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Convenience over control: qualitative insights from water system users in a rural setting in Gujarat, India

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Abstract

Piped water systems have become an increasing focus of global and national development goals. India is providing piped-to-premise water supplies to more than two million rural inhabitants every week. But rural piped water systems often operate intermittently and may not always provide water that is available when needed. This paper presents insights from a qualitative study that draws on 30 interviews and 11 focus group discussions investigating the extent to which piped-to-premise interventions have improved access to water supply in 6 rural hamlets in eastern Gujarat, India. Households with access to piped water revealed that the rigidity of the intermittent piped water schedules limited water availability, necessitating their use of additional water sources. Households that relied on handpumps or private wells described greater agency in how and when they collect water. Throughout the year, but particularly in monsoon season, participants reported that grid-powered and solar-powered piped water systems underperformed due to electricity blackouts (lasting as long as seven days) and cloudy weather, respectively. To mitigate the drawbacks of intermittently operated piped water systems, and to decrease the necessity for potentially harmful coping strategies, this study suggests that piped water system designs should enable operational flexibility, tailored to community needs, so that water is available when needed. To increase the resilience and reliability of rural piped systems, we recommend that systems design incorporate more storage and rely on robust and resilient energy sources.

1. Introduction

Piped water systems with household taps have become an increased focus of development policies (Fan *et al* 2014, Martínez-Santos 2017, Government of India 2019, WHO/Unicef JMP 2023). Ideal piped water systems are expected to provide water that is 'from an improved source that is accessible on-premises, available when needed, and free from fecal and priority chemical contamination' (WHO/Unicef JMP 2023). Meeting these conditions complies with the Sustainable Development Goal 6.1 (SDG) definition of safely managed drinking water services (WHO/Unicef JMP 2021). In addition to these conditions, an ideal piped water system also provides adequate quantities of water (Ghorpade *et al* 2021, Winter *et al* 2021a). But in many contexts, there is insufficient source water to provide adequate quantities of water; such source water scarcity can prevent piped water systems from operating continuously (Fan *et al* 2014, Taylor *et al* 2019).

Across the Global South, approximately 1 billion people rely on water supply systems that are run intermittently (Bivins *et al* 2017), and in many countries in the Global South, intermittent supply is the predominant form of water system operation (Ghorpade *et al* 2021). Contrary to the intent of SDG 6.1, intermittent water supply (IWS) restricts access to water (Huberts *et al* 2023). Numerous studies to-date have focused on the technical consequences of IWS including degradation of the pipe network, low or negative water pressures, contaminant intrusion, unreliable water supply, and inequitable water distribution (Klingel 2012, Kumpel and Nelson 2014, 2016, Ghorpade *et al* 2021, Meyer *et al* 2023). However, most studies to-date have focused on urban IWS and not rural IWS (Cook *et al* 2016), even though rural households are most in need of increased access to water supply infrastructure (Chaudhuri and Roy 2017).

Existing research on rural piped water systems in low- and middle-income countries has reported multiple issues with rural piped water supplies, including frequent system breakdowns (Kelly *et al* 2018), seasonal and climate-induced variations in source supply that reduce water availability and force users to find alternative (often unsafe) water supplies (Udmale *et al* 2016, Seifert-Dähnn *et al* 2017, Kelly *et al* 2018), and intermittent operations (Fan *et al* 2014, Cronk and Bartram 2018, WHO/Unicef JMP 2023). In rural Maharashtra, many piped water supplies fail (including those reliant on groundwater) due to drought, which greatly dimishes residents' access to water (Udmale *et al* 2016). Source sustainability, or the lack thereof, affects the reliability of water access for piped water users: slip back (reduction of piped water coverage) due to decreased groundwater supply has been estimated to be as high as 10% across India (Chaudhuri *et al* 2020) and as high as 32% to 50% in Maharashtra (Kabir *et al* 2022). Drought and other climate-change induced phenomenon may further impact vulnerable rural piped water supplies. Such challenges are not limited to India; a study exploring 5500 water supply systems across Latin America and the Caribbean found the prevalence of intermittently operated systems varied from 18% to 88% by country (Cronk and Bartram 2018). Within these intermittent systems, supply hours ranged from 6 to 22 h d^{-1}. As piped water supply becomes the gold standard for rural water supply, more research into the sustainability, intermittency and functionality of these systems is needed.

