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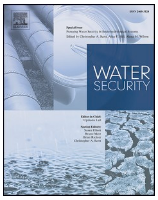

Household Water Containers: Mitigating risks for improved Modular, Adaptive, and Decentralized (MAD) water systems

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ABSTRACT

While the literature on the design and operation of safe water sources in low-income communities is huge, little attention has been paid to the design of systems for the safe transportation and storage of water by households between source and point of use. The design of water containers like the near-ubiquitous "jerry can" in relation to how they are used and the potential risks incurred has received little attention. This is despite, as we explain, the strong influence that water container design has on hazards associated with fetching and storing water. This paper advances the argument that MAD ("modular, adaptive and decentralised") approaches to rethinking water containers are possible and points to examples that have been trialled in different locations around the world. Placed in a broader theoretical framework, the objects that are used as water containers can even be viewed as "engines of history" through which human communities interact with the (water) environment and can create off-grid infrastructures. Key suggestions for design improvement include recognizing the role of water containers in heterogenous networks and in wider socio-technical systems that can reinforce marginalization, and the critical need for localized, community-collaborative co-production.

1. Introduction

In water insecure communities globally the humble (often yellow) "jerry can" is a familiar sight (Fig. 1). In many households it is – as we will explain, unpack, and explore – the critical element in the infrastructure of both water storage and transport between water source and point of use [1]. Our goal in this paper is to identify such common, everyday water containers as crucial objects – in both social-symbolic and practical terms – in the context of understanding and advancing safe and effective infrastructure for Modular, Adaptive, and Decentralized (MAD) water systems. This paper advances the argument that MAD approaches to water containers are not only warranted, but already in play in different locations around the world [1,2].

2. Water containers as (Less studied) objects of study

Currently water containers act as the primary object for water transport and storage in many water insecure households globally (Fig. 1). In 2022, for example, there were over 1.5 billion people worldwide who were dependent on water provisioning arrangements that required collection and transport from remote locations and storage in the home prior to use [3,4]. In the lived experience of erratic water infrastructures, such household water transport and storage objects as jerrycans, drums, and tanks of water are commonplace. So, why is it that they have received so little attention in the literature examining water systems, especially in in lower income countries where they are so clearly evident and widely used?

Here a 2018 essay by Shryock and Smail considering containers more generally is very useful. They explain how containers are objects that hold other objects, in ways that both encourage (e.g., through trade) and inhibit (e.g., through sequestration) all types of transactions. They are thus inherently social objects that fill our social worlds, aggregate like with like, are guards against entropy and loss, and keep the objects they contain from circulation (if only temporarily). In a more theoretical sense they can be viewed as "engines of history" through which human communities interact with and shape their experiences of the world [5].

All these points are relevant to our consideration of household water containers. So, the most likely answer as to why water containers have warranted relatively little study as central to many of-grid water systems is found in their mundanity – they are seen as things that holds other things, so that scholarship too quickly passes on to the thing/object contained rather than the container that shapes, constrains and bounds it. Yet containers have underappreciated agency which may be conducive to the ends/outcomes we intend for them. They are enmeshed in relational networks that connect users with uses – and with other users – through physicalities that are not entirely "neutral" [6].

With this in mind, it should be possible to imagine water containers designed to help achieve safer and more equitable water access

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Fig. 1. Common water containers (Licence: CC BY-NC-ND 2.0 DEED Attribution-NonCommercial-NoDerivs 2.0 Generic).

outcomes [7]. Yet truly modular, adaptive, decentralised containment systems are too often seen in terms of their potential to "undermine and divert resources away from the collectively devised industrial form of piped water provision" [8]. But we can perhaps start with the idea that it is possible to articulate alternatives water system that are "on, off, below and beyond the grid" [9]. As Stoler et al. [1] put it:

> *Leveraging social infrastructure and designing MAD water requires productive and generative partnerships with local water and environmental authorities. The conventional (and centralising) provisioning role of local water authorities in MAD water systems may evolve into more of a supportive role that simultaneously distributes risk and increases local autonomy for self-supplied or decentralised communities* [2, page 2].

