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Equitable urban water security: beyond connections on premises

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Abstract

Despite worldwide advances in urban water security, equitable access to safely managed drinking water remains a challenge in low- and middle-income countries (LMICs). Piped water on premises is widely considered the gold standard for drinking water provision and is expanding rapidly in small and medium urban centres in LMICs. However, intermittency in urban water supply can lead to unreliability and water quality issues, posing a key barrier to equitable water security. Leveraging mixed methods and multiple data sets, this study investigates to what extent urban water security is equitable in a small town in Northern Ethiopia with almost uniform access to piped water services. We have developed a household water security index that considers issues of quality, quantity, and reliability. We demonstrate that there is high spatial variability in water security between households connected to the piped water system. Moreover, reliability of piped water supply did not equate to high water security in every case, as accessibility of appropriate alternative supplies and storage mediated water security. Urban water planning in LMICs must go beyond the physical expansion of household water connections to consider the implications of spatiality, intermittency of supply, and gendered socio-economic vulnerability to deliver equitable urban water security.

1. Introduction

Across the world, small and medium urban centres are growing (UN 2018), with implications for urban water security—broadly defined as defined as access to an acceptable quantity and quality of water and level of water-related risk (Grey and Sadoff 2007), in, ‘an urban area, a municipality or urban agglomeration’ (Hoekstra *et al* 2018:2). In addition to demand increases from rising urban populations, the global climate crisis means that urban water services face increasing threats from extreme weather events (Pörtner *et al* 2022). This, alongside the financial and institutional constraints to urban water service delivery, challenges the ability to deliver sustainable and equitable urban water security. In definition and practice, *equitable* urban water security varies among water users and managers due to their diverse experiences, perceptions and notions of water security (Grasham *et al* 2022). Broadly, equitable urban water security can be considered as the even distribution of the risks and benefits of urban water governance.

Piped water supplies play a crucial role in global urban water security—83% of the world’s urban population are accessing *at least basic* water services from a piped supply (JMP 2021). Access to water from a piped supply can be either on premises (i.e. with a tap in the house or yard) or off premises (e.g. from a public waterpoint or neighbour’s house). Water supplies piped onto premises can mitigate the water safety risks from transporting water (Overbo *et al* 2016) and the time burden of sourcing and collecting water that, in many countries across the world, most often falls to women and girls (Geere and Cortobius 2017, Pouramin *et al* 2020). Piped networks are an infrastructure solution that have shown to be effective across urban areas worldwide and piped household connections are widely considered as the gold standard for

urban water provision. However, even with universal access to piped connections, households can experience water insecurity in uneven, and sometimes unexpected, ways due to patterns of infrastructure provision (Tiwale 2019) and multi-scalar social inequalities.

Access to piped water supplies *on premises* are a requirement to meet Sustainable Development Goal (SDG) Target 6.1—universal and equitable access to safe and affordable drinking water for all—as drinking water must be available on premises, available when needed, and free from contamination. As a result, access to piped water supplies on premises are increasing. However, access to household water connections can be inequitable (ADAMS *et al* 2019) along the lines of wealth disparities (Oskam *et al* 2021), and inequities can be exacerbated in systems where water supply is intermittent (Tiwale *et al* 2018)—i.e. water is not flowing through the piped water supply system 24 h a day, seven days a week. Intermittency does not always mean that water is not *available when needed*. As we explore in the paper, availability is mediated through access to multiple water sources and household water storage infrastructure. Inequities in urban piped water systems in small and medium towns in low- and middle-income countries (LMICs) are not well documented or understood, in part, due to the urban water literature having a skewed focus on cities (Grasham *et al* 2019) and because there tends to be a stronger scholarly focus on understanding how households access water at times of interrupted supply.

Inequities in access to water resources and water infrastructure are embedded not only in spatiality but in power relations, the articulation, (re-)production and (re-)negotiation of social differences, particularly along the lines of gender (Sultana 2009, Nightingale 2011). Most commonly, gender norms and certain socio-economic factors (among others that are contextually specific) mediate water access, use and governance (O'LEARY 2019, Sultana 2020). Moreover, in urban areas, where water is commonly distributed to some but not others, the questions of civic belonging and political marginalization become acute (Ranganathan 2014, Rodina and Harris 2016). In a small urban centre in an LMIC, with an extensive piped water infrastructure, we investigate to what extent urban water security is equitable and ask: (a) What factors are important to consider from a holistic evaluation of equitable urban water security? and (b) How do water inequities relate to socio-economic vulnerabilities? We argue that urban water planning in LMICs must go beyond the physical expansion of household water connections to consider the implications of spatiality, intermittency of supply, and gendered socio-economic vulnerability to deliver equitable urban water security.

This paper brings together multiple studies of water security, that use different methods, in Wukro, a town in the Tigray region of Ethiopia, conducted between 2016 and 2020. Since 2020, Wukro has been affected by Ethiopia's civil conflict, which has interrupted the supply of piped water services leading to residents relying on water trucking (*Wukro Water Utility, personal communication, March 2022*). Despite this tragic reality, the findings in this paper have strong implications for future projects that seek to improve urban water security in small towns in LMICs. We offer pragmatic, solution-based insights into furthering equity in piped urban water systems. This paper starts with an overview of the background for this study, followed by our empirical findings. We conclude with a discussion on the implications for strengthening equitable urban water service delivery.

1.1. Background

There has been a growing focus on delivering piped water to premises since 2015 when SDG 6.1 called for universal access to *safely managed* drinking water from an improved water source⁶ that is free from contamination, available when needed and accessible on premises. This upped the ante from the Millennium Development Goals Target 7c where the aim was access to *basic* drinking water—also from an *improved* source, but that could be collected within a 30 min round trip (including queueing). Therefore, the shift to targets that include water being available on household premises has wide-reaching implications for infrastructure investment and the operation and maintenance of water systems.

In 2020, 65% of the global population were using piped water (83% urban and 42% rural) (JMP 2021). Overall, sub-Saharan Africa (SSA) is lagging, with 35% of the population using piped water (56% urban and 20% rural). Ethiopia is lower than global average but higher than SSA average at 41% of the population using piped water (88% urban and 22% rural) (JMP 2021). Within these statistics, access to safely managed drinking water will vary within and between large cities, medium- and small-towns. Urban water insecurity in Ethiopia is driven by socio-political processes, climate change and urbanisation (Grasham and Neville 2021).

Access to water on premises in Ethiopia is 75% in urban areas, up from 33% in 2000 (JMP 2021). In Ethiopia, access to a piped water supply on private premises is the administrative responsibility of the town water utility and requires a one-time connection fee payment by the household and monthly service charge.

⁶ Includes: piped water, boreholes or tubewells, protected dug wells, protected springs, rainwater, and packaged or delivered water.

One of the recommendations in the Ethiopia's 2013 National Guideline for Urban Water Utilities Tariff Setting (FDRE 2013) is to encourage connections, *'by reducing connection fees and using soft payments distributed over months.'* Utility-managed water supplies are essentially insecure because utilities are often not well established, hence the managing capacity is low. On top of this, utilities are usually not financially self-sustaining because the water tariff is not sufficient to cover the full cost of supply (FDRE 2018). This has a critical effect on the provision of equitable urban water supply services.

Despite the increase in household connections, many urban water supply systems across Ethiopia are intermittent and unsafe. Intermittent piped water supplies are common; about one third to half of the urban water systems in developing countries operate intermittently (WHO/UNICEF 2000). Use of multiple water sources is one coping mechanism to increase water security, particularly to increase the quantity of water. However, it is also used to address water quality preferences (Nowicki *et al* 2020) and to increase convenience and affordability (Hoque *et al* 2019). There is no (inter)disciplinary agreement on what an acceptable (or tolerable) intermittent water supply is. Economists have calculated costs of coping with unreliable water supply (Zerah 2000, Cook *et al* 2016) while anthropologists and human geographers discuss the relationship of waiting and water collection trips with local or national politics. In a study in India, that collected data to see the differences in household benefits of continuous vs. intermittent supply, they *'found positive net benefits for households overall, but uneven distribution of these benefits across socio-economic strata'* (Burt *et al* 2018). Upgrading intermittent piped water systems has implications for achieving SDG 6, unless equity issues are managed to ensure universal access to water that is available when needed.

Affordability is a key part of the SDG target but has not been operationalized. Policy makers in the water sector often express affordability concerns, especially for low-income households (Vanhille *et al* 2018, Andres *et al* 2020). In urban areas of LMICs, the poorest households are more water insecure and pay more for water both in monetary terms and as a greater percentage of their household income than wealthier households (Beard and Mitlin 2021). National bodies and international organizations often use a benchmark of 3%–5% of income to assess whether water and sanitation services are affordable. However, it is often not clear whether this measure of affordability includes expenditure on both water and sanitation services or expenditure on a primary source or all sources a household uses. It is also not clear whether denominator should be expenditure or income. Hoque and Hope (2020:2) have thus deemed *'affordability a concept in search of consensus.'*

We approach our study from a hydrosocial position—that water resources are a socio-natural co-production—by putting society at the centre of the enquiry, arguing that improving equity in intermittent urban water supply systems requires societal, as well as engineering, solutions. Equity in intermittent water supply systems has been explored with an optimization modelling that argues for improved infrastructure to tackle it (Ameyaw *et al* 2013) while hydrologists use the term 'equity' to deliver a geographically equalised distribution of water (Ameyaw *et al* 2013, Ilaya-Ayza *et al* 2017) through demand and nodal head driven analysis (Gottipati and Nanduri 2014). We build on the study of Jimenez-Redal *et al* (2018: 12) who found that, *'focusing primarily on the increase of private water connections may overlook the pursuit of equity and inclusion.'* We consider issues of equity in urban water security through the lenses of gender and climate resilience with an interdisciplinary approach that contributes a nuanced and holistic understanding of the social dynamics that mediate inequities.

2. Research design

2.1. Case study site

Wukro, a town in the Tigray region in Northern Ethiopia, was selected for this study due to the, unusually, almost universal access of piped connections on premises (97% of households; see location in figure 1 below). With a population of around 50 000 (Central Statistical Agency 2013), Wukro has been growing rapidly and building construction has increased pressure on scarce water resources. Wukro is comprised of three urban *kebeles* (sub-cities) namely Agazi, Dedebeit and Hayelom (figure 1). The Tigray region has experienced a massive labour mobility (mostly of women) to Gulf and Middle Eastern countries resulting in social changes and growing inequalities (Johnson 2020). Despite the wide-reaching piped water network, households and small businesses remain water insecure to different degrees, primarily due to the unreliable and intermittent flow of water through the pipes. Wukro has a legacy of water insecurity and vulnerability to endemic drought (USAID 1985). Following the January 2020 hotspot analyses done by Emergency Nutrition Coordination Unit of Ethiopia, the Kilte Awlalelo woreda (district), in which Wukro is situated, was categorised as the highest priority requiring urgent humanitarian response ('water' is one of the six key indicators in this classification) (OCHA 2020).

