes a fundamental consideration of water justice (Sultana and Loftus 2019, Boelens et al. 2018, Wade 2018, Zeitoun et al. 2016).

We draw on the expansive scholarship on environmental justice to illustrate how the MAD water paradigm intersects with considerations of water justice (Table 3). As mentioned earlier, water security refers to access, affordability, adequacy, and reliability for all water needs, including physical, cultural, social, and economic. These needs are broadly defined and directly align with distributive definitions of water justice.

A challenge for MAD water is to ensure that these benefits of water security are experienced equitably. A goal we propose is to assess MAD water's efficacy as a paradigm to facilitate equitably distributed current and future water provision. Within *distributive justice* frameworks, one also needs to consider "the community of justice" (who are the recipients of these benefits?). For MAD water, we consider benefits to be accrued across individuals, households, and communities whose risks may be differently determined by race/ethnicity, indigeneity, class, gender~~, class, and race/ethnicity~~ and sexuality (Brewis et al. in revision, Leonard et al. 2023, Meehan et al. 2020). These dimensions are often difficult to balance, and in tension, but they do need to be considered. Indeed, *interpersonal justice* (or interactional justice) operates within the distributive paradigm in that as people navigate the waterscape, individuals, regardless of social category, should experience equitable treatment and respect (~~Beresford~~ Wutich et al. 2016).

We also recognize the critical importance of *procedural justice*, understood in terms of fair participatory processes and rules for decision making, for MAD water systems. This also draws from the definition of water security, as referring to securing "the ability of individuals, households, and communities to navigate hydro-social relations and secure safe and affordable water particularly in ways that support the sustained development of human capabilities and wellbeing in their full breadth and scope" (Jepson et al. 2017, 3). This is a central dimension of justice, navigating hydro-social relations as necessarily participatory, but it is often missing in transitions that are driven by technological change. Our argument is that MAD water systems need to incorporate regulatory governance systems to ensure inclusion, informed consent, and participatory efficacy, and to avoid elite capture~~,~~ (as described in Brewis et al. 2021). There are several principles of participatory governance, from shared decision-making to access to information, and considering the diversity of MAD water, and these principles will vary; however, inclusion of participatory approaches are critical for achieving just water security. We note a promising trend toward developing participatory convergence research to ensure that MAD Water interventions are co-designed (Hargrove and Heyman 2020, Hargrove et al. 2020, Roque et al. 2021, 2024) by communities and researchers, to make certain the community's needs and desires are centered in the design of MAD Water systems.

Water justice ~~also~~ incorporates another critical dimension that is salient for experiences with water provision and use: *recognition as justice*. The dominant paradigm of water provision considers modern water as an economic good that is commodified and transferable. Yet, that is only one water world view. Recently scholars have challenged the universality of water with different world views and values (Leonard et al. 2023, Yates et al. 2017, Wilson and Inkster 2018). The implications for calls to incorporate other water worlds and values hold wide-ranging consequences for MAD water systems. From a water justice perspective, MAD water systems should ~~also~~ be co-designed in ways that accommodate cultural values in ways that are respected.

Finally, and perhaps most powerfully, is the potential for MAD Water to address the need for *transformative justice* (Morris 2000), an approach similar to restorative justice (Nocella and Anthony 2011). Transformative justice seeks to redress past harms by addressing root causes of oppression, centering victims' need for justice, and reintegrating communities. Transformative and restorative justice are nascent fields in water research (Neal et al. 2014, Nikolakis and Quentin Grafton 2014, Corral-Verdugo and Frías-Armenta 2006), but research led by Indigenous scholars indicates that such approaches have the potential to powerfully reshape water systems and knowledge (Leonard et al. 2023, Wilson et al. 2021). The potential role of MAD water systems to contribute to transformative justice is currently unknown, but an important potential area for future research.