This approach follows earlier calls for "appropriate technologies" (e.g., Schumacher) and "participatory development" (e.g., Chambers) to create lasting and equitable water solutions through inclusive co-creation to address fundamental human rights such as the right to water.

In this paper we explore the role of water containers in shaping the experience of and outcomes from fetching, transporting and storing water in low-income communities in the Global South. We begin with an assumption that water containers in themselves are useful and necessary. Starting from this point, our goal is to consider how container type and the ways they are used to contain, constrain, etc. interacts to shape the risk profile identified with each step in water's journey from source to end use. By understanding how such risks are created, we can advance the recognition that MAD approaches to water containers are possible, and points to examples that have been trialled in different locations around the world. But this focus on risk allows us the scope for rethinking design of water containers and the water labour they implicate as households around the world seek to meet daily water needs.

Section 3 and 4 explore what we already know about different ways in which water storage containers themselves create hazards for users during the water fetching and water storing phases. The final sections consider MAD approaches to storage that can mitigate some of these hazards and returns to the more conceptual arguments about MAD approaches, water containers, and household water security to define an agenda for future MAD water research.

3. Hazards associated with carrying water in commonly used containers

While the literature on the design and operation of safe water *sources* is huge, less attention has been paid to the design of systems for the safe transportation and storage of water between source and point of use [10]. Even the minimal water provision targets for humanitarian relief of 20 L per person per day imply that somebody is going to have to carry anywhere from 60 to 100 kgs of water (for average households) from source to home every day. Full achievement of SDG6 is usually interpreted to mean access to at least 50–100 L per day per person within one kilometre distance, implying an even larger fetching burden [11,12]. The data overwhelmingly suggest that the majority of those water fetching somebodies are going to be women and children. Using data from UNICEF's Multiple Indicator Cluster Survey (MICS), Sorenson et al. [13] published one of the first systematic studies of water fetching, finding that women "are the most common water carriers around the world, and they spend considerable time supplying water to their households" [15, page 2]. Moreover, the evidence suggests that the longer the trip needed to fetch water, the less likely it is that men will be making it ($r^2 = -0.66$). Because households need significant volumes of water each day, water containers have evolved to accommodate volumes that can weigh up to 20 kg or more. Commonly used water containers include the "jerry can" (usually 20 L), the "kolosh" (5/10 L capacity) and open pails/buckets which are designed to maximise the volume of water that can be manually carried with ergonomics a largely neglected factor (Fig. 1: common water containers). Certainly none of these containers seem designed for ease of carrying. We need therefore to consider the combinations of container types and sizes, carrying methods, distances travelled and terrain to better understand how containers themselves can affect the physical burden of water fetching.

The three most common ways of carrying heavy loads are back, head and arm loading, the latter two being most commonly encountered in water fetching/carrying. Musculo-skeletal trauma (chronic and acute) is a well-known consequence associated with this sort of load bearing. A 2010 study in South Africa [14] found that more than two thirds of respondents reported back or neck pain as result of carrying water, which is usually done via direct head loading (as opposed to using headlines or back loading).[1] Where the prevalence of children acting as water carriers/fetchers is higher, there are greater risks of deformation of their smaller and more plastic musculo-skeletal frames [15,16]. Research also suggests that many women and children in low and middle income countries (LMICs) may spend up to 4 h per day transporting loads of up to 35 kg, equivalent to more than 50% of average body mass.[2] Though high-quality quantitative studies are difficult to find, there are suggestions in the literature that long-term head and back loading are associated with permanent deformation of bones (e.g., cervical spondylosis) and vertebral discs (e.g. degenerative disc disease, listhesis, etc.). Poor nutrition can accelerate development of these conditions by contributing to lower bone densities, particularly in children and adolescents [17,18]. Conversely, decreasing water fetching burden is associated with improved health outcomes including fewer recorded back/neck problems and “improved anthropometric indicators of child nutritional status” [19].