To improve urban water access in the town, Wukro water utility, with support from the National ONEWASH programme, UNICEF and UK Foreign, Commonwealth & Development Office, as well as the

Table 1. Summary of research methods.

Data collection method	Description	Type
WASH Household survey 2019 (<i>WASH dataset 2019</i>)	701 households (random spatial subsample of HDSS households) surveyed in August 2019 to capture detailed information about water access and management at the household level. 25 households removed as without household connections and too small a subset to do a separate analysis ($n = 676$).	Primary, quantitative
Water diaries (2018–19) (<i>diaries dataset</i>) (details: Hoque and Hope 2018)	117 households recorded their daily water sources, amounts, costs, sufficiency and itemised household expenditures every day for a 46 week period, supplemented with interviews to understand the drivers of their water use behaviour in relation to the diary records (Details in appendix A)	Primary, mixed quantitative and qualitative
Interviews (<i>interview dataset</i>)	50 semi structured interviews with entrepreneurs (mainly, women local alcohol shop brewers) conducted in 2020 to explore changes in the perception of water access over time and within different water crises. It was a follow-up study from a study conducted by Mekelle University in 2018–2019.	Primary, qualitative
Health and Demographic Surveillance Systems (HDSS) 2016 (<i>HDSS dataset 2016</i>)	4273 households (total enumeration) in Wukro surveyed in 2016 to capture household demographic and health data including detailed wealth indicators. (Dataset methodology: Abera <i>et al</i> 2020).	Secondary, quantitative
Billing records from Wukro Water Utility (<i>utility billing records</i>)	Monthly billing records of 6993 domestic customers between 17 September and 19 March (20 months).	Secondary, quantitative

Tigray regional and national governments, expanded and renovated the existing piped water system. Inaugurated in 2018, this included the development of more productive and reliable boreholes with a planning period from 2015 to 2035, designed to provide water equally over all water demand nodes of the distribution network (Salomon Lda. and YGRY., 2015). The period of our research extended from before implementation of the scheme, to after completion, capturing a period during the construction and transition. During this period, particularly focused on the first two years of a ten-year implementation period, the system was not operating optimally, so there were limited improvements in supply, hence this paper represents conditions during the transition. The findings in this paper are based on longitudinal engagement with residents and stakeholders in Wukro from 2015 to 2020, which has allowed us to observe changes in water security over time.

2.2. Methods

This research paper uses a mixed methods approach, drawing on multiple studies that were not designed for the purpose of comparison and, therefore, vary in sampling and methodology. Nevertheless, the breadth and depth of the studies allow us to offer nuanced insights into the implication of water insecurity for the most vulnerable urban residents, often missing from studies that rely solely on quantitative methods. We use primary quantitative and qualitative datasets (WASH survey, water diaries and interviews) with secondary quantitative datasets (HDSS survey and utility billing records) details of which can be found in table 1 and in the appendices. Ethical approval was given for primary data collection from Oxford University's Central University Research Ethics Committee.

Despite the benefits of using multiple studies and datasets, a challenge of comparison is the different timeframes over which the data was collected. As the water system was transitioning, it was experiencing periodic interruptions and studies were falling into times when tap water was either more or less available. Therefore, we have navigated this carefully when interpreting the data and offering conclusions. Another hurdle to overcome was matching up the quantitative datasets: 505/701 households in the primary *WASH dataset 2019*, could be matched to the secondary *utility billing records*, while 477/701 are matched to the secondary *HDSS dataset 2016*, hence have a wealth index associated with them. About 355/701 were matched to both the *utility billing records* and the *HDSS dataset 2016*. Of 117 households in the primary *diaries dataset*, 34 are matched to the *utility billing records*.

2.3. Development of composite wealth and water security indices

Composite indices, developed through aggregation of selected indicators, are commonly used in social science and development literature. They can be used as a means of identifying population groups, areas that

Table 2. The five variables used to develop the household water security index (WASH dataset 2019).

Indicator	Variable	Survey question asked	Percentage of households (n = 676)	Weightage assigned
Quality	Safety	Do you think your main source of water in the past one month was safe to drink?	Yes—55.7% No—44.3%	0.82
Quantity	Sufficiency	How many activities did your household have to stop in the past two weeks due to lack of enough water?	None—73.2% One or more—26.8%	1.32
	Storage	What is the combined water storage capacity of your household?	Less than 200 l—61.7%; More than 200 l—38.3%	0.48
Multiple sources	Reliable piped access	Has piped water been your main source of drinking water in the past week? If so, has it also been in the past year?	Yes/yes—77.2% Yes/no and No/yes—19.7% No/No—3.1%	1.67
	Number of sources	How many sources of water did you use for drinking in the past one month?	One—59.4% Two or more—40.6%	0.90

require targeted interventions, or to monitor progress over time⁷. While composite indices are often criticised for being reductionist, they remain popular in illustrating social and spatial inequities since they produce easily digestible pointers for policy and decision-making. Construction of previous composite indices has usually involved three steps: (a) selecting indicators based on conceptual understanding of the phenomenon; (b) defining cut-off points to separate cases based on their deprivation level; and (c) aggregating indicators into a single metric using weightage that signifies the relative importance of indicators. While most indices calculate the arithmetic mean of indicators based on equal weightage, others allocate context specific weights based on subjective judgment. Data-driven statistical techniques like principal component analysis (PCA) or fuzzy clustering methods are commonly used.

Various water security metrics have been developed by scholars and practitioners, reflecting the diverse conceptualisations of water security (Octavianti and Staddon 2021). Building on work by anthropologists Wutich and Ragsdale (2008), the Household Water Insecurity Experiences (HWISE) consortium designed a 12-item experiential scale combining perceptions of adequacy, reliability, accessibility, and safety, and related experiences of psychosocial distress in the prior four weeks (Jepson *et al* 2017, Young *et al* 2019). Shrestha *et al* (2018), on the other hand, focused on resource-based or physical dimensions of water security, and combined 15 indicators on main and alternative water sources, per capita consumption, monthly expenditures, water treatment practices and storage capacity to develop an ‘objective index’ of household water security. Drawing on the widely used Water Poverty Index by Sullivan (2002) and Lawrence *et al* (2002), Hailu *et al* (2022) developed a more comprehensive water security index that includes the physical availability of water resources, household water needs for drinking, domestic, livestock and irrigation purposes, the socio-political and institutional context that mediate water resource access and use, as well as the need to allocate water for ecosystem services.

2.3.1. Household water security index development

Influenced by the above approaches to household water security index development, ours uses fuzzy set analysis (FSA) with five indicator variables from the *WASH dataset 2019*, explained fully in table 2. The variables relate to the respondent’s perception of water quality, quantity and use of multiple sources. With this, we have separated households into five water security groups and the index has been validated, in line with the indicators of ‘safely managed’ drinking water services defined by the United Nations Children’s Fund and World Health Organisation (UNICEF/WHO) Joint Monitoring Programme (JMP 2021) for SDG 6.1. However, the specific selection of the variables was guided by the context: e.g. since all households in our sampling frame had piped connection on-premises, variables on distance were not included in our water security index. The index we calculated included 676 households that reported using water from a tap on their premises, excluding the 25 households without a tap. With this, we have separated households into five water security groups and the index has been validated with the data from the water diaries and with reported, household water security perceptions that significantly correlate with the water security index, details of which can be found in appendix B.

⁷ Examples include: (a) The Oxford Poverty and Human Development Initiative (OPHI)’s Multidimensional Poverty Index (MPI) (ALKIRE and SANTOS 2014, UNDP and OPHI 2020) and (b) FILMER and PRITCHETT (2001)’s and Cheli and Lemmi (1995)’s seminal work on assessing multidimensional poverty.

2.3.2. Household wealth index development

The HDSS dataset 2016 ($n = 4273$) was used to calculate household wealth indices using PCA. PCA is a commonly used method of assessing multidimensional poverty, whereby the factor loadings of the first principal component (PC_1) serve as the weights of selected asset variables (Filmer and Pritchett 2001, Vyas and Kumaranayake 2006, Katuva *et al* 2020) of 11 variables on education (percentage of adult member with at least primary education), assets (radio, TV, refrigerator, percentage of members above 13 years possessing a personal mobile phone), housing (wall, floor and roof materials, number of rooms used for sleeping), cooking fuel and bank account. The wealth disaggregated analysis presented in this paper is based on 477 households, of which 22%, 27%, 23%, and 28% belonged to the bottom to the top wealth quartiles (see appendix C for detailed calculations).

3. Results

3.1. Spatial inequities in water security

There are pronounced spatial inequities in Wukro and, drawing on multiple datasets, we will walk through the complex, and at times seemingly contradictory, evidence that offers insights into why these inequities exist. Indicators of the spatial inequities in water security in Wukro are given in summary statistics in table 3, with key indicators disaggregated by urban *kebele*⁸, while some are visualised in the maps of Wukro in figures 1 and 2. We observe interesting socio-economic differences across the three kebeles in Wukro. Dedebit (North) is the poorest area of the town (appendix D, table D1), has the largest proportion of tenants and smallest proportion of landlords as well as the most household entrepreneurs. Household entrepreneurs generate income at home; those that undertake water-intensive income-generating activities, such as brewing, have higher water needs. However, they are in the same water use category as households, as classified by Wukro Water Utility.

Urban water insecurity in Wukro impacts household enterprises through constraining the operation of small, water-intensive businesses such as making coffee and brewing beer (*siwa*) (Zerihun *et al* 2020). Female entrepreneurs in Wukro have unique urban water security experiences, written about in detail by Korzenevica *et al* (2022). The *diaries dataset* shows higher usage for those households involved in small enterprises. Household enterprises were undertaken by 23% of households (WASH dataset 2019) and were highly gendered: 80% were led by women; and households that reported being female-headed (often single/divorced/widowed women) were more likely to have household enterprises. Household enterprises are often seen as the only possible source of income for women since they require low investment and skills, though they offer the possibility of controlling their own finances and developing their independence. At the same time, the businesses are extremely dependent on water and the largest proportion of households with enterprises were found to be in the least water secure group.

