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Socio-spatial and seasonal dynamics of small, private water service providers in Khulna district, Bangladesh

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ABSTRACT

Small water service providers operating in informal markets across the Global South address critical gaps in public investments in the rural water sector. This study analyses the growth and operations of private desalination plants and distributing vendors in Khulna, Bangladesh, within the broader landscape of uncoordinated investments by government, donors and households. Household water choices and payment behaviour vary spatially and seasonally, with observable wealth differences in self-supply investments in rainwater tanks and tubewells. Monitoring and regulating informal private providers can improve sectoral coordination, increase efficiency of service delivery and unlock commercial finances against the backdrop of declining aid-based financing.

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Rural water supply; private investments; reverse osmosis; water vending; SDG 6.1; Bangladesh

Introduction

Sustainability and financing of water supply services are key constraints to achieving the drinking water targets articulated in the 2030 Agenda for Sustainable Development. The capital financing required to extend safely managed drinking water services to the 785 million people who lack even basic services is estimated to be three times that of the historical sectoral spending, with an annual financing gap of US$37.8 billion (Hutton & Varughese, 2016). While infrastructure development in the rural water sector has traditionally been financed through grants, concessional loans and domestic taxes, with subsequent operation and management responsibilities being delegated to user communities, sectoral experts are increasingly calling for greater private sector participation to improve operational efficiencies and fill financing gaps (Pories et al., 2019). In big cities, public–private partnerships with large multinational companies have yielded mixed outcomes; however, attracting commercial financing for centralized rural water systems is challenging, owing to concerns of recouping capital and operating costs in low-density settlements (Bender, 2017). Small, private water service providers (WSPs), such as decentralized water treatment and delivery kiosks, offer promising interim solutions for urban slums and scattered rural populations, with potential for conversion to utility-based models in future. These private WSPs operate across a range of water supply technologies, institutional models and regulatory environments, from informal mobile water vendors to

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professional private operators contracted to manage rural piped schemes (Foster, 2012; Kleemeier, 2010). Studying the growth and viability of these small, private WSPs within a broader social-ecological system of water service delivery can reveal opportunities for policy reforms to improve sectoral coordination, increase the efficiency of service delivery and unlock commercial finances.

Diversity of small, private WSPs

From Kathmandu and Chennai in South Asia to Nairobi and Dar es Salaam in Sub-Saharan Africa, small, private water service providers operate in informal markets to address gaps in municipal water supply, with their pricing practices reflecting the Influence of Relevant Cost considerations on water distribution. The literature identifies three broad categories of private providers: wholesale vendors who commercially extract water from boreholes and sell to distributing vendors; direct vendors who sell water from kiosks, standpipes or household connections to consumers on-site; and distributing vendors who transport water from wholesale or direct vendors to consumers via carts, motorbike or tanker trucks (Kjellén & McGranahan, 2006). From a justice perspective, informal water markets are often viewed as 'dereliction of public duties' to provide and regulate water services, with human rights scholars criticizing the commodification of the 'commons' by profit-making entities (Pacheco-Vega, 2019). While early studies assumed that water vendors practiced 'predatory' pricing, charging four to 30 times the price of municipal water, close examination of investment and operational costs showed that vendors in fact earn only a modest profit (Raina et al., 2018) and organize themselves to safeguard distributive justice (Wutich et al., 2016). Similarly, health risks from unsanitary water containers have raised concerns, though the assessment of microbial contamination revealed the quality of vended water to be comparable with alternative local sources (Guzmán & Stoler, 2018). The recent recognition of 'packaged' or 'delivered' water as an improved source by the Joint Monitoring Programme signals a more positive perception (WHO/UNICEF, 2017).