<Table 3. Defining justice for MAD water approaches>

5.2 Political Economy of MAD Water: Economics & Governance

Economies of scale tend to favor larger, centralized systems. This may be changing, even for large municipalities in the Global North, due to the cost challenges of maintaining or expanding aging infrastructure to meet capacity and sustainability goals of communities (Garrido-Baserba et al. 2022). The move to MAD systems may be driven by financial pressures in these cases, but it is an open question what the financial logic of MAD solutions may be across countries and contexts. On one hand, the development and maintenance of smaller scale systems may increase total spending on water systems in the short term, adding financial pressure to governments and households. Yet, MAD solutions may represent an investment in employment and skill transfer to currently underserved populations and more efficient water and energy use, leading to more sustainable long-term benefits. Safety, f~~F~~inancing, affordability, and education and training are key. Table 4 lists economic considerations for factors and examples of how MAD water and conventional water systems (Table 4) fit into those factors.

The high fixed costs, low variable costs, and scale of centralized systems allow for high levels of subsidy and cross-subsidy. These can be progressive, such as lifeline tariffs or legal restrictions on cut-offs, or they can be regressive (Fuente et al., 2016; Morales-Novelo et al., 2018), such as in the United States where poor, urban communities must address deteriorating infrastructure after White flight to suburbs. Other examples of regressive costs include high connection fees or bulk discounts when the system is functioning correctly, or—when it is not—cutting off poorer and more marginalized communities or neighborhoods when underinvestment reduces system reach or performance ("shove out"). Those remaining on the system continue to receive water at a cost that is lower than the long-term cost of production. In either case, these subsidies are often hidden or implicit.

As they capitalized on economies of scale, centralized public utilities created institutional structures that, along with policies, enabled ~~the progressive~~progressive contributions and cross-subsidy that led to more equitable access for users of the public system. The move to MAD systems will change this. Being decentralized, the costs of supplying water using MAD water systems could be more closely linked to the local cost of supply, making cost differences overt and subsidies explicit. The regulatory and policy environment for water supply has been built around the natural monopoly of centralized water systems. These governance structures, and the discourse around subsidies, will have to adapt to the different economic characteristics of MAD systems to ensure that water remains affordable, and outcomes are sustainable and equitable. An important line of inquiry in the shift from centralized systems to MAD approaches will be the economic implications in terms of affordability and progressive (or regressive) distribution. The need to address this at both national and local levels is not the only political consideration associated with MAD water. Table 5 lists factors associated with water governance and example application of these factors to MAD water.

The development of large, centralized public utilities also reshaped political landscapes, with public good and natural monopoly arguments combining to create mandates for government involvement in water and sanitation services. Yet, the political challenges created by these centralized approaches have undermined their ability to deliver on promises of universal access and financial efficiency. As governments managed public utilities, either as direct service providers or as principals overseeing contracts with private providers, many could not overlook the opportunities for corruption and patronage (Herrera 2017). Achieving good governance of centralized systems entails a complex approach of creating avenues for participation and representation while also insulating utilities from special interests and parallels the principle of participatory justice outlined above. The political pressure to keep tariffs low can undermine the ability of managers to maintain and expand infrastructure, leaving an uneven patchwork of service and reifying the inequities centralized approaches aimed to address. Those being left out of the maintenance are usually the same groups that are excluded from politics and are economically vulnerable.