Contrasting water security measures help us to understand that an engineering-based explanation of intermittency in the piped water supply system is insufficient to explain water security inequities in this case. Dedebit *kebele* is a complex case with the most reliable piped water supply according to the *diaries dataset* (figure 2—revealing water available through household taps seven days a week), as well as the WASH dataset 2019 (shown in figure 3) but it is the least water secure of the three urban kebeles in Wukro according to the water security index (figure 1, data given in appendix D, table D2). Almost 50% of households in Dedebit were using river water for domestic uses.

In terms of the water security index, figure 2 reveals spatial water security clusters⁹, with Dedebit, observed to be the least water secure compared to Agazi (central) and Hayelom (south); Dedebit scored lower in 4/5 of the binary indicators used in the water security index (safety, sufficiency, storage and use of multiple sources, figure 3 (explained above in table 2)). These spatial inequities are quite stark, even though the context is a small town. We continue the explanation for these inequities throughout this section by presenting results from the analysis of the indicators used in the index in more detail below.

3.2. Quantity: sufficiency of water access and storage

Climate variability is a driver of water access in Wukro, with greater access to water during the wet season, particularly July to September (figure 4). In the dry season, around 43%–45% of households rely solely on piped water to meet domestic water needs, which is mostly supplemented with buying water. In the wet season, just over half of households rely on piped water only for drinking and cooking, while rainwater is used widely for washing clothes, cleaning and bathing (appendix D, table D3); a smaller proportion of households still rely on bought water for drinking and cooking. Despite access to tap water on premises, 27%

⁸ *Kebele* is the Amharic word for the smallest government administrative unit; Wukro has three urban kebeles.

⁹ The heatmap was created using ArcGIS 10.8, with Inverse Distance Weightage (IDW) interpolation of the water security index values.

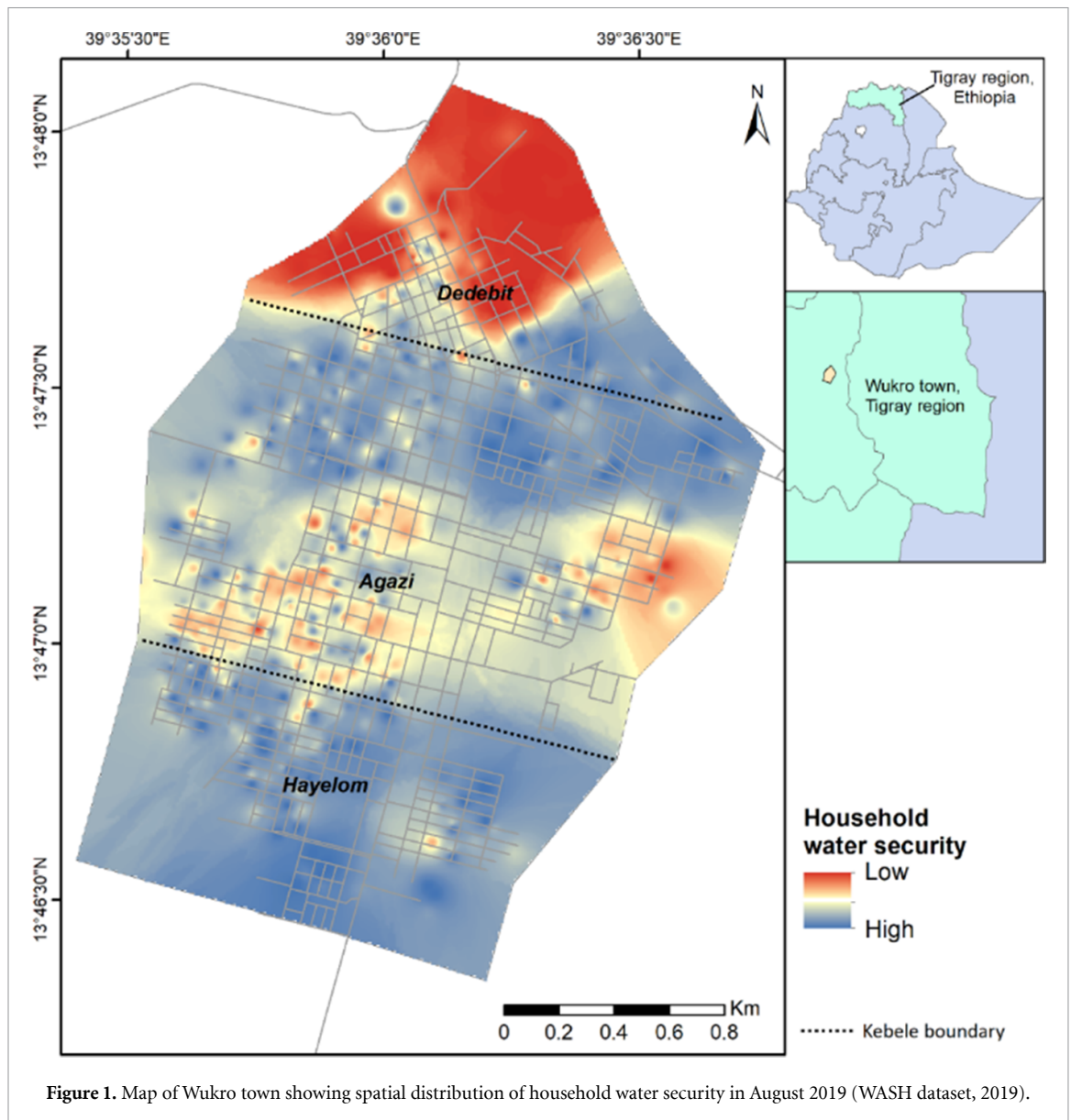


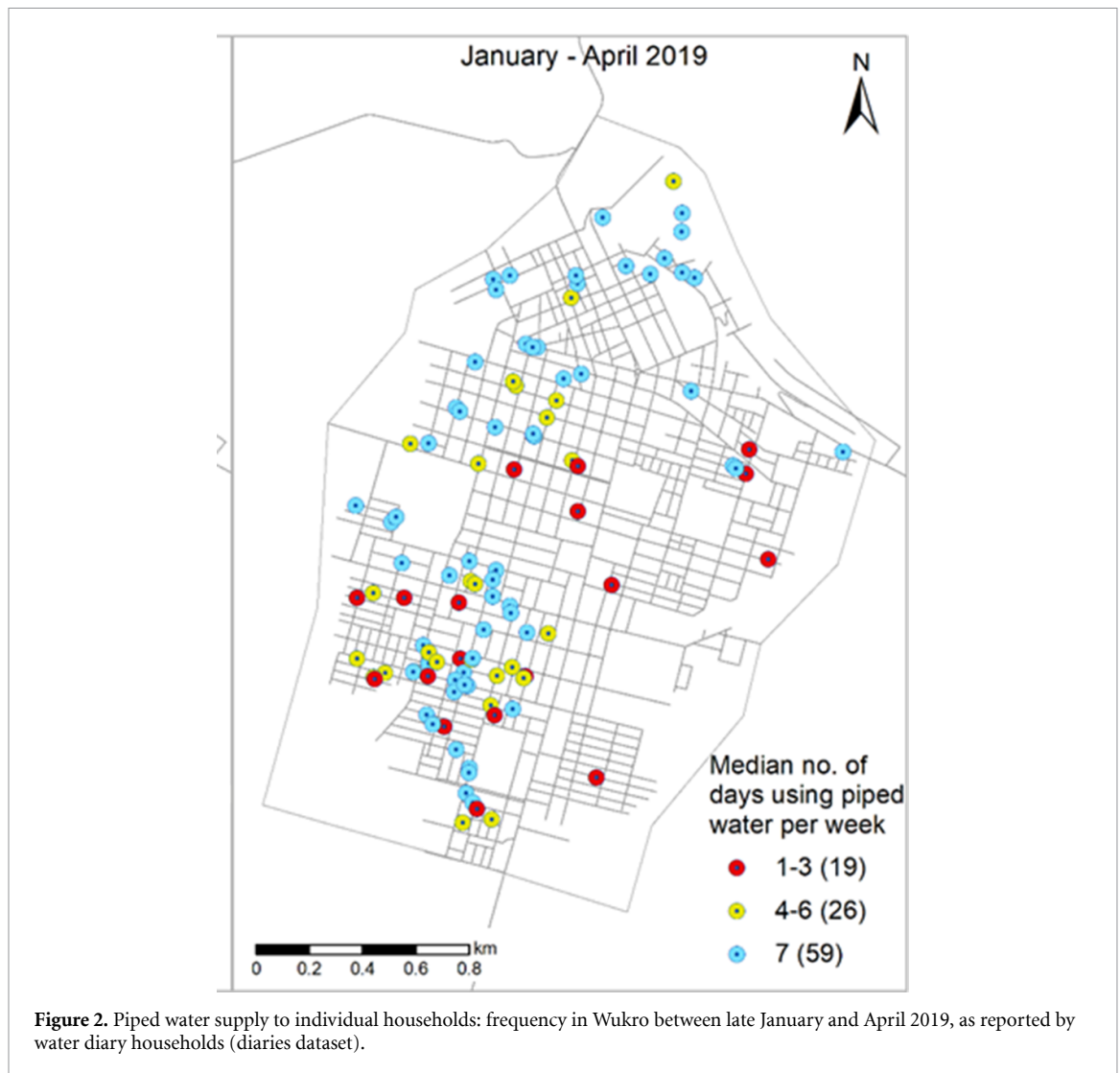
Figure 1. Map of Wukro town showing spatial distribution of household water security in August 2019 (WASH dataset, 2019).

of urban residents reported having to stop water-using activities at some time of the year due to poor availability of water, with laundry (25%) and cleaning (16%) the activities most commonly stopped. The problem of water shortages was more notable for household entrepreneurs with 42% reporting having to stop water-using activities due to poor availability of water.

The impacts of water shortages varied spatially. In Agazi, only 8% of respondents reported stopping activities due to water scarcity and reported that trouble accessing water would normally extend for less than three months, compared to Dedebeit where 66% of respondents reported stopping activities, with trouble accessing water for six months of the year. The reported duration of shortages ranged from 87 days in Dedebeit to 30 days in Agazi. Weak trends were identified between decreasing wealth and increasing duration of water scarcity, while there were limited differences in water scarcity for tenants, owners and landlords.