In addition to physiological and chronic musculo-skeletal issues, transporting water manually also carries with it a higher likelihood of *acute* injury, particularly bone fractures and muscle and ligament damage [20]. A study by Rosinger et al [21] found that slips and trips were the most frequent injuries reported by 20% of respondents whilst 13% of respondents in a study by Venkataramanan et al [22] reported physical injury during water fetching. Both temporary and longer-term/permanent injuries become even more likely where transport surfaces are uneven, hilly or loose and when there is any axial asymmetry in loading (i.e., carrying different loads on either side of the body) [22,23]. That is to say that unless carrying equal loads in identical containers in both hands, asymmetric loading is likely to result in gait asymmetries that may themselves cause acute as well as chronic injury. Geere et al [15] suggest that “frequent loading beyond capacity for adaptation or repair may lead to injury through fatigue failure, accumulation of fatigue damage”.

So based on current (if limited) studies, it is clear that fetching water from source to home entails both chronic and acute hazards, and that the size and configuration of water containers contributes to these hazards. As Zolnikov [24], page 624] notes “…water gathering transport times along with accompanying physical distress needs to be moved to the forefront of problems associated with poor access to quality water.”.

4. Hazards associated with storing water in commonly used containers

Whilst water fetching with commonly available containers clearly has many associated risks, so too does water storage in the home prior to use. For example research conducted by Opryszko et al [25] found that although 91% of water samples taken at a well-designed water supply kiosk met WHO water quality guidelines, by the time water reached the domestic point of use, only 40% of samples were still within guidelines. The same study also found that water without residual protection (e.g., chlorine dosing) became recontaminated with E. coli 60% of the time within 48 hours of collection (even if from a well-managed small water vendor rather than an unimproved or unmanaged source). Water storage seems to be a particularly risky phase in the water chain of custody with its own particular risk dynamics, many of which are linked to the containers themselves. Bain et al., [26, page 14] have suggested the need to “…better understand the role of water collection and storage on microbial contamination and the associated risk to health.” In this section of the paper we focus on storage risks that are a product of the configuration of the containers used.

Data from the Global Enteric Multicentre Study (GEMS) showed that the simple act of storing water overnight increased likelihood of faecal bacterial contamination and therefore incidence of mild or severe diarrhoea [27]. Even where water was sourced from well-managed public taps with chlorine dosing, storing water overnight resulted in a reduction of residual chlorine to near zero and increased incidence of *E. coli* bacteria above 10 CFU/ml to over 60% of samples. Similar results have been found elsewhere by Feleke et al. and Harris et al. [28,29]. Harris et al. noted, but did not quantify, the increased contamination risk associated with source intermittency (which may cause longer storage times or more frequent use of “bottom of the barrel” water). These and other studies make it clear that storing water brings a significant contamination risk in the absence of specific disinfection measures.

There are multiple recontamination pathways including those related to filling at source location, transfers between vessels of differential cleanliness and poor hand/implement hygiene [30]. There are also problems associated with the storage vessels themselves. Mellor et al. [31] found that persistent biofilm layers in collection containers could cause a significant increase (five to six times within 24 hours) in microbiological contamination of stored water. One of the authors (Staddon) has observed use of ill-fitting and inappropriate caps on water vessels such as pieces of wood, plantains, or rags. The general finding that water storage practices can exacerbate contamination related risks has been replicated and echoed in a variety of studies including [29,31–37], all of which suggest strongly that WaSH specialists need to pay more attention to water containers and the practices they enable.