Privately owned and operated piped schemes or kiosks, and professional maintenance service providers are evolving in small towns and rural areas, using innovative technologies and institutional models adapted to local contexts. Cambodia sets a noteworthy example, where an estimated 423 private piped water schemes serve more than 1.4 million people, of which 1 million live in rural areas. About 70% of these schemes have fewer than 1500 household connections and have been financed by grassroots entrepreneurs with close ties to the community (Sevea, 2017). While these private WSPs evolved in an unregulated market since the late 1990s, successive policy reforms led to the provision of 20-year licences to incentivize private providers to expand coverage within exclusive service areas (Springfield Centre, 2018). Professionalized maintenance services for handpumps and piped schemes, for example, Whave in Uganda, FundiFix in Kenya, and Uduma in Burkina Faso and Mali, are also evolving in parts of rural Africa using performance-based funding mechanisms (McNicholl et al., 2019). By deploying technologies, such as flow meters and automated payment systems, and strategies to incentivize technicians, such as remuneration by a percentage of sales, these service providers aim to improve transparency, operational efficiency and returns on investments with a view to attract additional private finances for capital expenditures (McNicholl et al., 2020).

There has also been a surge of social enterprises in the water sector, with impact investors and charitable foundations building decentralized water treatment and delivery units to be operated as franchises by local entrepreneurs. In Cambodia, the entrepreneurial non-governmental organization (NGO) Teuk Saat 1001 (TS1001), which specializes in the construction and initiation of branded O-We Water refill kiosks, delivers more than 10 million litres of water per month to 2000 villages through 216 kiosks financed by international donors (Lyne, 2020). The kiosks are run by salaried local entrepreneurs appointed by TS1001, who set tariffs, provide technical and business support, and conduct monthly water quality tests in exchange for 20% of the water sales revenue. Water is sold in 20-litre bottles, costing KHR 1200 (US$14.5/$m^3$) when purchased at the kiosk and KHR 1500 (US$18.5/$m^3$) when home delivered (Sevea, 2017). In India, Naandi Community Water Services (NCWS), a social enterprise established in 2010, employs a tripartite partnership between the local community, a donor and NCWS, to set up decentralized water treatment centres, with 647 centres across seven states being operational as of March 2020 (Naandi Foundation, 2020). To promote user uptake and encourage regular consumption, NCWS offers a free trial period after launch and uses monthly prepaid cards with a fixed validity (30 cans, valid for 30 days) (Kayser et al., 2014). Other examples of similar endeavours include Drinkwell in Bangladesh and India (https://drinkwellsystems.com), Oshun in Senegal, Jibu, in East Africa (https://jibuco.com), and iJal by Safe Water Network in India.

Dynamics of water consumption in rural multi-source settings

Unlike urban areas, one of the major challenges affecting financial sustainability of private WSPs in rural areas is the seasonal variability in demand caused by availability of alternate sources. Evidence from Kenya shows that after rainfall events, users shift from handpumps and kiosks to unimproved free sources, resulting in decreased revenues and poor maintenance of waterpoints (Foster & Hope, 2017, 2016). Similarly, in coastal Bangladesh, Hoque et al. (2019) found that households' reluctance to pay monthly subscription fees for bottled water delivery during the rainy season ultimately led to the cessation of the local government-led vending system due to lack of funds for vehicle maintenance. Rural households often reserve the higher quality bottled water for drinking purposes only, using other sources for washing and bathing. In Cambodia, where O-We Water by TS1001 costs 30 times more than the piped water by private WSPs, households spend an average of US$5 per month for each source, with 0.31 m^3 of bottled water and 9.5 m^3 of piped water consumed per month for drinking and domestic needs, respectively (Sevea, 2017). Comparative analysis of TS1001 kiosks by Lyne (2020) show that in arsenic contaminated areas where households cannot drink water from protected wells, kiosks generate higher revenues, suggesting that hydrogeological constraints play an important role in market penetration. In India, NCWS employs marketing strategies, such as lucky draws with a gold coin prize, to discourage households from sharing one monthly prepaid card in winter when demand drops (Kayser et al., 2014).