In 2022, approximately 2.2 billion people still lacked access to safely managed water services, and rural areas continue to lag behind urban areas (WHO/Unicef JMP 2023). Rural water policies are increasingly focused on implementing piped water supplies globally: the rural population that gained access to piped supplies was more than double the population that gained access to non-piped water supplies since 2000 (WHO/Unicef JMP 2023). In South and Central Asia the gap between rural and urban access to water from an improved source on premises has recently closed (WHO/Unicef JMP 2023), which is likely the result of an extremely ambitious rural water policy in India. India's Jal Jeevan Mission (JJM) began in 2019 and aimed to provide every rural household with a 'functional household tap connection' by 2024 (Government of India 2019).

Progress towards goals like that of JJM or SDG 6.1 is typically measured using quantitative indicators for household water access. But large data gaps in national statistics continue. The reports from JJM focus on administrative accounts of activities completed. Data published by the Ministry of Jal Shakti suggests these systems operate for an average of 3 h d^{-1} and that within communities listed as having 100% functional taps, <70% of households have functional tap connections (Ministry of Jal Shakti 2022). Joint Monitoring Programme (JMP) data coverage on progress towards SDG 6.1 is improving, yet it still covers only half of the global population (WHO/Unicef JMP 2023). The JMP also warns that their monitoring of drinking water service is based on a survey representing a single point in time, possibly obscuring how water accessibility and availability vary throughout the year. Such surveys also obscure the typical variations experienced in water service in IWS, where supply varies within days or weeks.

Critical gaps exist in the current quantitative measures of variations in water availability and access. A more detailed understanding of availability and access may help engineers and policy makers strategize solutions to improve water availability and/or access (Nganyanyuka *et al* 2014). Qualitative data provides us with a more comprehensive picture of the lived experiences of rural piped water users and may help us uncover gaps in water supply coverage and service not captured by current quantitative data indicators. Our paper aims to provide exactly this type of qualitative data—aiming to describe the lived experiences of rural water users in India including challenges (or lack thereof) of water availability and access so that they may be further examined in future studies.

In this study, we contrast user reports about the non-functionality, unreliability, intermittency, and inequality issues associated with their rural piped water systems defined as safely managed in tracking SDG 6.1. In addition, we examine the differences in water supply experiences between piped and non-piped water users. Furthermore, we analyze the themes of water access that emerged from qualitative data and present findings that suggest piped water systems do not inherently lead to increased access to water. Lastly, we underscore how understanding user experiences can help water system planners and designers to mitigate the shortcomings of rural IWS and better design water systems to meet the needs of users.

2. Methods

2.1. Study design and setting

The study was conducted in Dahod district, located in eastern Gujarat near the border with Rajasthan and Madhya Pradesh. This area experiences a monsoon season (typically between June and September), a cool–dry season (between October and February), and a hot and dry season (between March and June). An initial list of possible hamlets was created using data on primary water sources collected by a local partner. Hamlet site visits were conducted and included a water system tour to enable the researchers to become familiar with the community and verify the status of the water system. Following the hamlet visits, six hamlets were selected for inclusion in this study. Inclusion criteria prioritized communities which differed in the primary improved water sources that residents rely on. Secondary selection factors included selecting hamlets that contained similar numbers of households. The number of households in each hamlet ranged from twenty-six to thirty-six. Within the communities, all residents are Scheduled Tribe. Although Scheduled Tribe is a minority across India, according to the 2011 Indian Census, Scheduled Tribe constitutes 74.3% of the population in this district area ('Dahod District Population Religion—Gujarat, Dahod Literacy, Sex Ratio—Census India' 2025). Of the six hamlets included in the study, two had functioning piped water systems, two had non-functioning piped water systems, and two had no piped water systems. In hamlets without functioning piped water systems (i.e. no systems or non-functioning systems), residents mostly relied on community handpumps, private borewells, or private open wells.

2.2. Data collection

Water system surveys were conducted with community members, facilitated by a local community development organization. Surveys included inspections of the water sources, community water tanks, piped taps, private borewells, and shared nonpoint sources such as handpumps and open wells. Following the surveys, semi-structured interviews and focus group discussions (FGDs) were conducted with participants in each community. These interviews and discussion groups took place during a three-week field visit in September 2022 and aimed to capture participants' experiences, feelings, and interactions with rural water infrastructure. A limitation of this study is that it was conducted during the rainy season when (in Gujarat) water availability is highest (i.e. water is least scarce).