Water dispensing/serving practices have been noted as another area of risk. Elala et al. [30] noted that many households in their Indian study group used dippers of various sorts (ladles or cups) or pouring/tipping to directly access water from storage, rather than taps. Indeed very few commonly used water storage containers have built-in taps which could reduce cross-contamination risk. In their study of rural Honduran households Trevett at al. [38] also observed that household water was often decanted from transport containers into larger containers from where it was subsequently served via dipping or pouring. Though lids were used on storage containers, the researchers observed proximity of animal faeces (particularly chickens and ducks) and general uncleanliness, suggesting risk of direct or aerosolised contamination pathways. In one of the few studies focussing on actual contamination pathways Harris et al. [29] found that the riskiest moments in water storage occurred when vessels were first filled and when they were subsequently emptied. Often poor container hygiene is the culprit, leading to a clear recommendation about public education around proper washing and disinfection of containers. In particular, users need to be sensitised to the fact that sluicing a mixture of water and sand around inside the container prior to refilling (a common practice) may actually introduce further contamination, despite its apparently abrasive action [39]. Also, it is likely that the repeated dipping of ladles or cups into the stored water introduces sufficient additional bacterial load to lead to higher risk of gastrointestinal illness. Copeland et al. [31, page 329] conclude that “[i]ndependent of the specific route for transmission, vulnerable storage methods limit the potential gains from a protected water supply.”.

Social perceptions also play a role here, with various studies [32] showing that packaged water from commercial sources is popularly assumed to be less risky even in the absence of clear evidence. In particular, sachet, bottled or “mineral” waters are often considered cleaner and safer than other sources, even tap, notwithstanding studies that have found significant coliform contamination in 87% of samples of packaged water [40]. This study also found that the source of the contamination was – ironically– the packaging itself. A similar study in Nigeria [41] found high contamination levels in commercially available sachet and bottled water including *Escherichia coli, Enterococcus faecalis and Pseudomonas aeruginosa*, all known causes of diarrhoeal illness. Water users often incorrectly perceived this water to be safer because it came in apparently trustworthy containers, sometimes with purity

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[1] Firewood/charcoal is the other domestic requirement most commonly carried on the head [20].

[2] Though Porter et al., (2013) documented loads of up to 70 kg.

claims on their labels.

Finally, it is important to comment on something often overlooked in considerations of water storage – the political economy of storage space availability. So far this exploration has focussed on the fetching journey from the source to the home, but has not yet understood the home space as a space of differential storage opportunities [9]. Householders who own their homes and the land they sit on usually have more options for storage– perhaps even including huge 5–6 kilolitre storage tanks used in groundwater and rainwater harvesting systems compared with renters, residents of informal settlements or refugees. They may also be better able to keep incompatible space uses such as kitchen/washing/water storage and animal raising separate. Building materials play a role too, with homes with dirt floors and thatch roofs more likely to cause recontamination of stored water. Put another way low-income households are more vulnerable to water shortages because they have fewer options to build resilience through safer storage. These differentiations are often clearest in times of acute crisis, as in 2014–15 in Sao Paolo, Brasil and in 2018 in Cape Town, South Africa [42,43]. In both cases "[u]neven experiences of scarcity were produced by the combination of existing inequities in the city's water infrastructure and the differentiated abilities of residents to store water" [42, page 26]. The consideration of challenges related to fetching and storing water is ineluctably entwined with other political economies: of housing, of transport, of livelihoods, etc. And the availability of different types of storage containers is an optic into these political economies; as Shryock and Smail [5] put it, water containers are "engines of history" with which human communities co-evolve.

5. Possible MAD solutions to identified risks

In previous sections we reviewed the range of harms that are related to water fetching and storage and noted that it is too often the case that the role of the containers used is under-examined. Container-related risks are a product of the material configuration of the vessels used, and some are related to the acts of filling, transporting, storing, and decanting water containers. Fetching-related harms are more likely to do with acute or chronic injury and with the opportunity costs attendant on time spent water fetching. Storage-related harms are usually linked to contamination especially with microbiological agents. All of these risks are also connected with other material domains, especially related to quality of the domestic space used for water storage. In this section we review solution pathways addressing both fetching and storage risks that follow MAD principles of modularity, adaptability, and decentralisation. While it is unlikely that identified risks can be designed out completely, there is good evidence to suggest that they can be significantly reduced.