MAD water holds the potential to address these challenges, but this shift can have divergent impacts on political representation, accountability, and equity (Table 5). Water systems are managed at different scales with complex networks of overlapping jurisdictions, including utilities, regulatory agencies, watershed or river basin management, and specialized water districts. It is hard for citizens to know which actor to hold accountable for service failures, and coordination across these actors is very challenging (Mullin 2009). In addition, small scale community systems, especially privately-owned ones, may not be well integrated into larger scale planning efforts, increasing risks during drought for already vulnerable communities (Mullin 2020). "Temporary" shifts to MAD solutions, such as bottled water distribution during contamination and natural hazards or POU water treatment for household wells or hauled water, can overcome dangerous drinking water quality or quantity conditions. MAD solutions provide flexibility in the timing and scale of emergency response since different systems can be introduced at different times as local needs shift (e.g., Roque et al. 2021). However, they have high costs and place financial burdens and monitoring challenges on already marginalized communities (Jepson and Brown 2014). Emergency relief is also vulnerable to political pressures and electoral cycles (Cooperman 2022), and short-term shifts to MAD systems can reduce the urgency of public investment and let officials off the hook for fulfilling mandates to provide secure, reliable drinking water or sanitation services (*e.g.*, Vandewalle and Jepson ~~2016~~2015). Over time, MAD approaches may disincentivize public officials from expanding piped water and sanitation systems, leaving residents in an indefinite precarious situation. MAD approaches often require local collective action, and communities that are more likely to successfully engage in collective action, often due to long-time relationships of trust and reciprocity, are better able to harness the gains of MAD systems. Those communities that ~~sfail or~~ lack the political connections for adequate distribution and maintenance are left even farther behind, leading to increased inequality between groups (Cooperman 2019, Dobbin and Lubell 2021).

<Table 4. Economic Considerations for MAD Water >

<Table 5. Governance Considerations for MAD Water >

5.3 Human ~~and~~ & Environmental Health

MAD water systems have the potential to improve human health and broader environmental health. The human health implications are broad, spanning communicable and non-communicable diseases, injuries, and mental health disorders (see Table 6). Improvements to water quantity and quality have long been associated with preventing a wide range of waterborne, water-washed, water-related, and water-based communicable diseases originally organized by the Bradley-Feachem classification (Bartram and Hunter 2015). Reducing water fetching and the need to store drinking water by having a nearby, reliable system will drive down these communicable disease risks. The non-linear relationship between water quality and diarrheal disease (Thomson et al., 2022) by which even short periods of drinking contaminated water have disproportionate health impacts (Hunter, Zmirou-Navier and Hartemann, 2009; Brown and Clasen 2012) makes addressing water-related health risks all the more important. Minimizing fetching needs and increasing autonomy is also theorized to reduce other non-communicable health risks including dehydration and carriage-associated injuries (Geere et al. 2018; Rosinger & Young 2020). Finally, more recent scholarship has shown that further health gains associated with improving water services provision are related to improved mental health (Wutich et al. 2020). All of these can be addressed through *properly designed, implemented, and managed* MAD water systems.

Water quality improvements~~, in particular, also~~ also reduce non-communicable disease risk factors associated with natural and anthropogenic water pollutants ranging from arsenic to old industrial pollutants like benzene or lead and emerging organic chemical pollutants like PFAS and phthalates (Wutich et al. 2021). MAD water systems are particularly well-positioned to help with emerging contaminants because they can be tailored to local water needs. However, the monitoring, management, and disposal of difficult toxicants such as PFAS or disinfection by-products, and pathogens such as *Cryptosporidium*, may challenge MAD water systems. MAD water systems may be able to respond more quickly than large, centralized systems to changing water quality and treatment needs. For example, products like PFAS can be readily absorbed, and removed from, water on activated carbon blocks or separated from water by reverse osmosis in commercially available POU systems (Herkert et al. 2020). However, these updates can be narrow, including only the users with the knowledge, salience, and resources, or short-lived compared to upgrading treatment at centralized facilities. Moreover, MAD system managers may not be well-suited to properly dispose of the forever chemicals.

MAD water approaches should also prioritize environmental sustainability and ideally promote ecosystem services, sustainability, and resilience for local communities (Table 7). For example, wastewater reuse systems can discharge water into appropriate green infrastructure, providing benefits to the community and the environment. MAD water systems can also be compatible with ecosystem services, such as locating rainwater collection infrastructure in a drainage basin that already needs to absorb floodwaters. At the very least, MAD water systems must not undermine ecosystem services provided by wildlife or natural landscapes. MAD water systems should be sustainable and not impose any downstream burdens, such as new waste streams, which are likely to affect water supplies or compromise ecosystem services elsewhere. This implies the adoption of recyclable treatment media, protocols for safely handling any dangerous waste products that accumulate during treatment and filtration or using sustainably sourced or renewable consumables.