Interviews and FGDs included questions regarding participants' background and family size; available sources of water; feelings around water collection; impact of seasonal weather patterns on water collection and other daily activities; and feelings/reflections about how access to water, sanitation, and food has changed over the long-term in the hamlet (complete question list is included in the Supplemental Materials). Inclusion criteria required participants to be at least 18 years of age and to identify as the head of household (or next available). Households were selected based on snowball sampling methods. Within each hamlet, the research team aimed to interview four to six Households (constituting 11% to 23% of households in each hamlet) and conduct two FGDs (one with men and one with women). The ideal FGD size was three to ten participants and only included households that were not included in the interviews. The aim was to gain insight into the varied experiences of households within each hamlet, but due to the limited time in the field, this approach may not have resulted in reaching saturation. In total, thirty interviews were conducted, of which, twenty-nine were conducted in the six hamlets with women only, who self-identified as the primary water managers of their households. The remaining interview was conducted with a (man) local water supply professional. A total of eleven FGDs with men and women were conducted in the six hamlets. Each group was gender separated and the number of participants in each discussion ranged from two to ten. The interview and FGDs were led by the researchers who asked questions in English which were then translated into Gujarati (the local preferred language) by a hired research assistant. The responses were captured on audio recordings. During interviews and FGDs, real-time translation between English and Gujarati occurred, which allowed the researchers to be flexible when asking appropriate follow-up questions.

2.3. Data methods and analysis

The recordings of the interviews and FGDs were transcribed in English (completed in May 2023) by Parikh Info Solutions, a company based in Mumbai, India. All identifying information was removed from transcripts. English transcriptions were uploaded to Dedoose software (SocioCultural Research Consultants, LLC 2023, an online qualitative and mixed methods data analysis software) for data management and analysis.

Interview and FGD data were analyzed iteratively following the thematic qualitative data analysis methods outlined by Lester *et al* (2020). Field notes and transcripts first underwent an unstructured review to create an initial codebook. A two-stage coding process refined the initial codebook, with the updated codes used in a second coding stage. The final codes and excerpts were then organized into categories and themes.

3. Results

Participant interviews and FGDs provided insights into lived water experiences of community members and showed that acquiring a piped water tap did not necessarily increase access to water. Specifically, reviewing the infrastructure surveys and qualitative data uncovered five major findings and themes: (1) long-term improvements in water access: new water sources and source type have made getting water easier and faster; (2) pipes reduce agency: users have more agency over the volume and timing of water withdrawals from handpumps and borewells than from intermittent piped systems; (3) power supply disruptions: unreliable grid and solar power resulted in unreliable piped water; (4) supply is irregular, infrequent, and short : intermittent pipe systems bring water closer and need less physical labor, but are prone to irregular, infrequent, and short supply; and (5) households prefer pipes: households prefer the ease of piped systems over other source types. Before elaborating on these findings and themes, we begin with a description of the water infrastructure in these communities.

3.1. Overview of water infrastructure in six hamlets

Although four of the six hamlets had piped water infrastructure, only two of the four piped water systems were functioning. Observations and inspections of the two functioning piped water supplies, which pre-date JJM, showed that each piped water system relied on a community borewell. In one of these hamlets, the well pump was powered by the electrical grid, whereas in the other hamlet, the pump was solar-powered. In both communities, the well pumps discharged water into approximately 20000-liter community storage tanks located at a relatively high elevation within the hamlets. Typically, once per day in each hamlet, an operator would open a valve on the tank outlet piping to supply water to household taps. Typical valve operation varied between the two hamlets. In one hamlet, the operator opened the valve at approximately the same time every morning. In the other hamlet, there was no consistent valve operation time: it changed based on the personal schedule of the valve operator. However, in both hamlets, the valves were left open until the tank was drained. Reportedly, tank filling usually occurred in the morning or just prior to opening the tank valve.

Within the two hamlets that had non-functioning piped water systems, the cause of disfunction was broken pipelines. The community borewells and storage tanks were still functional. Between these two hamlets, one hamlet had a solar powered well pump that discharged into a 20 000-liter storage tank and the other hamlet had an electrical-grid-powered well pump that discharged into a 10 000-liter elevated storage tank. In both hamlets the tap located immediately downstream of the tank was functioning. The pipelines and taps further downstream were non-functioning, and the cause was attributed to JJM infrastructure construction damaging current water infrastructure. As described by one woman, 'earlier the water came from the tank… [but] when the new [JJM] taps were going to be installed, they broke [the main pipeline] …It has been a year [without tap water]'. In an FGD, participants expressed frustration that they did not possess the power to prevent the broken pipes: 'the contractor who comes for digging, he does not know… [we informed] them that there are pipes here so dig somewhere else. [But] he does not listen to us. This is the way it happens'. At the time of the study, the community members were unaware of the timeline to repair the broken pipelines, despite promises from the contractors to repair the broken pipes. Participants that no longer had functioning taps then relied on community handpumps or privately owned borewells.

The remaining two hamlets never had piped water supplies, relying instead on other water sources. In one hamlet, approximately eleven households owned their own private borewells and shared access with neighbors. In the other hamlet, households shared community handpumps and privately owned open wells.