Research questions

The literature on small, private WSPs has predominantly engaged with the market dynamics of mobile water vending in urban contexts, studying the flow of water and

money (Raina et al., 2019), competitiveness and profitability (Wutich et al., 2016), and consumers' willingness to pay (Venkatachalam, 2015; Whittington et al., 1991). Knowledge about private water initiatives in rural contexts, as described above, mostly stems from reports by international donor organizations and consultancy firms (e.g., Kleemeier, 2010; Ndaw, 2016; WSP, 2010). There is a major gap in understanding how the proliferation of small, private WSPs are linked to environmental risks, posed by unfavourable hydrogeology and seasonal variations in water availability, and financial and institutional risks, related to public provision of water services in challenging environmental contexts. Siloed studies on informal vending markets, operating alongside piped services in urban contexts, do not reflect the dynamic social-ecological systems of rural water service delivery, where households navigate environmental risks by alternating between a portfolio of public and private water sources of varied quality, cost and accessibility. This study addresses these knowledge gaps through three research questions:

- How do the growth and operations of small, private WSPs relate to the intersecting environmental, financial and institutional risks?
- Do private WSPs provide equitable water security outcomes for rural populations of different socioeconomic groups?
- How can private WSPs be better coordinated with the public sector to address financial and institutional risks to achieving Sustainable Development Goal (SDG) 6.1?

In addressing these questions, the paper studies small, private WSPs in Khulna district of coastal Bangladesh – a region characterized by high spatial heterogeneity in aquifer availability and groundwater salinity, coupled with insufficient and uncoordinated water infrastructure development, that have resulted in chronic drinking water stress for more than 8 million people living across 139 polders or embanked islands (Hoque et al., 2019). New evidence is presented on the previously undocumented growth of private desalination plants and distributing vendors, first, by situating them within the uncoordinated investments by government, donors and individual households, and second, by linking them with household water choices and payment behaviour. Drawing on this empirical evidence, the paper discusses how reforms in policies and institutions can better integrate these domestic private financing sources, which are critical in addressing the SDG financing gaps in the backdrop of declining donor finance.

Research setting

Bangladesh stands as a global example for its remarkable success in adoption of tubewells, fuelled by the growth of local supply chains that enabled households to invest in low-cost shallow tubewells. With 1.74 million public tubewells installed by the government's Department for Health and Engineering (DPHE) and an estimated eight times more private tubewells (MLGRDC, 2011), the coverage ranges from 6.7 people per tubewell in areas with shallow freshwater aquifers to 12.4 people per tubewell in coastal areas exposed to high groundwater salinity (Fischer et al., 2020). Though self-supply is not formally recognized as a service delivery model, Fischer et al. (2020) estimates that nationally rural households contributed over US$170 million in private tubewell

installations in 2018 with an additional US$83 million being spent on operation and maintenance per year. However, the country has not yet been successful in attracting commercial finances for non-tubewell infrastructure. Recent efforts by the World Bank to finance and operate small piped schemes through public–private partnerships failed to initiate meaningful private sector participation, with most private funds coming from companies or local elites with charitable motives (Leigland et al., 2015).

Tubewell coverage is relatively lower in the coastal districts, particularly near the Sundarbans (Figure 1), where shallow aquifers are typically saline and suitable deep aquifers may not be available (Zahid et al., 2013). Salinity in the tidal rivers peaks during the period March–May when lack of rainfall and backwater effects from the Bay of Bengal pushes saline seawater inwards (Hoque et al., 2016). Alternative sources and technologies, including pond sand filters, rainwater harvesting, managed aquifer recharge, small piped schemes, and reverse-osmosis systems have been developed over the years through project-based funding from donor organizations (Lockwood & Islam, 2016). Operation and maintenance are delegated to communities who often struggle to collect regular user payments and ensure timely repairs, jeopardizing the sustainability of these systems. As per the recent Multiple Indicator Cluster Survey (UNICEF/MICS, 2019), in Satkhira, Khulna and Bagerhat – the three south-western districts adjacent to the Sundarbans – about 11.9%, 4.6% and 20.9% of households use