Finally, MAD water systems could enhance community abilities to recover and thrive from extreme events such as floods and droughts, rapid socio-demographic changes such as a mass migration event, or economic shocks such as a depression or sudden currency devaluation. In such high-risk contexts, MAD water infrastructure should ideally be quickly scalable to a sudden increase in usage, potentially physically mobile to help relocate away from danger, and require maintenance sustained through reliable supply chains that are relatively insulated from global institutions and politics. However, small water systems often struggle to provide water security during drought shocks due to economic, infrastructural, planning, and enforcement challenges (Mullin 2020). A shift toward MAD water systems could enhance human and ecosystem resilience, depending on the political, economic, and justice perspectives described above.

<Table 6. Human Health Outcomes for MAD Water >

<Table 7. Environmental Sustainability for MAD Water >

6. **Conclusions and Next Steps**

MAD water systems may have the capacity to provide better water and sanitation services for communities and households currently relying on poor water supplies, and for whom piped water to the home is a pipe dream rather than a realistic policy goal. It will be important for MAD water to be built, as a field, on empirical assessments of how specific MAD configurations perform in terms of key outcomes like justice, environmental sustainability, human health, governance, and economic wellbeing. We suggest a simple framework (Figure 1) as a place to start. We invite scholars to join us in this effort. Many scholars are already working on crucial components of this research agenda, but not yet in conversation with each other as part of an integrated field. Others are beginning convergence efforts, working with interdisciplinary teams to solve intractable water or sanitation problems. Still others are developing ways to work ethically, equitably, and respectfully with water-insecure communities, contributing new methods for research, communication, and collaboration. And many practitioners have ~~crucial~~ important practical insights that are not yet well-understood in the academic literature. All of these perspectives will be crucial as we move beyond the 20th century water provision paradigm. MAD water systems are poised to make substantial contributions to confronting the global challenges of climate change, population displacement, and financial upheaval expected later this century.

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TABLES

Table 1. Key Terms, Definitions & Examples for MAD (Modular, Mobile, Adaptive, or Decentralized) Water Approaches

Term	Definition	MAD Water Example(s)	Counter-Example(s): NOT MAD
Modular (and Mobile)	Fit-for-purpose, easily replicable, can be expanded or reduced according to need, and are often mobile or portable, i.e., do not rely on fixed, permanent infrastructure (Mobile systems that can be easily deployed as populations move & resettle are by nature modular and included in our definition.)	Point-of-use water filtration systems: can be expanded to process more water Onsite/Decentralized wastewater treatment and reuse system that can be expanded modularly to meet demand. Water vending trucks that move water from source to customers Mobile desalination or treatment systems for disaster response.	Conventional water & wastewater treatment plants designed for specific capacity (e.g., due to both site and permitting constraints)
Adaptive	Can be quickly and responsively modified to meet immediate needs	Household water sharing: norms-based system can be modified to encompass different water needs and relationships	Systems governed by Federal water legislation are often not adaptive because the change process is long and slow
Decentralized	Dispersed, distributed, and localized. Lack of central coordination in water distribution	Rainwater harvesting: Individual households collect & allocate water independently Onsite wastewater treatment and reuse to amend rainwater harvesting.	Municipal water & sewer utilities typically have centralized infrastructure & decision-making

Table 2. Examples with modular~~/mobile~~, adaptive, or decentralized characteristics for water harvesting, treatment, distribution, monitoring, or governing.