To manage seasonal water shortages and droughts, water service rotation has been used by the Wukro water utility which has created spatial inequities, with some areas prioritised for more regular flow due to the presence of critical services such as the hospital. This has led households to purchase household-level water storage infrastructure. Households with greater than 200 l storage capacity were able to cope more with unreliable supplies. One respondent reported:

“We usually do not suffer from water shortages, as we have enough storage to support for two weeks. The overhead tank has been there since we moved to this house seven years ago. About three years ago, when water crisis started to aggravate in this area, we purchased another 2000-litre tank. During the crisis period last year, we got free water from the government tanker trucks. On one



occasion, we purchased an entire truck load of water to meet our needs. Our monthly water bill ranges from 50 to 80 Birr.”¹⁰

Water storage volumes per household member ranged from 28 l in Dedebeit to 150 l in Hayalom. Water shortages, storage capacity and the use of alternative sources, will affect the amount of money households spend on water, especially for the 74% who pay depending on water use.

3.3. Intermittency and the use of multiple water sources

Household water access in Wukro is unreliable due to the demand-supply gap, managed intermittency with water service rotation across the different water supply delivery zones within the town, household storage availability and socio-economic dynamics. Most households reported accessing water from more than one source in the past 12 months (84%), with 74% buying water from another house in Wukro (see table 4).

Intermittency of household access to piped water on premises varied spatially and temporally, resulting in households accessing water from multiple sources—confirmed by both the *WASH dataset 2019* and the *diaries dataset* (figures 5 and 6). Respondents reported using multiple water sources and 16% had changed their main water source in the past 12 months, most commonly in Dedebeit (58%). The unpredictability of water significantly impacts female entrepreneurs’ wellbeing and business development. When piped supply was inadequate to meet demands, households supplemented with purchased water from donkey/ horse cart vendors or borrowed from neighbours. One of the diary participants running a *siwa* business, reported,

“Water comes 2 days a week, and it is just enough to meet essential needs. If the frequency decreases further, I have to buy water from horse cart vendors and pay 4 Birr per jerrycan (2 Birr for water

¹⁰ 50–80 ETB ~ 6.5–10.4 USD

Table 3. Summary statistics for Wukro town by urban kebele (WASH dataset, 2019 and HDSS dataset, 2016).

	Agazi	Dedebit	Hayalom	Total
n	440	118	143	701
Gender of respondent is female	80%	80%	90%	81.6%
Respondent is household head	51%	74%	41%	52.40%
Average household size (mean and sd)	4.8 (2.0)	4.0 (2.1)	4.4 (1.8)	4.6 (2.0)
Household enterprise	25.5%	33.1%	11.2%	23.8%
Occupancy—tenant	16.1%	35.6%	11.9%	18.5%
Occupancy—owner	41.4%	36.4%	28.0%	37.8%
Occupancy—landlord	39.5%	19.5%	56.6%	39.7%
Main drinking water sources include				
Piped	95.9%	94.1%	97.2%	95.9%
Bought from neighbour	22.7%	55.1%	11.9%	26.0%
Bought from further away	14.1%	61.0%	15.4%	22.3%
Main drinking water source has changed in past 12 months	10.9%	55.1%	0.7%	16.3%
Treated drinking water	25.4%	1.2%	1.8%	14.5%
Perceive water quality to be worse in the wet season	14.8%	2.5%	52.4%	20.4%
Perceive water quality to be worse in the dry season	38.4%	75.4%	44.1%	45.8%
Difficulty paying water bill in past 12 months	7.5%	18.5%	2.9%	8.1%
Wet season: rely on 1 source for drinking water	45.1%	6.8%	65.0%	42.7%
Dry season: rely on 1 source for drinking water	51.8%	29.7%	66.4%	51.1%
Average storage litre per capita (mean and s.d.)	74.4 (289.0)	27.9 (22.3)	147.8 (308.4)	81.6 (270.5)
River water used (domestic uses)	10.9%	49.6%	6.3%	16.5%
Household must stop 1 or more activities due to water shortages	23.20%	66.90%	7.70%	27.40%
Average number of days activities stopped (mean and s.d.)	30.6 (24.4)	86.7 (55.7)	62.3 (50.1)	55.2 (49.5)

and 2 Birr for transport). The vendor usually brings water from neighbours in the hospital area, as they always have water. If the distance increases, for example in times of acute crisis, the cost rises. Before the tariff hike the price was 0.5–1 Birr per 20–25 litre jerrycan.”

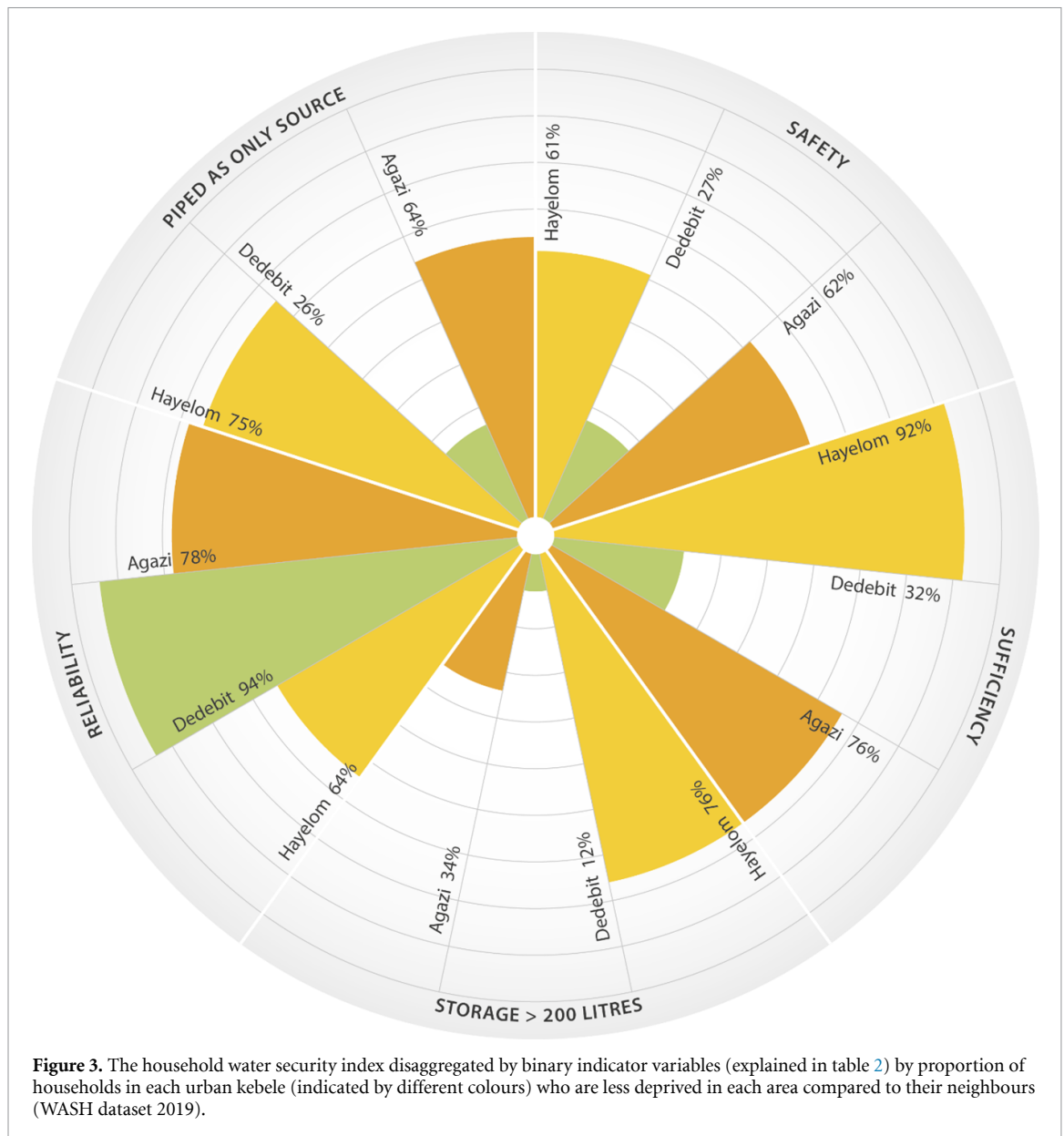
The lack of information on when water will flow through the household tap brings significant stress and feelings of helplessness, causing women (who often combine intense business leading, household and caring of children) to miss many nights of sleep as they sit and wait, afraid of missing the water (Korzenevica *et al* 2022). Many note that they spend most of their energy on worrying about or arranging water access rather than developing their business or taking care of the household. Water re-selling is illegal in Wukro, so with the lack of public water sources and shortages of private water, women are going onto the streets, hoping that someone will let them buy illegally some jerrycans of water. Buying water from the cart on these occasions may be easier, but not faster, often takes the whole day and women are suspicious about the sources and safety as they are not disclosed.

Clustered spatial water inequities were co-constructed with water service rotation and inequitable access to household-level storage. Clustered inequities are a double burden for urban residents (table 4); households living in the same area have similarly limited access to tap water and storage, hence water must be accessed from a secondary source that is further away. This increases either the time burden for water fetching (with much borne by women) or the water transportation costs.

3.4. Water safety

Water quality was not measured at the time of the study, but the piped water was consistently perceived to be of safe quality by the majority of the population (56%), with the main concerns being the visual appearance (57%) and taste (47%) of the water, with 19% of households reporting concerns about illness. During interviews, residents of the town reported that interruptions to the supply created problems for water quality, with complaints of sand in the water and red colouring. Household water treatment was not common with only 1% of respondents indicating the water they were drinking on the day of the survey was treated with chlorine, while 5% had left their water to stand and settle before drinking.

To achieve the health benefits of safe drinking water, people must have access to safe water at all times. In Wukro, two key risks were identified to continuous use of safe water: non-exclusive use of piped water, including river water use; and seasonal changes in water quality. Reported usage of river water for drinking was very low: only two households (0.3%) identified it as a source of drinking water generally, while this increased for specific questions about use in the dry season (0.4%) and in the wet season (0.6%). By contrast, considering all reported uses of river water for domestic purposes (drinking, cooking, bathing, cleaning and laundry), 16% of households reported collecting water from the river or using water at the river. There was a



strong spatial relationship with river use increasing in areas near the river in the north of the town.

Two-thirds of respondents reported that the water was less safe to drink in particular seasons. This varied by location, with water considered less safe in the dry season in Dedebit, where illness was a greater concern; in Hayelom respondents were split between concerns for water safety in the wet and dry season.