3.2. Long-term improvements in water access

Participants across all six hamlets, regardless of their current primary water source, expressed feelings that the overall water supply situation improved over the past several decades. Fetching water at the time of the study took less time and effort than several years prior. In each hamlet, participants described experiences of previously relying on unimproved water supplies such as rivers and ponds or the need to travel much farther distances to collect water. Traveling long distances to collect water was reported to both increase the time required to collect water and reduce how much water women could collect, with subsequent consequences on hygiene practices. One woman described, 'we used to go 2 kilometers away to fetch water…carrying vessel on our heads…. [and] still, we did not get enough water to bathe'. Another woman shared, 'earlier we used to spend a whole day [collecting water], now it is not like that…now it will take around half an hour'.

3.3. Pipes reduce agency

Despite the universal feelings that water collection had improved, experiences of agency (i.e. feelings of control over one's actions (Gallagher 2000) over water collection depended on source type. Handpump and private borewell users, specifically, felt agency and flexibility over water collection. For example, one woman described collecting water 'whenever we get time… morning, noon, or evening'. In a community that no longer had a functioning piped water system, handpump users in an FGD described the positive outcomes of not being constrained by the schedule of piped water supply: 'If we are free and there is no water then we go to fetch water… we fetch anytime from a handpump. And for tap, we used to fill on its time'. The timing of water collection was decided by the borehole and handpumps users based on their individual circumstances.

Intermittent piped supplies, in contrast, delivered water at a specific time, constraining household water collection activities and flexibility. For example, one woman reliant on a piped system described the absence of agency, 'water will come once [the operator] start on their time. Water will come when they start'. Another woman similarly noted the inconveniences of relying on piped water supply: 'while cooking, and making roti, if someone says that the tap water has come, we leave everything and fetch it first'. The strict tap water schedules required household planning and adapting around water collection. For example, one woman described, 'There is always one person at home to collect water'.

Tap water was not always supplied in inadequate quantities, which forced users to rely on alternative and multiple sources. For example, a woman who relied on multiple water sources shared, 'we do not get a chance to fill the water from the tap in the morning. We need to fetch water from a handpump in the morning'. And another woman described, '[we collect water] from the river in the morning and in the evening, we get water from tank [tap]'. Adjustments to the tap water schedule were not made based on individual household needs. One participant explained, '[the operator] starts [the water supply] only once. No one starts it again [if we ask] …if there is no water then we need to go to the handpump'. This was even true in the summer season, which was often identified as a time period when more water was needed. The piped water operation did not shift based on households' needs; it remained rigid at one supply period per day.

Participants reliant on piped systems emphasized how they had to manage their lives around the tap water schedule. The rigidity of piped water schedules meant women frequently relied on secondary sources that could be accessed at any time of day to meet their daily demand patterns.

3.4. Power supply disruptions

Frequent power interruptions diminished the availability of piped water supply and often disrupted the IWS schedule. In one community the piped water supply relied on the electrical grid to power the well pump and grid outages were reported to last for several days to weeks in monsoon season. In the other two seasons, grid outages were reported as occurring weekly (e.g. every Tuesday). Weekly power outages were due to load-shedding (rolling blackouts), as described in one interview, 'yes, sometimes it gets cut off and comes back again. On Tuesday, it gets cut off in the morning and comes back at 3–4 PM'. In addition to regular power outages, unplanned outages were also a common problem and can result in poor water supply reliability. Residents shared experiences such as, '[the] electricity went off during the heavy rain…We did not get water for 3 days'.

Participants in the other community with a piped water supply system reported that they opted to install solar panels to power the well pump to increase the reliability of their water system, avoiding the frequent and sometimes long-term power grid outages. The solar powered pump was reported to provide a more consistent water supply compared to previously when the pump had been connected to the grid; however, solar panels are not a panacea for robust electrical supply. Users reported that periods of cloudy weather result in limited energy output for the well pump to run on. One woman described limited operation during monsoon season, 'if it is a sunny day, we get water for longer hours and if it is a cloudy day, we get water for lesser hours'. Another woman described, 'sometimes we get water, sometimes we did not. When there is a lot of rain, and no sunshine, the [pump] could not start, so, we do not get water'.

To cope with inconsistent solar power supply, one participant described relying on the private borewell located at their farm when the solar-powered pump was underperforming. To mitigate other water supply interruptions, piped water users typically tried to store enough water to last until the next supply period. However, household storage was not always sufficient to outlast the supply interruption, so participants had to sacrifice some water uses, like washing clothes, or find alternative water sources, as discussed in this group discussion:

> '[when the tap water is] not enough then we need to go to fetch water. If there is no electricity, then the tap doesn't work so we have to go to the handpump. We need to go to the handpump anyhow [at other times too]. If we have less water, then we have to go. Yes, if there is less water and there is no electricity, then for animals we fetch from well…Even if it takes 1 or 2 hours we go and feed them.'