Physical design of water containers seems an obvious place to start, so it is puzzling that relatively little attention has been given to this topic. The most ubiquitous water containers in the world, including the 10/20 L "jerry-can", and the 5/10 L "kholosh" were clearly not designed with manual water fetching in mind (Fig. 1). MAD design solutions would proceed from direct engagement with users with a view to optioneering sustainable, scalable design solutions that meet local needs at least cost – solutions that would in other words express the well-known principles of "appropriate technology" [44,45].

The humanitarian and development organisation Oxfam has designed a bucket that incorporates contamination avoidance features including a tight-fitting lid and a durable spigot (Fig. 2). While certainly an improvement, it does little to mitigate risks related to transporting water. In a more radical design solution Martinsen and colleagues co-developed a plastic backpack design (the so-called "pack H_2O" – Fig. 3) with Haitian community partners [45]. This more ergonomic backpack design alternative offers significant mechanical advantages over conventional jerrycans or buckets that must be head or arm carried. Originating as a CSR project for a US-based plastics company in 2012, the pack H_2O design has now been taken up by a few development NGOs including Partners for Care and Habitat for Humanity [46,47]. A longitudinal study of user experience in Kenya showed that the pack design was greatly preferred by users who reported fewer injuries in use [48]. Design improvements such as better padding of carrying straps and smaller volumes (10 L was preferred over 20 L) were identified by users in all studies as likely to increase use.

Another innovation in container design is the "drum roller", where a sturdy plastic drum is designed to be rolled from water source to point of use, eliminating the need to directly bear weight. The best known of these devices is the South African "Hippo Roller", originally developed in the early 1990s and capable of holding up to 90 L [44]. Traction for the Hippo Rollers is still usually provided by women and children, who can push or pull the roller as per preference, but the work of moving it is more easily shared. Whilst more than 65,000 of these devices have been distributed in more than four dozen countries, they are considered expensive (up to US$90 per unit) and so have largely depended on humanitarian gifting as the primary mode of distribution. There is no published research reporting on the relative ease of use, injury or

Fig. 2. Oxfam Water Bucket Source: Oxfam.

Fig. 3. Backpack and a woman carrying backpack as an alternative water transport method in Kisumu in Kenya, 2015. Source: Kim et al. (2020).

contaminant risk associated with use of this device.

An alternative innovation that follows MAD principles involves changing the way the water fetching journey is made. If carrying significant volumes of water is unavoidable, it is sensible to design a wheeled conveyance to make water transport easier. There is some literature that suggests that simple innovations such as wheeled trailers, pulled by people, animals, bicycles or motorcycles, can contribute to a reduction of fetching/carrying burdens on people lacking alternatives [49–51]. Local innovators have retrofitted both human-powered (bicycles) and hydrocarbon-powered (motorcycles) vehicles for water transport. A study to Oyesiku et al. [51] showed that bicycle trailers (Fig. 4) could be useful in facilitating goods transport (including water) though much depended on local road quality and traffic conditions. Moreover, ergonomics, socio-cultural factors and finance however have tended to favour male users, meaning that benefits to the mostly female water fetching workforce have to date been limited.

Other solutions involve decreasing the distance required for water fetching through proliferation of alternative safe water supply sources. Conventional "improved" water sources such as boreholes or standpipes are capital intensive and usually beyond the capabilities of communities and households acting alone, but there are a few more decentralised technologies that may be appropriate. In particular, rainwater harvesting (RWH) is in fact a "traditional" technique that has been rediscovered as a strategy for drastically decreasing the distance to water source by harnessing the potential of domestic roofs (dwellings and outbuildings) to act as water collectors for adjacent storage tanks [52] (Fig. 5). The concept has been used for millennia and is in fact considered a "traditional" method of water management in many parts of the world.