These spatial inequities were reflected in several different metrics: In Dedebit, respondents were less satisfied with their water, more concerned about safety and less likely to consider the water consistently safe. Relatively small differences between renters, owners and landlords existed; more notable differences existed between wealth quintiles including Q1 (least wealthy) more likely to be concerned about water quality and have concerns about illness, while those in Q3 and Q4 were more likely to do something to their water to make it safer.

3.5. Unpacking the inter-relationships of water security and wealth

In Wukro, we observed a low correlation between water use from households' piped connections and income ($\text{corr} = 0.06$) and wealth ($\text{corr} = 0.03$). This is consistent with previous research in the region (Fuente *et al* 2016). We also found no statistical relationship between our household wealth and water security indices, suggesting that households across the wealth spectrum experience water insecurity. However, as we started to break down the statistical analysis, analysing affordability and including the perception of respondents, we started to see a different picture. When disaggregating across different indicators in the water security index, and across different spatial wealth clusters, we observed some connections between wealth and water security

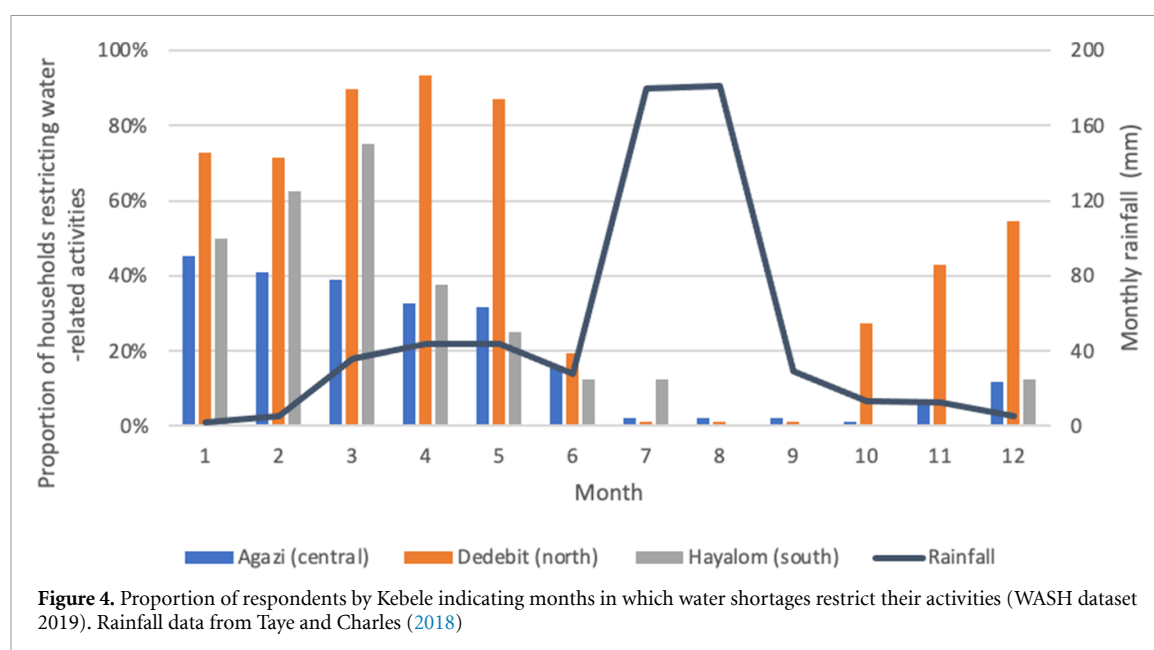


Table 4. Use of alternative water sources when piped water was not available.

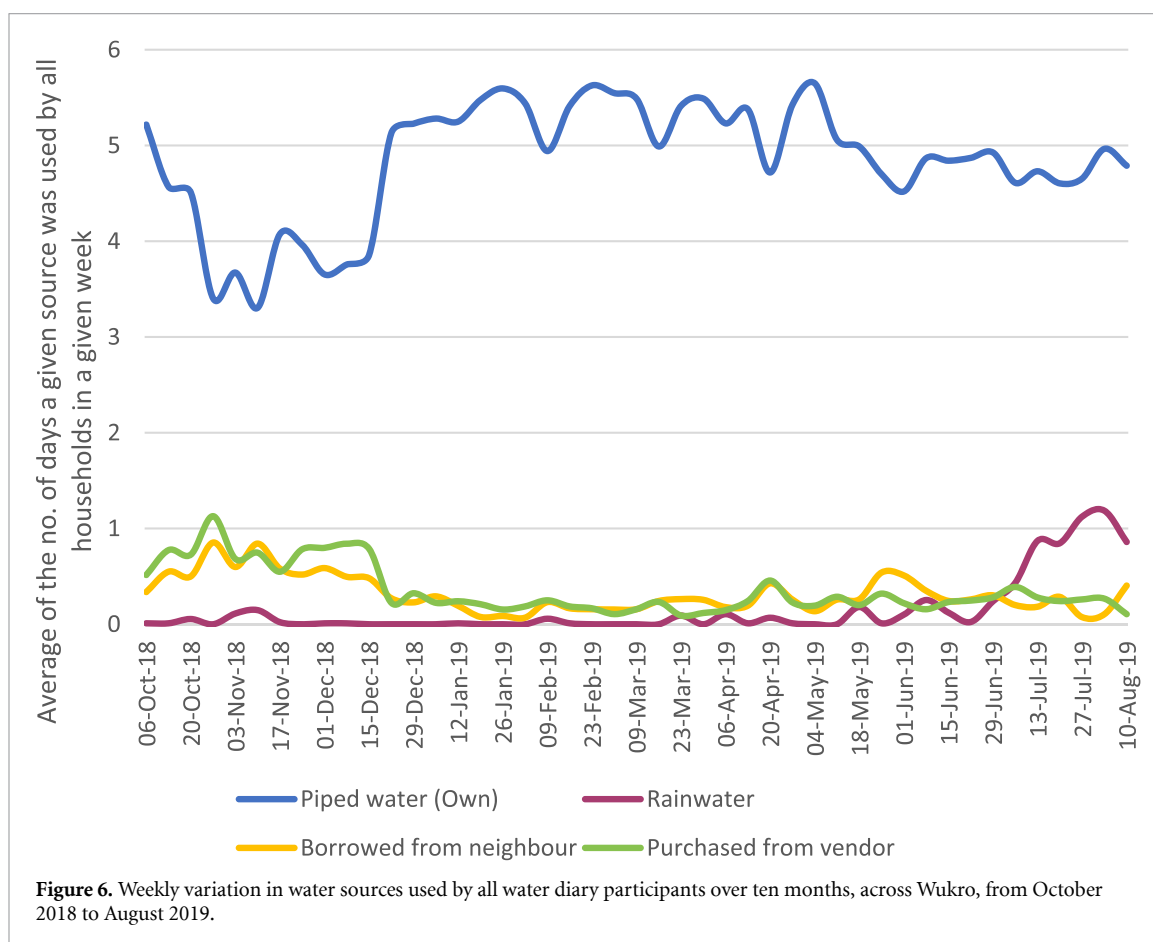
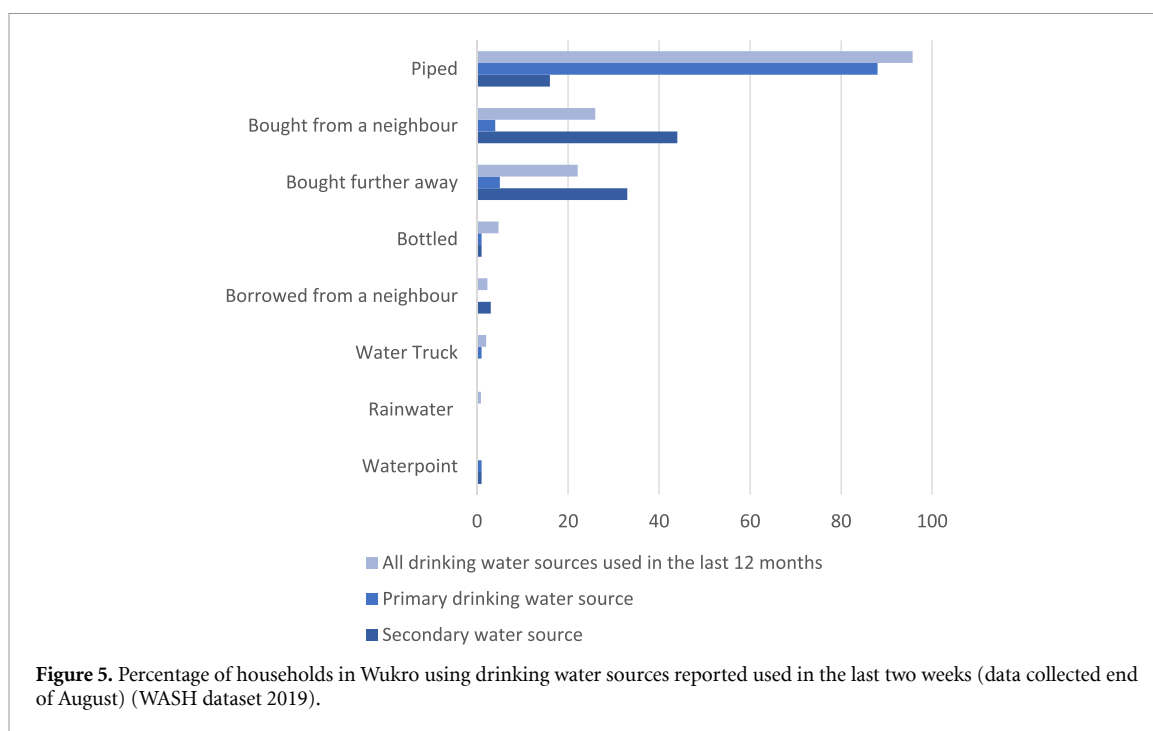
	Agazi	Dedebeit	Hayalom	Total
Alternative water source				
Not needed	18.2%	0.0%	21.0%	15.7%
Bought from neighbour	48.9%	20.3%	46.9%	43.7%
Bought from further away	23.2%	73.7%	28.7%	32.8%
Reasons for preferring alternative source (where needed)				
Cost	11.9%	17.8%	8.0%	12.4%
Time	63.1%	40.7%	64.6%	58.9%
Quality	18.6%	38.1%	0.0%	19.0%
Adult female collects water from alternative source	74.8%	82.5%	93.7%	80.2%
Pay for alternative water source	91.1%	94.9%	98.2%	93.2%
Pay for transport	31.4%	55.9%	52.2%	40.3%
Adult female pays for water from alternative source	63.7%	73.2%	76.6%	68.2%
Average time to collect water in minutes (s.d.)	25.3 (21.7)	41.2 (18.5)	21.1 (16.9)	27.7 (21.4)

that could not be determined with the indices alone, revealing a limitation of aggregated analysis in this case (see appendix D, table D5 for summary statistics).