Unfortunately, communities with piped water supplies did not always maintain their alternate sources of high-quality water like handpumps. During piped supply interruptions, therefore, some participants had to rely on unimproved water sources: '[when the solar pump] stops working. We fetch water from around. We cannot live without drinking [water]. We [collect water] by digging a hole [by] the river'.

3.5. Supply is irregular, infrequent, and short

Piped water supply has the potential to reduce the time and labor women spend collecting water, unlocking important long-term health benefits (Winter *et al* 2021b, Sultana *et al* 2022). However, the potential time and health benefits can be compromised if the piped water supply operates intermittently. Neither of the functioning piped water systems studied operated continuously; instead, the piped systems operated intermittently. Between the two communities, users' lived experiences with IWS varied due to differences in supply regularity (water supply arrives within a predictable timeframe); frequency (number of supply periods per week); and duration (length of supply time) (Galaitsi *et al* 2016).

In one community, piped water users reported that water was regularly supplied at the same time every morning, whereas the other community reported that water supply varied from each day, dependent upon the water operator's schedule. One woman who received irregular water supply described, 'sometimes it comes early in the morning at 6 AM. Sometimes it comes late…If the tank is already filled up, they supply water early in the morning.…No fixed time'. Irregularly supplied users primarily relied on word-of-mouth reports about when the water would be turned on. If someone was not at home when the water was turned on, the participant would miss the water supply for the day. Another woman described, 'the person who starts the water comes to tell us that the water has started…it is off but when water is about to come, it makes noises. But [if] we are not present at that time, then [we] miss the water'.

The potential to miss water supply was worsened by the relatively short duration of water supply. Most water users in both piped water systems reported that water was typically available for 30 minutes a day. One participant with short supply described, 'water used to come for 10–15 minutes only … We did not get enough water for drinking and bath'. To mitigate their limitingly short supply duration, the household moved their tap location (including the connection to the water main) and reportedly increased their supply duration to 20–25 minutes.

Frequency of supply was also reported to be only once per day in both piped water systems, even if, as described earlier, participants felt they needed more water that day. Due to this limited supply frequency and the short duration of water supply, users collect as much water as they can, as indicated in a discussion between FGD participants: 'what if we run out of water? So, we fill all the vessels we have (woman 1)', and 'we need to fill all vessels (woman 2)'.

Handpump and private borewell users described their water access as regular and flexible—in stark contrast to piped water users. Handpump and borewell users described accessing water at flexible times and with flexible frequencies throughout the day. One handpump user described, 'we go [collect water] 2–3 times a day…. whenever we need water, we go to fetch it,' and one borewell user described 'if we require more [water], we ask them to switch on the borewell and we fetch again'. Borewell users described reliably collecting water multiple times a day in order to collect as much water as needed. For example, one borewell user shared that she frequently collected water twice per day: 'two times…In the morning and in the evening…It does not take much time now…we use motor and pipe to fetch…Water is available [now]'.

Borewells were typically owned by one family and shared this source with others. Borewell owners had this supply on their premises, and they had priority in collecting water, while others may have to travel and queue to collect water. This can result in the water collector needing to wait for water, for the homeowner to be present, or in a queue between those who use the borewell. For example, 'if [the owner] goes to the farm and there is no one at home, who will [start] the water? …we have to come back to fill the water'. Borewell users were also dependent on reliable electricity, so these participants experienced the same power supply disruptions as piped water users, which can again result in reliance on non-electrical water supplies like handpumps and unimproved sources. A borewell user shares that if there is no electricity, 'we go to the handpump when we are in need'. Borewell owners occasionally experienced motor breakdowns, and as a result often turned to neighbors for water. Although if fetching water from a neighbor, some participants shared being restricted to 'collect less quantity … for drinking only'.

Queues to collect water were experienced by both borewell users and handpump users. The queues were often negotiated between community members as described in one interview with a handpump user: 'In the line, they say that my number is first, second…when I go [I ask to go first, because] I [say] I have to take a bath'.

The amount of time spent collecting water (including queues) was similar between the piped water users (approx. 30 min) and the handpump and private borewell users. Handpump users commonly reported spending only 10–30 minutes collecting water with rare reports of queuing up to three hours. Borewell users also reported generally spending 10–30 minutes once or twice a day collecting water. Although one borewell user described that water collection took additional time (up to 60 minutes) due to the need to clean water collection vessels.