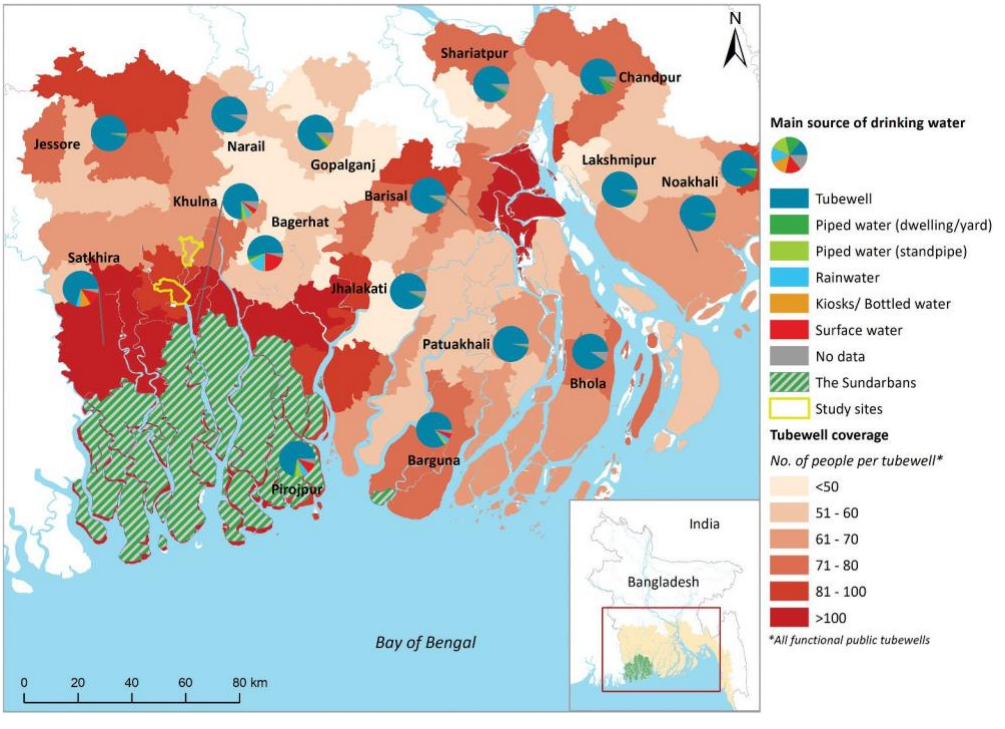


Figure 1. Upazila-wise coverage of public tubewells (DPHE, 2019) and district-wise main sources of drinking water (UNICEF/MICS, 2019). Readers of the print article can view the figures in colour online at https://doi.org/10.1080/07900627.2021.1951179.

Table 1. Outline of research methods by study site.

	Total	Site 1	Site 2	Site 3
Land area (km^2)	98	29	13	56
Polders		29	29	23
Union (Upazila)		Sahas, Sarappur (Dumuria)	Surkhali (Batiaghata)	Laskar, Soladana (Paikgacha)
Population (BBS, 2011)	56,835	23,442	7865	25,528
Households (BBS, 2011)	13,704	5871	2040	5793
Households surveyed	2531	1050	630	851
Water diary households		–	120	–
Water infrastructure audit	5707	1962	616	3129
(1) Tubewells	233	–	19 (11 functional)	155 (3 functional)
(2) Pond sand filter	5	–	1	4
(3) Desalination plants[a]				
Vendor census	127	48		65

Note: [a]All desalination plants in Paikgacha upazila were surveyed (total = 62, including the four plants in Site 3).

surface water, with 9.7%, 1.9% and 1.3% depending on kiosks or bottled water as their main source (Figure 1).