Example	Harvesting			Treating			Distributing			Monitoring			Governing			Citation
	M	A	D	M	A	D	M	A	D	M	A	D	M	A	D	
Sand scoops in ephemeral rivers	✓	✓	✓	✓	✓	✓	✓	✓	✓					✓	✓	Quinn et al. 2019
Water truck vending in Bolivia	✓						✓	✓	✓				✓	✓	✓	Wutich et al. 2016
Remotely-monitored handpumps in Kenya	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓		✓	✓	Thomson 2021
Rainwater harvesting in Brazil, Uganda, Mexico	✓	✓	✓				✓	✓	✓							Staddon et al 2018; Lindoso et al 2018; Adrich and Page-Tan 2020
Water sharing after Hurricane Maria, Caribbean							✓	✓	✓				✓	✓	✓	Roque et al. 2021
Sistema de Saneamento Rural (SISAR) communities in Brazil				✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Cooperman 2019; Dos Santos Rocha and Salvetti; Meleg 2012
Packaged water in West Africa	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓				Stoler 2017
Hauled water in U.S. colonias							✓	✓	✓							Garcia et al. 2016
Bottled water among unhoused people in London, U.K.	✓	✓	✓				✓	✓	✓							Meehan et al. 2022

In-home water treatment systems in Kathmandu Valley, Nepal				✓	✓	✓										Shrestha et al. 2018
Water kiosks in Delhi, India				✓	✓	✓	✓	✓	✓							Sarkar & Choudhary 2020
Water ATMs in Delhi, India				✓	✓	✓	✓	✓	✓							Sarkar 2019
"Luxury Techno-Libertarians" in Puerto Rico	✓	✓	✓	✓	✓	✓										Lloréns 2021

Table 3. Defining justice for MAD water approaches

Forms of Justice	**Brief Description**	**Example**
Distributive	Access to resources and outcomes are fair and equitable across social groups and classes (e.g. gender, sexuality, class, race/ethnicity, ~~region~~indigeneity)	No disparities in water quality between genders or racial-majority and racial-minority water users
Interpersonal	Individuals are treated fairly and equitably, no matter who they are	Low-income and high-income people are treated equally when buying water from private vendors
Procedural	Rules, norms, and decision-making processes are fair and equitable	All genders are equally represented in decision-making to change to water rules
Recognition	Different worldviews and values are fairly and equitably represented	Indigenous conceptions of the value of water are equally considered when determining water allocations and definitions of "use"
Transformative (or restorative)	Root causes of oppression in water systems are collaboratively addressed and communities are peacefully reconstructed	The root causes of oppressive water systems are identified and corrected in ways that address victims' needs, rehabilitate offenders, and reintegrate society

Table 4. Economic Considerations for MAD Water

Economic Factors	**Brief definition**	**Example**
Financing	Capital investment and O&M of systems must be paid for.	✓ Potentially lower up-front costs relative to replacing aging centralized infrastructure.

		× Unclear the extent to which decentralized systems can generate economies of scale.
Affordability	Costs of water access do not place an undue burden on users relative to their household income	✓ Users no longer pay high connection costs to large piped systems across large distances that are prone to high water leakage and corruption. × Previously hidden cross-subsidies no longer possible, leading to higher prices for marginalized.
Workforce and business development	MAD systems provide opportunities for local skills development and employment.	✓ Brazilian programs to implement rainwater harvesting targeted gender empowerment and training in cistern construction (De Moreas 2013) × Proprietary treatment systems lock in the need for external support.