3.6. Households prefer pipes

Throughout all six hamlets, most residents strongly preferred tap water as their primary water source. Descriptions of these preferences focused on how much easier it was to collect water from a yard tap than from community handpumps or a neighbor's private borewell. In an FGD, one woman described her preference for tap water: '[with tap water] we neither have to go far, nor have to carry weight, but right now [without tap water] we have to do it, what to do? If tap will come, then it will be great'. In each hamlet, all participants were asked to share their preferred method of water supply, and all participants currently relying on handpumps or taps said tap water was their preferred source. Amongst participants that relied on private borewells as their primary water source, many preferred continuing to use their borewell and did not want to install a water tap. The ease of collecting borewell water was described by one woman, 'what difficulties in fetching water? I start the borewell and collect water'.

4. Discussion

If water is available when it is needed, it reduces the burden of water collection that falls primarily on women and girls. Hence 'available when needed' is one of the three pillars of safely managed water in SDG 6.1. To align water availability with when water is needed, women and girls need to be given agency and power in water management decisions—especially when water is intermittently available. Yet, despite their central role in water collection, women are often left out of water management decisions (Adams *et al* 2018). For women and girls to realize the benefits of piped water, physical access alone is not enough. Rather, as Ribot and Peluso (2003) argue, access to water should be defined by women's ability to benefit from the water, and women need to be granted agency in controlling this resource (Adams *et al* 2018).

The rigidity of intermittently operated piped water systems limits users' ability to exercise agency in managing their household water supply. Other researchers have shown that convenient access to water is important for realizing education and career options for women and girls mainly due to time savings that result from not having to travel far for water and being able to collect water at convenient times that fit into work and school schedules (Jansz and Wilbur 2013, Santiago Ortiz-Correa *et al* 2016, Ahiabli *et al* 2023). In our study, all participants had access to water but only the participants reliant on non-piped systems could choose when and how often they collected water. In contrast, users of intermittent piped systems described having to collect water at either a set time daily (e.g. 11:30 AM) or whenever the operator chose, which varied. Pre-determined schedules likely provide advantages over irregular supply schedules as households are better able to plan around water supply periods. However, we suggest that strict supply times likely restrict women's ability to leave the house during the day or, as noted in previous research, water availability times can force women to leave work early (Chen *et al* 2019). Thus, contrary to the typical discourse, moving from non-piped to piped systems can result in a reduction of women's agency in household water management due to the limitations of piped water system operation.

Further complicating the proposed benefits of piped systems, the convenience (particularly in terms of availability) of piped water is dependent on a constant, reliable power source. Electricity interruptions cascaded into frequent and unplanned water supply disruptions in the study communities, as also reported in other studies (Galaitsi *et al* 2016), including one conducted within Gujarat (Das 2009). Water supply disruptions due to electricity interruptions are often outside the control of water utilities or operators (Totsuka *et al* 2004), though they can be mitigated with generators, storage, or by relying on a different power source. To increase system reliability, one study community opted not to connect to the electrical grid and instead installed solar panels. However, in contrast to recommendations in the literature (Chandel *et al* 2015, GIZ 2020, Jovanović *et al* 2023, Keskar *et al* 2023), solar powered piped systems are not a panacea. Water supply interruptions persisted due to insufficient solar power. Solar panels for community water systems have not always been designed to meet the typical water demand patterns of water users, which results in inconvenienced and unsatisfied water users (Ingram and Memon 2020). Piped systems are more complicated, and therefore failure prone, than handpumps, and piped systems usually rely on external power availability, challenging the prevailing notion that movement from non-piped to piped systems is universally beneficial.

To mitigate some of the challenges presented by piped systems, elevated storage tanks in piped water systems can greatly increase system reliability. Many solar powered systems rely on in-tank storage to compensate for cloudy days and to supply water at peak times (Hamidat and Benyoucef 2009, Bouzidi 2013, Chandel *et al* 2015, Water Mission 2021). In the study communities, IWS were typically operated by first filling the tank and then opening a valve to let water flow to user taps until the tank is empty. But under this operation mode, the tank is drained each day, reducing its ability to compensate for day-to-day variations in solar irradiance. Hence the solar-powered piped water supply was still frequently interrupted due to daily and seasonal variations in solar irradiance, leaving users unable to get water for several days in some cases. Similar findings were reported in Kenya, where solar-powered water kiosks sometimes had to be shut down for an entire rainy season (Kelly *et al* 2018). Research is needed to inform the design and operation of solar powered piped systems when intermittent water system operation is expected.