As noted above, current designs of common water storage containers do not seem ideal, either from water fetching or from recontamination prevention perspectives. Some common designs, like the "jerry can" were originally designed for other purposes (petrol storage and transport), but latterly adopted for carrying and storing water. Yet, jerry cans commonly have lots of nooks and crannies that are difficult to clean thoroughly. They also suffer from the high likelihood of lid loss (making contaminant ingress more difficult to prevent and internal scratching (providing more sites for biofilm accumulation). Might it be possible to design a better jerry can? One of the few research groups to look

Fig. 4. One bicycle tailer design optimised for local bicycles in Nigeria Source: Oyesku et al. (2020).

Fig. 5. Schematic indicating basic configuration of domestic rainwater harvesting systems in Uganda. Source: Staddon et al. (2018).

specifically at this challenge was led by Brian Reed at Loughborough University in the UK. In a review of relevant design criteria Reed et al. [53] note that optimal water container design needs to be manufactured from local materials, robust and durable, time efficient and affordable, and be manageable by lots of different sorts of users (including young, elderly or disabled people). More recent work by Mounir et al. [54] has extended the earlier work of Reed et al through a consideration of the potential role of willingness to pay for a better water container to result in better health and livelihood outcomes. The "Oxfam bucket" (Fig. 2) is one design that manifests all the above principles except local manufacture and therefore offers a starting point on which to build further.

6. Challenges and Opportunities: Water containers and evolving MAD water systems

Water containers are a vital part of household water infrastructure in many locations globally, and will continue to be so as MAD water systems evolve. But as the most mundane of objects, they are often overlooked as a design-use problem in need of a solution. We have, above, identified some of the clear design challenges and potential proposed solutions, many already trialled in different locations. But we also note that whether these can be seen as truly "MAD" depends ultimately on the extent to which they are linked to processes of decentralised community-led development and management. Transport and storage infrastructures that are decentralised and therefore *co-produced* by beneficiary communities would maximise design, fabrication, and life cycle benefits achievable through localization [53]. More to the point of both this paper and this collection, we argue that adaptability of modular container solutions best emerges from decentralised design, manufacture and use.

Finally, returning to our opening points about containers, we note that deploying some combination of local innovations in water containment, porterage, etc. as "solutions" also demands a careful eye to larger socio-technical systems of exploitation [7]. For example, in locations where water abundance and scarcity may co-exist in close proximity, Water Hippos and Pack H_2Os are at best partial mitigations only. At worst they may form part of a discourse and a network of practices that reinforces marginalisation while simultaneously convincing us that everyday infrastructure such as water containers are politically neutral [7]. What if our analysis starts from a different place: from the view that water insecurities can be exacerbated by the teleology of networked water infrastructure, including containers?

Common water containers such as the jerry can are the epitome of networked heterogeneity, so ubiquitous in much of the water-insecure world that they can even sometimes serve as a unit of exchange. But as we have seen, jerry cans impose differential burdens on households, depending on households' existing capabilities with respect to actually using them for sourcing, filling, transporting, and storing water for use. Above we have seen that the number and types of storage vessels, access to labour for water fetching, access to mechanised transport and space within the household for accumulation of storage vessels are all implicated in a political economy of hydro-precarity that needs to be challenged. The ontology of the jerry can (as an archetypical water container) needs to be reconceptualised away from one of failure and lack and towards one of water security through bricolage and networked heterogeneity.

The power of objects such as water containers to both enable and constrain interactions needs to be more fully appreciated, especially if the scholarly goal is to strengthen capabilities supportive of water security. More to the point, continual reliance on an evolution towards centralised piped water systems may actually make many communities around the world more rather than less vulnerable. Local, decentralised systems should not be seen as "undermin[ing] and divert[ing] resources away from the collectively devised industrial form of piped water provision" [11, page 252]. Water containers can be "engines" of a better future if we are able to adequately attend to MAD water principles.

CRediT authorship contribution statement

Alexandra Brewis: Conceptualization, Writing – review & editing. **Chad Staddon:** Conceptualization, Formal analysis, Writing – original draft.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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