The water utility in Wukro uses an increasing block tariff (IBT) with a fixed charge to calculate customers' water bills. According to the billing records, the mean average price households pay for water from the utility is 6.5 Birr m^{-3} . Because the utility does not provide 24 \times 7 water service, households report using multiple sources to meet their water needs. Households reported paying 0.12 Birr l^{-1} (120 Birr m^{-3}) for water from alternative sources, which is two orders of magnitude higher than the price paid for water from the utility. Many households (40%) who report obtaining water from a secondary source, indicate that they also pay to transport water from secondary sources. Our estimate of the volumetric price of water from secondary sources does not include this additional transportation cost.

Only 7% of respondents reported that their household had trouble paying their water bill in the past year. It is often assumed that water bills might always be too high but there are other reasons households might have difficulty paying their bills. In Wukro, 86% of households who had trouble paying their bill cited an unexpected large expense as the reason they struggled. This suggests most households in Wukro view their water utility bill to be affordable and that an unexpected expenditure shock was the primary reason households had trouble paying their bills.

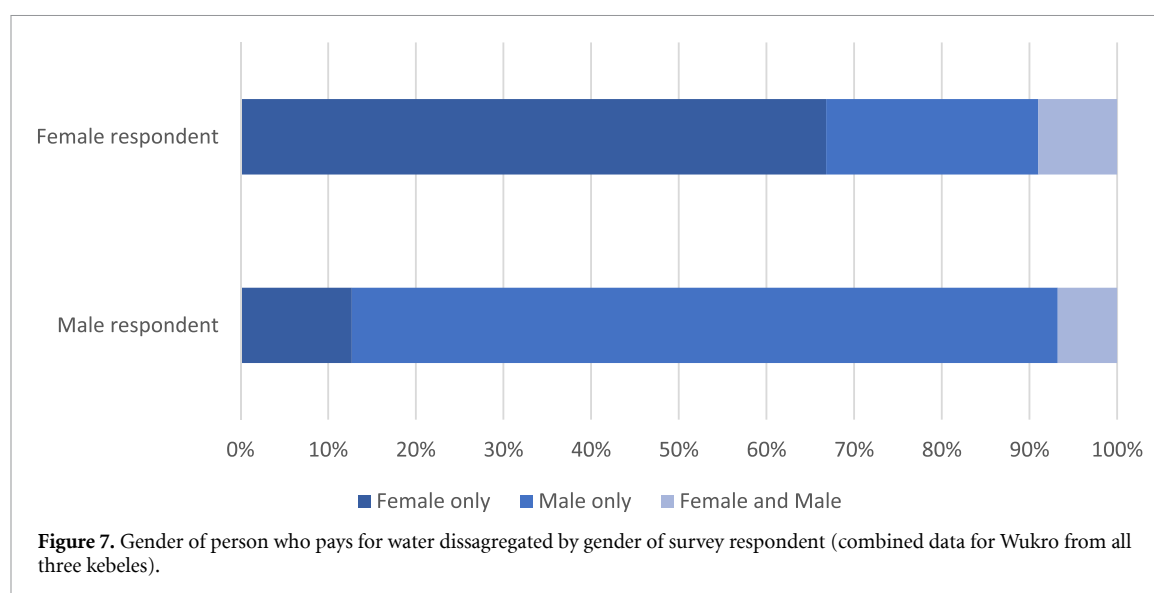
As per the billing records, the water diary households consumed an average of 5.2 m^3 of piped water per month (25.2 l per capita per day), with usage dropping to 3.8 m^3 (15.7 l per capita per day) during Oct-Nov 2018, when there were operation and maintenance (O&M) issues, and half of the households reported having piped supply only for 1–3 days a week. Analysis of itemised annual expenditures show that, on average, households spent 2.4% of their total expenditures on water, with 40% of households spending less



than 1% and 14% spending more than 5%. Expenditures were particularly high in late 2018 when many households purchased water from neighbours or mobile vendors to cope with lack of piped supply (figure 7).

3.5.1. Who pays and who is constrained?

We found that payment for water, and household water management is gendered, with women predominantly responsible for household water access, water payments and water fetching. There were no



significant gendered differences between the water security index and either the reported gender of household head or gender of respondent. However, 80% of households that collect water reported an adult female doing so. There were also significant gendered differences ($p < 0.001$, independent t-test) in the reporting of who pays for water, with male respondents more likely to report that men pay for water (figure 7).

Household entrepreneurial activities are constrained by water, which is a women's issue since these are female-dominated activities. The unreliable interruptions of water made it hard for entrepreneurs to operate their businesses; they experienced the stress of unpredictability and loss of income due to lack of water. Water significantly hampers small business trajectories as shops may be forced to close for days, or weeks, due to water shortages, resulting in the loss of regular customers. Despite some household entrepreneurs paying considerable sums for water (one woman paid 1500 Birr (~39 USD) for one month) all claimed that the cost is not the main problem, as one woman put it (36 y, divorced, four children, *siwa*, migrant): '*I am not worried about the financial cost of water [her water cost is higher than house rent] but what I am going to lose because of [the absence of] water*' (Korzenevica et al 2022).

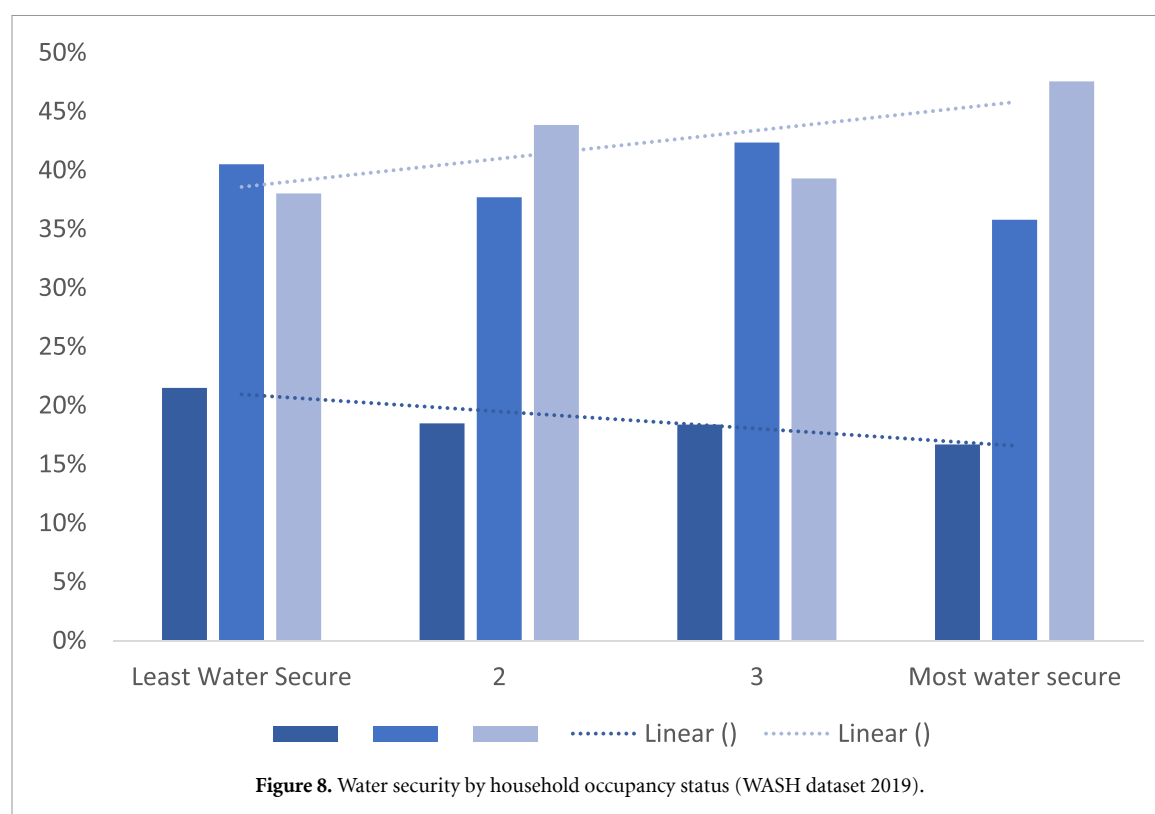
To unpack the relationship between wealth and water security in Wukro further, we have undertaken a disaggregated analysis across three groups with different household occupancy status: landlords (also owners, 42% percent), owners (40%) and tenants (18%)¹¹. There was no statistically significant correlation between occupancy status and water security index (chi-squared test) but there was a weak trend of landlords being more water secure and tenants less water secure (figure 8). Landlords reported being more concerned about water security (21% of landlords compared to 14% of owners and 8% of tenants). From the *interview dataset* study we infer that this can be explained in three ways: (a) people change rented houses very quickly, so poor water access means that tenants may leave; (b) water can be a source of conflict between landlord and tenants, as well as tenants themselves and (c) landlords are responsible to solve water problems, not only for themselves, but also for their tenants.

4. Discussion: strengthening urban water development planning in small towns

Piped water systems with household connections are considered the gold standard in advancing progress on SDG6.1. However, achieving constant, 24 × 7 water supply is uncommon across urban Ethiopia and much of urban SSA. Intermittent urban water supply service delivery is the norm, due in large part to the substantial capital investment needed to overhaul these systems, while system management is poor. It is within this framework, and with pragmatic realism that intermittent urban water supply is unlikely to disappear soon, that we ask: How can we move towards more equitable access to water in systems with intermittent urban water supply?

In Wukro, an intermittent water supply piped on premises resulted in a range of experiences of water insecurity, with intermittency ranging supply every day, to once per week. While water security was higher in some areas with easier access to multiple sources and storage, water security was worse in Dedebeit, Wukro's

¹¹ From our data, we calculated that wealth and occupancy status are significantly correlated ($p < 0.001$, chi-squared test) with landlords the wealthiest and tenants the poorest. We found no statistically significant gendered differences in household occupancy status.



northernmost *kebele*. In Dedebeit, households had a high reliance on piped water, with low levels of satisfaction (see table D4), and limitations on water-related activities with implications for livelihoods, health and wellbeing. Adaptive mechanisms were lower, with fewer relying on alternative water sources, small household storage volumes and high use of river water with implications for health (Hussen *et al* 2021). Below we frame what can be done in light of these findings.