Contrary to the typically described benefits of piped water supply, the piped water systems examined in this study did not provide water that was available when needed—a key aspect of safely managed water. Our findings generally concur with those of similar studies on urban and rural piped water systems: the systems operate intermittently, the intermittent water is unreliable and not always available when needed, and households are forced to create a patchwork of strategies to collect enough water to adequately meet their water needs (Kleemeier 2000, Spencer 2008, Brown *et al* 2013, Fan *et al* 2014, Seifert-Dähnn *et al* 2017, Beard and Mitlin 2021, Lebek *et al* 2021, Ngben and Yakubu 2023). In our study, frequent interruptions of the water supply were attributed to unreliable electrical and solar power. The unreliability of these piped systems negates many of the hoped-for benefits, consequently resulting in systems that did not increase water safety nor decrease time burdens for women and girls.

In comparison to IWS systems globally, the community members in our study sites relied on piped water systems that were highly intermittent (<1 hr./day), which is far more intermittent than most IWS systems reported in the literature and less than the JJM average (3 hr./day) (Fan *et al* 2014, Erickson *et al* 2017, Ministry of Jal Shakti 2022, Meyer *et al* 2023, Ngben and Yakubu 2023). Although these communities rely on water supplies that are highly intermittent, a local water professional described 'they have made it a habit not living with enough water'. Issues with the electrical power supply meant that households could go days or weeks without piped water supply. Similar to the findings in the WHO/Unicef JMP (2023) report, households in this study identified that the non-piped improved water sources were more reliable than the intermittent piped water systems. To cope with the short duration and unreliable IWS, households found secondary sources and increased their stored volumes; these coping strategies have been reported in other rural and urban IWS (Majuru *et al* 2016, Smiley 2017, Price *et al* 2019). The lived experiences of households reliant on intermittent water systems highlight how water supplies that are reliable and available when needed can prevent the use of unsafe secondary water supplies, saving time and reducing health risks for both women and their households.

One of the main purported benefits of on-plot water supplies (accessible on premises) is a reduction in both travel distance and time spent fetching water, which are important for women's health and gender equality (Sorenson *et al* 2011, Truelove 2011, Adams *et al* 2018, Chen *et al* 2019), but IWS subvert these benefits. In this study, all participants (accessing water from all system types) reported similar collection times. This similarity may stem from the small sizes of these communities and/or the convenience of non-piped systems in these communities (e.g. the absence of queuing). In other contexts, particularly in Sub-Saharan Africa, queueing times can be inconveniently long in communities that share piped water sources (Thompson 2001, Sorenson *et al* 2011, Zuin *et al* 2011, Devoto *et al* 2012, Chen *et al* 2019, Choudhuri and Desai 2021, Ahiabli *et al* 2023). In contrast to those findings from sub-Saharan Africa, we found that tap water does not always save households time in water collection.

Intermittent operation of rural water supply often results from scarcity (Totsuka *et al* 2004): scarcity of water, scarcity of infrastructure capacity, scarcity of workforce, and scarcity of technical expertise. The communities in this study all relied on groundwater supply, which is typical across rural Indian water schemes. The rapid depletion of groundwater supplies due to water supply and irrigation has been reported with increasing concern (Panda 2011, Biswas-Tortajada 2014, Udmale *et al* 2016, Khatri *et al* 2017, Singh *et al* 2020, Kabir *et al* 2022). Yet groundwater availability is not always taken into consideration when implementing water supply projects (Chaudhuri *et al* 2020), which can lead to poor siting of borewells, including in shallow aquifers or other hard rock areas with naturally poor groundwater storage potential (Kabir *et al* 2022). Poor siting of wells can lead to wells that go dry in summer season (Kabir 2016, Kabir *et al* 2022), which can affect piped systems as well as handpumps and private borewells (Udmale *et al* 2016). As discussed previously, additional research on the balance of pump capacity and water tank storage capacity needs to be conducted so that water system designs consider (1) the sustainable pumping of groundwater aquifers (to avoid groundwater depletion, excessive well drawdown, and burnout of the pump); and (2) balancing pump operation with storage tank capacity such that storage tanks provide sufficient water availability that can span relatively short interruptions in supply as needed. In addition, management of water systems by water committee has been described as varying seasonally, and periods when the management is less active can result in slower response times for addressing community needs or system repairs (Kelly *et al* 2018). Other workforce scarcity, in terms or insufficient operator time or knowledge, can compromise system performance and longevity. In the study communities, the operator had many responsibilities in addition to running the water system. The layering of scarcities (e.g. limited operator capacity on top of groundwater depletion as one example) may be at least in part responsible for the gap between user's expectations and needs and the lack of adequate availability, quantity, and quality in rural water supply systems.