Table 5. Governance Considerations for MAD Water

Governance Factors	**Brief definition**	**Example**
Representation	Users participate and/or have their interests present in local government / higher level decision making	✓ Users can more easily serve on decentralized water boards. × Decentralized rural systems may cause governments to ignore rural constituents

Accountability	Service providers (utility/NGO/other) are accountable to users (depending on who/where service providers are)	✓ Local providers are closer to users and better able to respond to requests; users can more easily communicate and protest × Central governments may no longer respond to concerns or requests related to other public services from decentralized water system users who no longer rely on or pay into centralized water systems
Equity	Users have equal access to reliable, secure water sources	✓ Users previously unserved or underserved by centralized systems have better access × Wealthy residents are better able to self-provide off-grid solutions that poor residents cannot afford

Table 6. Human Health Outcomes for MAD Water

Human Health Outcomes	**Brief definition**	**Example**
Water-related diseases	MAD water systems reduce disease morbidity and reduce the overall burden of waterborne diseases.	✓ Reliable supplies close to home reduce use of unsafe sources. × Small scale treatment struggle with tricky contaminants.
Physical wellbeing	Physical burden, risk of injury and threat associated with water fetching is minimized.	✓ Supplies close to home reduce risk of exposure to physical violence when collecting water. × Non-piped systems necessitate water fetching.

Mental health	The transition to MAD water systems reduces or eliminates mental health impacts associated with water insecurity.	✓ Reliable supplies close to home reduce worry. × Responsibility for O&M by non-professionals increases mental stress.

Table 7. Environmental Sustainability for MAD Water

Environmental Sustainability Components	**Brief definition**	**Example**
Ecosystems Services	System(s) or feature(s) that are compatible with existing services, or otherwise do not interfere with their function.	✓ Integration of high-tech MAD treatment systems with natural or constructed wetlands. × Modular systems not designed for specific local environmental conditions.
Sustainability	System(s) or feature(s) that do not generate downstream ecosystem burdens or tradeoffs, such as creating problematic waste products, or reducing ecosystem services.	✓ Lower carbon footprint from initial construction. × Difficulties with handling and disposal of brine or chemical waste accumulated during treatment.
Resilience	System(s) or feature(s) that enhance a community's ability to recover from extreme weather or other shocks.	✓ Infrastructure that is portable and can be rapidly expanded/scaled during an emergency. Supply chains for infrastructure parts is buffered from global financial risks, etc. × Decentralized systems have less redundancy and may be more vulnerable to shocks such as operator errors and cyber-attacks.

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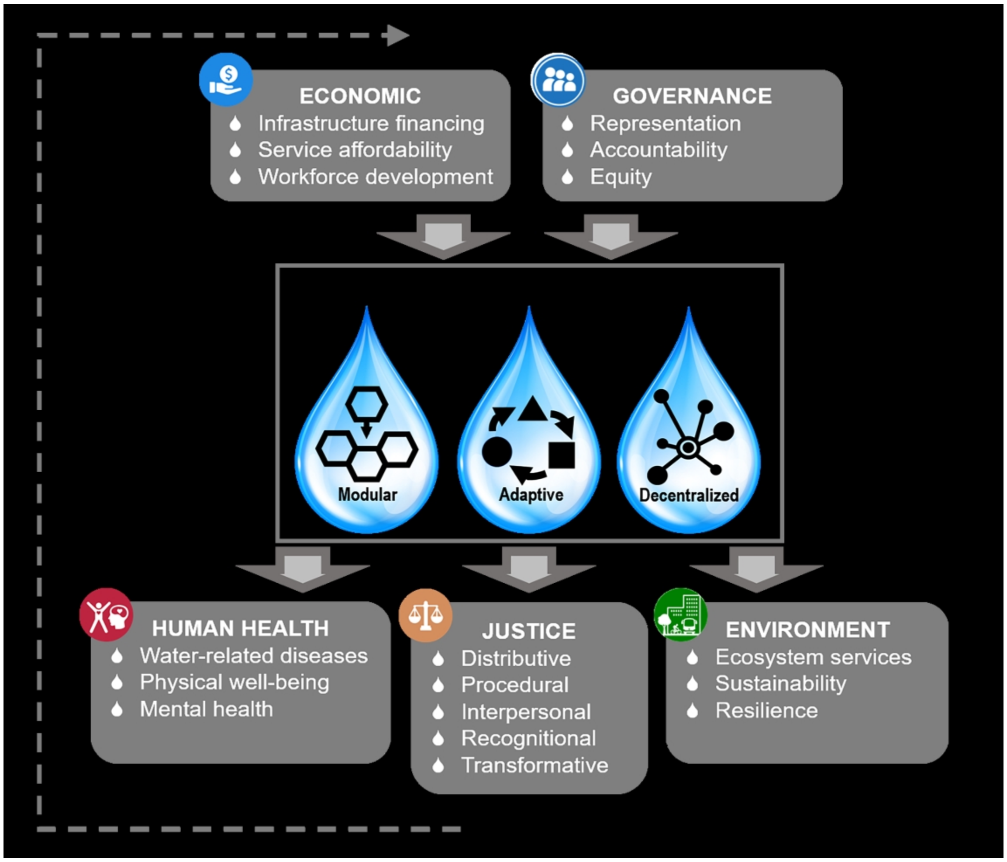