4.1. Financing and affordability implications for equity in service delivery

Water prices are too low to cover water supply costs and far below the amount that households pay for alternative sources. Households in our sample reported paying an average of 6.5 birr m^{-3} (0.13 USD m^{-3}) for water from the piped network. This price did not reflect the full cost of providing water service. While we do not have precise estimates of the full cost of providing water services in Wukro, other studies have estimated the cost of piped water supply to be approximately 1 USD m^{-3} (51 birr m^{-3}) (Fuente *et al* 2016). At current prices, Wukro Water utility does not have the financial resources to provide regular, high-quality water services, though financing is not a panacea to the institutional barriers to service delivery.

The current IBT structure is not appropriate for the Wukro context. The water utility in Wukro uses an IBT to calculate customer water bills. In an IBT the marginal price for water in each block (quantity of water use) increases as customer water use increases. IBTs remain widely used in LMICs with the objectives of: (a) targeting subsidies to low-income households; (b) cost recovery; and (c) sending a clear price signal to customers to encourage efficient water use. However, there is considerable evidence that IBTs in LMICs do not usually achieve these three objectives (Whittington 1992, Fuente *et al* 2016, 2021).

We observed two factors in Wukro that suggest that an IBT is inappropriate for the local context. First, there is a low correlation between income and water use from the piped network in Wukro. This suggests that volumetric water use is a poor proxy for income and an IBT cannot effectively target subsidies to low-income households. Second, we document a considerable amount of water sharing among households. An IBT penalizes households for sharing water with neighbours. Although it is illegal for private residences to sell water in Ethiopia, if informal water resale is occurring, the IBT would increase the price of water for those re-selling water, which would likely result in higher prices for the low-income households purchasing water. Given the context in Wukro, the utility would likely be served by implementing a simple uniform price for the volumetric portion of the water tariff. This would be easy for customers to understand, easy for the utility to implement, and not disincentivize the sharing of water among households, which will likely remain an important coping strategy for households until the utility can provide regular, 24 \times 7 service.

Our results indicate the utility can—and should—increase the price of water from the piped network towards improving their technical capacity and providing reliable water services to underserved areas.

Affordability of water was not an acute problem in Wukro; water from the piped network is cheap and very few households face affordability problems with high-priced water from alternative sources¹². Nevertheless, if the utility did raise prices to improve cost recovery, some households may face affordability problems. In the short-run, prices from the piped network would increase while the price from alternative sources may also increase. In this instance, policymakers may need to develop targeted programs to help low-income households (Cook *et al* 2020, 2020). However, failure to generate the revenue necessary to improve service quality will result in a steady decline in service quality over time. Additional research, that includes affordability and willingness to pay assessments, is required to identify the point at which different households might face acute affordability problems and how to design well-targeted tariffs and customer assistance programs in Wukro.

4.2. Management of intermittent urban water supply for improving equity

The study highlighted spatial inequities in water service delivery which was demonstrated by the occurrence of more marked intermittent water supply in certain areas. While this spatial inequality of water supply can be a result of several underlying factors, such as insufficient water resources or production, poor financial management, poor maintenance of equipment, absence of a non-revenue water management strategy or even weak human resources, this research study has not assessed these factors in detail. It is, however, clear that the utility should be able to address these inequities by investing in its management system.

Specific national policy guidelines for intermittent urban water supply systems, that currently do not exist in Ethiopia, should be developed. Urban residents living with intermittent water supply services need: (a) reliability and (b) safety, of paramount importance. First, although intermittency is very common, unreliability and unpredictability do not need to be. For example, residents in Addis Ababa report being informed of knowing when their house/neighbourhood will receive water through the taps, and it arriving as planned (*personal experience of co-authors*). This shows that water service rotation can be effectively designed to remove some of the uncertainty around household water access. Second, intermittent water supply systems require strong water quality monitoring (Kumpel and Nelson 2016) and there must be strategies for intermittent water supply systems in water safety planning.

Our study shows that there is an important consideration to be made around policies to support access to, and management of, household-level storage. However, this is not straightforward. In terms of increasing equity, we found that storage is strongly correlated with wealth groups, indicating that the poorest are disadvantaged in accessing household water storage infrastructure. As we saw in Dedebeit, despite the most regular water supply through the tap, households in that kebele were highly water insecure and the least likely to have access to storage. This indicates that increasing access to household level storage may go some way to improving household water security. Additionally, there are significant water safety implications for increasing household level water storage, with water quality deteriorating with storage time. Kumpel and Nelson (2013) have found that stored water was more contaminated than water through the taps in both intermittent and 24×7 water supply systems, hence any policy to increase household level water storage would need water quality monitoring and support for households in appropriate safe storage management. Finally, the other issue with household level storage is that: when increasing household level water storage, without increasing the amount of water running through the overall system, the benefits to water access will be limited.

4.3. Supporting the socio-economically vulnerable in systems with intermittent water supply

There must be an increased consideration of the water demands of household entrepreneurs in urban water planning and service delivery. Currently, the impacts of intermittent water supplies on household entrepreneurs, which are female-dominated activities, are not acknowledged, nor prioritized in policy. Since household entrepreneurs are included in urban water demand calculations and projections as simply, 'households', their higher water demands are not being accounted for, having an overall impact on the design and delivery of urban water systems. Moreover, there are no specific mechanisms to support household entrepreneurs to access the water that they need for their livelihoods. As shown with the evidence above, water access for household entrepreneurs has a critical capacity to weigh them down or lift them up, with repercussions for the wider urban economy. There needs to be targeted approaches at both the policy and household level to protect the water security of urban residents conducting enterprise activities at home.

Urban water planning for SDG 6 should emerge from two starting-points: (a) Preventing improvements in urban water security from exacerbating existing inequities and, ideally, (b) reducing inequity. The first step in this process should be to examine, include, and evaluate the various impacts of water security on

¹² Faced with intermittent supply and seasonal water shortages, households in Wukro were obtaining water from alternative sources and reported paying an average of 120 birr m⁻³ (2.35 USD).

different vulnerable groups throughout implementation. Measuring access to household piped water connections, or regularity of tap water access on premises, does not capture inequities in climate resilience which is strongly related to socio-economic indicators. There are inequities across social groups, with household entrepreneurs and residential tenants being at a particular disadvantage. Water security is experienced and viewed differently by landlords, owners, tenants, and those who run businesses out of their homes. The importance of water security on socially insecure single mothers who lead their water dependent business is paramount in multiple areas of economic security, wellbeing, surviving and supporting family. Key index groups should be identified within urban water programmes to assess the impact on the most vulnerable. In Wukro, and likely in many other small towns, single mothers leading water dependent entrepreneurial activities would be one such index group. For these specific groups, water security should be viewed beyond water infrastructure, but as a unique opportunity to improve gender equality (SDG 5) and reduce inequalities (SDG 10).

5. Conclusion

Urban water planning in LMICs must go beyond the physical expansion of household water connections to consider the implications of spatiality, intermittency of supply, and gendered socio-economic vulnerability to deliver equitable urban water security. Piped water supply is the best form of service compared to others, but alone, is not enough. We have demonstrated how inequities are (re-)produced and experienced within an urban piped water system. Piped water connections on household premises do not automatically result in reliable, safe drinking water access, nor equitable water security, since considerable spatial heterogeneity in water insecurity can still occur. This research highlights that household occupancy status, and whether a household is engaged in entrepreneurial activities at home, are key social considerations for policy makers in working towards reducing inequity in water access in urban areas. Moreover, sustainable financing, climate resilient service delivery management and access to household-level water storage play significant roles in mediating equitable urban water security. This study shows how to strengthen urban water development planning in LMICs while reducing inequities in water security.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Acknowledgments

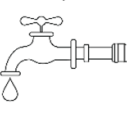


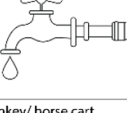









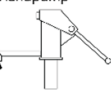



We would like to thank the residents of Wukro town for their participation in this study and they are in our thoughts while we remain hopeful for a swift return to peace in Tigray. Without the Health and Demographic Surveillance System (HDSS) at Mekelle University and the other Ethiopia research staff that were employed to collect this data or were participating in other important studies that were crucial for understanding Wukro's water security. Particularly, we would like to thank Dr Kelemework Tafere, Leake Zegeye, Chekol Hadis, Tsegazeab Abadi Moges and Tsiden Abadi, as well as, Dr Zenawi Zerihun, Amleset Gebreegzabher and Samrawit Mebrahtu.



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Appendix A. Water diary design

A water diary study was conducted to capture household water use behaviour and expenditures every day for a 46 week period starting 22 September 2018. The diary design was guided by similar studies in Kenya and Bangladesh under the same research project (Hoque and Hope 2018, 2020). The diaries were structured as pictorial charts divided into three sections, with section 1 comprising columns on water sources, amount, cost, and collection responsibilities, section 2 including charts on sufficiency for drinking, washing, bathing, agriculture and livestock related activities, and section 3 recording household expenditures for food, water, energy, education, health, enterprise, transport and other items (figure A1) participating households were provided with hard copies of the diary sheets and trained to fill them up every day for a one-year period, which was later truncated to 46 weeks due to logistic challenges. The diary design ensured that participants








SECTION 1. WATER SOURCES AND PAYMENTS

Where did your HOUSEHOLD collect water TODAY?	How many CONTAINERS did you collect?	How much did you pay for water today?	Who collected the water?
None			
Own water tap at home 	 _____  _____		Man Woman Boy Girl
Borrow/ purchase from neighbour 	 _____  _____		Man Woman Boy Girl
Donkey/ horse cart 	 _____		Man Woman Boy Girl
Motorised vehicle 	 _____		Man Woman Boy Girl
Tanker truck 	 _____  _____		Man Woman Boy Girl
Handpump 	 _____		Man Woman Boy Girl
Rainwater harvesting 	 _____		Man Woman Boy Girl

Where did your HOUSEHOLD collect water TODAY?	How many CONTAINERS did you collect?	How much did you pay for water today?	Who collected the water?
	Collecting water from the river  _____		Man Woman Boy Girl
	Washing/ bathing at the river		Man Woman Boy Girl

SECTION 2. WATER SUFFICIENCY

Did your HOUSEHOLD have SUFFICIENT water for TODAY's needs?