To navigate the challenge of limited water availability, participants used three coping strategies which further eroded the expected benefits of piped water supply. Participants (1) used less water, (2) relied on household water storage, and (3) collected water from unimproved sources. First, participants described coping with lack of available water by using less water, particularly by decreasing water used for hygiene purposes. In previous studies, water for personal hygiene can constitute up to half a person's water use per day (Sultana *et al* 2022). Restricted access to water makes hygiene practices such as handwashing and bathing more difficult, not only because there is less total water available for hygiene purposes, but also because participants must now make difficult decisions on how to partition their water use (e.g. between hygiene and consumption) (Howard and Bartram 2020, Sultana *et al* 2022). Insufficient water availability for hygiene practices can have an impact on physical health (Shrestha *et al* 2013, Sultana *et al* 2022), and water intermittency or interruptions can have a negative impact on mental health (Thomson *et al* 2024).

Second, relying on increased volumes of household storage also presents a potential health risk because water quality deteriorates during storage in the household due to recontamination (Wright *et al* 2004, Eshcol *et al* 2009, Günther and Schipper 2013, Kumpel *et al* 2017, Seifert-Dähnn *et al* 2017, Gärtner *et al* 2021, Ali *et al* 2023) and regrowth of pathogens (due to longer storage) (Nnaji *et al* 2019). Third, participants reported relying on unimproved and surface water sources, including river water, which also constitutes a health risk. In a similarly rural context in India, intermittent supply of water drove users to other sources, including microbially contaminated river water (McGuinness *et al* 2020). Consuming unsafe drinking water is the leading cause of preventable disease across the globe, and pathogenic exposure in drinking water results in a major burden on human health (Brown and Clasen 2012, World Health Organization 2022). Even occasional consumption of contaminated water can erode the health benefits of safely managed water (Brown and Clasen 2012). Hence it is essential to address the reliability issues of IWS to mitigate unsafe coping strategies.

Our study has some important limitations. We separated FGDs by gender to reduce any discomfort for women sharing their experiences in mixed company. However, the research assistant was a man, which could have influenced data collection. The FGD format may have limited opportunity for participants who were not comfortable speaking in groups to share their personal experiences. Our descriptions of non-functionality, water supply timing, and supply interruptions reflect the descriptions of the participants and therefore are subject to recall bias. To further advance this research, we recommend future quantitative studies focused on water supply timing and volumes in both piped and non-piped water supplies. Further research should also be conducted over multiple seasons in order to determine the effect of seasonal changes on access and availability of water in piped and non-piped water systems. While our work focused on water access, water quality is another key aspect of safely managed drinking water. While we did not investigate water quality, prior research has established clear links between water quality and the mode of water supply. Intermittent water supplies are associated with reduced water quality (Brown *et al* 2013, Kumpel and Nelson 2014, 2016, Bivins *et al* 2017, Erickson *et al* 2017, McGuinness *et al* 2020) and water collection from non-piped water systems, even improved sources, is associated with (re)contamination (Gärtner *et al* 2021, Manga *et al* 2021). Some research has shown lower microbial contamination levels in intermittent piped water compared to other improved water sources (Brown *et al* 2013). But both modes of water supply are associated with household water storage, which reduces water quality (Elala *et al* 2011, Kumpel and Nelson 2014, McGuinness *et al* 2020), To complement our work we recommend future studies consider water quality differences between rural piped and non-piped water systems.

5. Conclusion

The preference for piped water supply was high amongst study participants, and the trend for implementing piped water supplies is likely to increase. Across the six study communities, there was general agreement that water access has improved over the long-term. The lived experiences of early adopters of rural piped water infrastructure highlight that piped water supplies should be designed and operated with a greater focus on operational flexibility and users' agency to ensure water is available when needed. Interestingly, non-piped water users felt more control over their water collection practices than piped users. Rural piped water supplies face challenges with regularity, duration, and frequency, when compared to non-piped water systems. Further, rural piped water supplies are susceptible to unpredictable and limited supply durations, exacerbated by unreliable electrical supplies. Disruptions in electrical supply were a common factor for non-functional water supply, so increased electrical reliability (through multiple or more robust and resilient sources and/or storage) has the potential to improve the reliability of rural piped water supplies and their benefits. Further, IWS often forces users to adopt coping strategies to meet their water needs and these coping strategies may put users' health at risk. Despite these issues, participants highly desired a private water tap due to the perceived convenience of piped water. Water development goals aim for systems that are available when needed, yet such visions stand in stark contrast to the piped water systems in this study that only operate when water, power, and the operator are available.

Data availability statement

The data cannot be made publicly available upon publication because they contain sensitive personal information.

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Ethics statement

This human study was approved by the Research Ethics Boards at the University of Toronto (Protocol Number: 42911). All adult participants provided written informed consent in Gujarati to participate in this study.

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