Conceptual model outlining examples of economic and governance considerations for successful implementation MAD water systems; measurable benefits to justice, human health, and the environment; and the feedback loop that helps MAD water systems adapt to new contexts.

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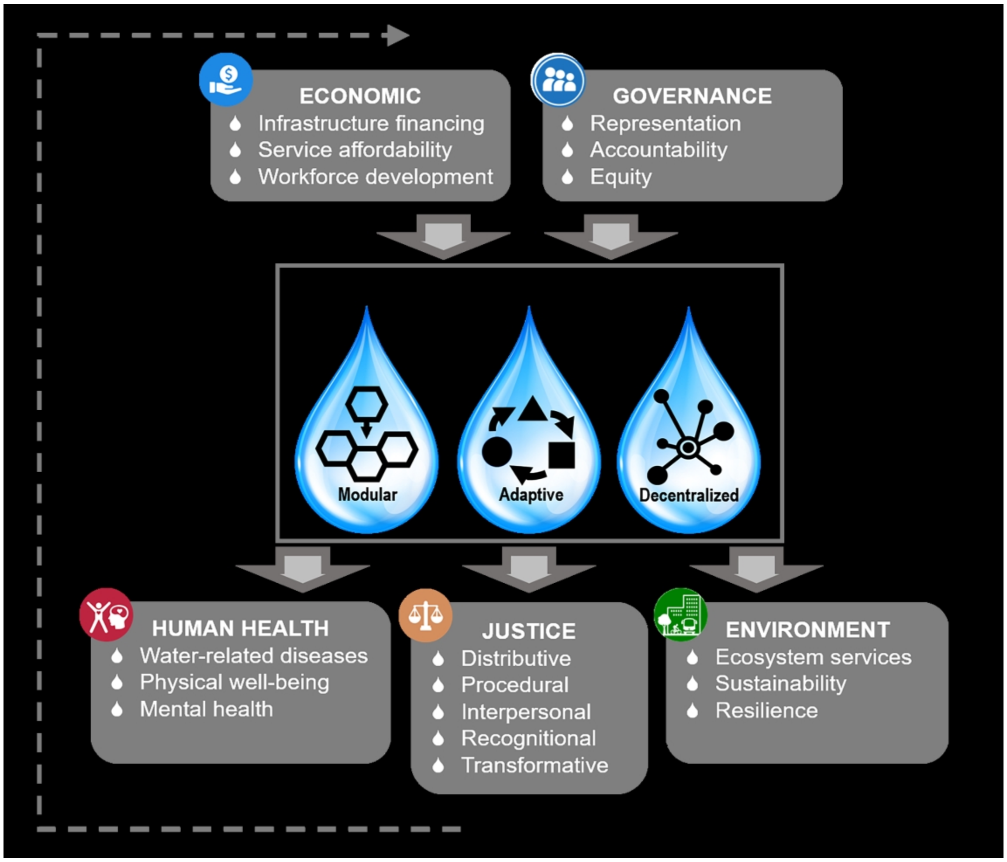

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