Drinking	Cooking	Laundry / dish washing	Washing/ bathing	Livestock	Small-scale irrigation	Enterprise
						

SECTION 3. WEEKLY FINANCIAL EXPENDITURES

Expenditure Items	Expenditure (Birr)
Food (food bought for eating)	
Farming (crop & livestock) (fertiliser, tools, seeds, labour, purchase animals, etc.)	
Transport (easy bike, bus fare, vehicle maintenance)	
Health (medicine, doctor fees, etc.)	
Education (school fees, uniforms, books, pens, etc.)	
Energy (electricity, kerosene, fuel wood, etc.)	
Water for domestic and productive uses (cost of water, maintenance of infrastructure)	
Small enterprise	
Others	
Total	

Figure A1. Water diary charts filled by households in Wukro.

required minimal education to fill them up, limiting entries to ticks/ crosses or numbers where applicable. They were translated to Tigrinya, the language spoken in the Tigray region of Ethiopia.

A.1. Sampling and training

A stratified random sampling using ArcGIS 10.6 was used to recruit households from the HDSS 2016 sampling frame, ensuring equal representation from the four wealth classes and spatial distribution across the town. The initial list had 120 households, with an additional 30 as back-up in case those from the main list declined to participate. Selected households were contacted via phone or in-person visits and invited to attend a training session in groups of 30 households. Those attending the training sessions, which were facilitated by five researchers from Mekelle University, were asked to maintain the diaries for a one-week pilot period, after which the researchers visited all households to collect the diary sheets and address queries and errors in entries.

A.2. Data submission

The main study commenced with 117 households, of which 18 households dropped out over the course of the study period. While 99 households participated till the end of the study period, the data analysis included all households that participated at least 35 weeks, that is equivalent to 113 households. Participating households were given grocery items worth Birr 250 at the end of each month as a token of appreciation. During the study period, the research team visited all the households every two weeks to ensure data quality, collect completed sheets and distribute new ones. Following collection, the diary data were entered into a digital survey platform (ONA, www.ona.io) by the researchers and quality checked.

Table B1. Checking for internal coherency in the distribution of variables not included in the FSA.

Variables	Household water security Low to High			
	1	2	3	4
Percentage of households surveyed ($n = 676$)	19.5%	23.2%	22.6%	34.6%
Number of months during which at least one activity was stopped due to water scarcity	3.7	1.0	0.2	0.0
Number of drinking water sources used in the DRY season	2.7	2.0	1.5	1.2
Used tanker truck water for drinking in DRY season	17%	1%	0%	0%
Borrowed water from neighbour for drinking in DRY season	7%	4%	2%	1%
Bought water from neighbour for drinking in DRY season	49%	33%	39%	13%
Used tanker truck water for drinking in WET season	9%	0%	0%	0%
Borrowed water from neighbour for drinking in WET season	8%	4%	2%	1%
Bought water from neighbour for drinking in WET season	47%	29%	39%	12%
Goes to river for washing oneself	25%	2%	2%	0%
Goes to river for washing clothes	43%	4%	2%	0%

Appendix B. Water Security Index development

B.1. Calibration and aggregation

An FSA technique based on Cheli and Lemmi (1995)'s frequency-based method was used to calibrate the five variables and assign weightages (internal coherency was checked - see table B1). The calibration process converts the variables into a continuous set of deprivation scores, whereby 0 indicates no deprivation and 1 indicates full deprivation (or higher water insecurity). The weightage is assigned using the formula $w = \ln [(1/n) \cdot \sum \mu(x)]$, whereby $\sum \mu(x)$ is the summation of the deprivation scores of all households for variable x , n is the total number of households, and w is the weightage for that variable. One of the strengths of this method is that it assigns lower weightages to those variables in which higher number of households are deprived. For instance, of the 676 households included in the calculation, 62% were deprived in terms of storage, meaning that they had a combined storage capacity of less than 200 l. Hence, storage was assigned a lower weightage of 0.48. In comparison, only 22.8% households were deprived in terms of reliability, that is, they did not use piped water as their main source both in the past year and also in the past week, resulting in reliability receiving a higher weightage of 1.67. Conceptually this indicates that in a context where most people possess a certain asset or enjoy a given service, those that do not have that asset or service will be categorised as highly deprived, making it useful for differentiating between households or people in the study area. The five variables were aggregated to calculate the household water security index, using the following formula.

Water security index for household n ,

$$WSI_n = [(w_1 * \mu(1)_n) + (w_2 * \mu(2)_n) + (w_3 * \mu(3)_n) + (w_4 * \mu(4)_n) + (w_5 * \mu(5)_n)] / [w_1 + w_2 + w_3 + w_4 + w_5]$$

where 1, ..., 5 refers to the five variables, $\mu(1), \dots, \mu(5)_n$ is the deprivation score for household n for the given variable, and $w_{(1), \dots, (5)}$ is the weight assigned to each of the five variables

The values for the water security index (WSI) ranged from 0 to 1, where 1 indicates higher deprivation, or less water secure. To perform disaggregated analysis, households were allocated into four water security categories based on the natural breaks in the WSI values, with 19.5%, 23.2%, 22.6% and 34.6% of households being in the least to the most water secure categories. The accuracy of these calculated indices was ensured by checking for internal coherency in the distribution of other variables not included in the FSA. For example, households categorised as more water secure are less likely to use non-piped sources like tanker trucks, borrowing/ purchasing from neighbours or harvesting rainwater for drinking.

Appendix C. Wealth Index: Tables of variables used for PCA

Variables used for PCA for the wealth index are given in table C1 and their assigned weightage in table C2. All four components with eigenvalues > 1 were extracted, which explained 54.3% of the total variance in the dataset with a Kaiser–Meyer–Olkin Measure of Sampling Adequacy of 0.772. The factor scores of PC₁ were then used to disaggregate the households into four equal wealth quartiles.

Table C1. Correlation matrix of variables used for principal component analysis.

	% of adults with at least primary education	Radio	Television	% of members >13 years with a personal mobile phone	Refrigerator	Floor material	Wall material	Roof material	Number of rooms used for sleeping	Cooking fuel	Bank account
% of adults with at least primary education	1										
Radio	0.041	1									
Television	0.078	0.016	1								
% of members >13 years with a personal mobile phone	0.135	0.086	0.268	1							
Refrigerator					1						
Floor material	0.059	0.083	0.283	0.119	0.224	1					
Wall material	0.135	0.03	0.31	0.162	0.15	0.549	1				
Roof material	0.085	−0.02	0.245	0.133	0.007	0.066	0.007	1			
Number of rooms used for sleeping	−0.009	−0.02	0.045	0.024	0.274	0.14	0.119	0.007	1		
Cooking fuel	0.028	0.059	0.204	0.069						1	
Bank account	0.099	0.055	0.347	0.18	0.313	0.401	0.279	0.031	0.225	0.258	1
	0.151	0.082	0.297	0.186	0.189	0.235	0.208	0.023	0.139		

Table C2. Weightage assigned to variables used for calculation of household wealth index.

Variables	Weightage (Factor loadings of the first principal component)
Percentage of adults with at least primary education	0.257
Radio	0.125
Television	0.650
Percentage of members >13 years possessing a personal mobile phone	0.418
Refrigerator	0.535
Floor material	0.699
Wall material	0.602
Roof material	0.072
Number of rooms used for sleeping	0.413
Cooking fuel	0.678
Bank account	0.541

Appendix D. Supplementary data tables

Table D1. Wealth quartiles by kebele.

	Agazi	Dedabit	Hayalom	Total
n	319	69	89	477
Q1 lowest	23.2%	30.4%	12.4%	22.2%
Q2	27.3%	34.8%	20.2%	27.0%
Q3	24.5%	14.5%	24.7%	23.1%
Q4 wealthiest	25.1%	20.3%	42.7%	27.7%

Table D2. Water security index by kebele.

	Agazi	Dedabit	Hayalom	Total
n	424	110	142	676
Least water secure	14.2%	52.7%	3.5%	18.2%
2	21.2%	18.2%	18.3%	20.1%
3	30.0%	14.5%	41.5%	29.9%
Most water secure	34.7%	14.5%	36.6%	31.8%
Less deprived for				
Safety	61.3%	28.2%	60.6%	55.8%
Sufficiency	77.6%	31.8%	92.3%	73.2%
Storage	33.0%	12.7%	73.9%	38.3%
Piped reliable	76.9%	94.5%	63.4%	76.9%
No sources	63.2%	28.2%	72.5%	59.5%

Table D3. Household use of rainwater by kebele.

	Agazi	Dedabit	Hayalom	Total
Use of rainwater for at least one domestic activity	88.9%	94.9%	92.3%	90.6%
Drinking	2.7%	6.8%	2.1%	3.3%
Cooking	18.4%	59.3%	11.2%	23.8%
Cleaning	83.4%	78.0%	89.5%	83.7%
Bathing	43.6%	50.8%	23.8%	40.8%

Table D4. Satisfaction with household water.

	Agazi	Dedabit	Hayalom	Total
Satisfied household water needs have been met in last month	64.5%	39.8%	61.5%	59.8%
Of those who were dissatisfied, reasons included				
Unsafe	13.5%	32.4%	0.0%	15.6%
Taste	3.2%	7.0%	0.0%	3.5%
Not available when needed	73.7%	90.1%	80.0%	79.1%
Unknown availability	46.2%	80.3%	3.6%	46.5%
Insufficient	64.1%	93.0%	61.8%	70.9%
Unaffordable	8.3%	81.7%	0.0%	25.2%
Far away	4.5%	71.8%	3.6%	21.3%
Time consuming	3.8%	29.6%	0.0%	9.6%
Of those who were satisfied, would like to see improvements in				
Safer	51.9%	21.3%	27.3%	38.2%
Available all the time	63.8%	46.8%	88.6%	60.9%
Unexpected disruption	39.9%	80.9%	26.1%	37.7%
More water	31.3%	38.3%	27.3%	28.2%

Table D5. Monthly water consumption by wealth quartile (m³/month).

	Obs	Mean	Std. Dev.	Min	Max
Overall	505	5.5	4.0	0.1	34.6
1st wealth quartile	73	5.2	3.5	0.6	16.5
2nd wealth quartile	99	5.5	4.9	1.2	29.7
3rd wealth quartile	84	5.7	3.4	0.3	18.9
4th wealth quartile	99	5.5	3.6	0.1	22.2
No wealth data	150	5.6	4.2	0.4	34.6

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