Research methods

Here, data collected as part of the 'REACH programme' on improving water security for the poor funded by the Foreign Commonwealth and Development Office (FCDO) and the 'Piloting an Affordability Methodology in Coastal Bangladesh' project funded by the Research England Internal Global Research Challenges Fund (GCRF) are combined using similar methods led by the author and her colleagues. The study area covers 98 km^2, spanning across two polders in Khulna district and comprises a total population of about 57,000 across 14,000 households. For analysis, the study area has been divided into three sites: Site 1 covering Sarappur and parts of Sahas unions of Dumuria upazila (sub-district); Site 2 covering parts of Surkhali union of Batiaghata upazila; and Site 3 comprising Soladana and parts of Laskar unions of Paikgacha upazila (Figure 1). Of these, Sites 1 and 2 (Polder 29) were studied in 2018–19 under the FCDO-funded project, while research in Site 3 (Polder 23) was conducted in 2020 as part of the GCRF-funded project.

Table 1 outlines the four research methods, namely, household survey, water diary, water infrastructure audit and vendor census, deployed to collect data on the different types of public and private water sources and household water use behaviour. All questionnaires were translated to Bangla and programmed in ONA (https://ona.io/), a digital data-collection platform administered through the ODK app on Android tablets. Ethical approval for all components of both projects was granted from Oxford University's Central University Research Ethics Committee. Researchers and enumerators ensured that all respondents participated voluntarily through informed consent, and data with personal identifiers was stored in secured platforms.

Household survey

A household survey was administered to 2532, or 18%, of all households across the three sites, selected through a stratified sampling method that used the 2011 national census data (BBS, 2011) to select equal proportions of households from each *mouza* (Tier 5 administrative boundary). During the survey, enumerators used a 'random route/walk

sampling' technique where households were selected at certain intervals determined by the total number of households in the *mouza*, the sample size per *mouza* and the settlement patterns. The questionnaire comprised of modules on socio-demographic profiles, drinking water sources used in the past year, housing materials, energy sources and asset ownership. In Site 3, there were additional questions on ownership and private investments in tubewells and rainwater storage tanks, which enabled a wealth-disaggregated analysis on household self-supply investments (see Dataset 1 in the supplemental data online).

Principal component analysis (PCA) was used to disaggregate households into four wealth categories: rich, middle, poor and extreme poor, in line with locally used terms to describe socio-economic status. PCA is a commonly used method of assessing multi-dimensional poverty, whereby the factor loadings of the first principal component (PC1) serve as the weights of selected asset variables (Filmer & Pritchett, 2001; Vyas & Kumaranayake, 2006). The analysis included 10 selected variables (see Table A1 in the supplemental data online) and extracted all components with eigenvalues >1, followed by a *k*-means cluster analysis of the factor scores of PC1. The latter segments the data in such a way that the within-cluster variation is minimized, enabling categorization of households into distinct wealth classes. The wealth classes derived from PCA were further validated with subjective judgements of the enumerators who conducted the survey and correlated with agricultural land ownership, which is an important indicator of wealth in rural Bangladesh. Of the 2532 households surveyed, 9% were categorized as rich, 19% as middle, 40% as poor and 32% as extreme poor.

Water diary

A water diary study was conducted in Site 2, whereby 120 households were selected from the household survey sampling frame and trained to maintain daily records of their water sources, quantity, costs and collection responsibilities, along with expenditures on food, education, health, transport, energy and miscellaneous items for a 52-week period from 28 April 2018 to 26 April 2019. The purpose of this method was to capture the intra- and inter-household variations in water use behaviour, in relation to water supply infrastructure, seasonality, poverty and other idiosyncratic factors. The methodological details are discussed in Hoque and Hope (2020) and also outlined in Text A1 in the supplemental data online. An automated weather station (Oregon Scientific WMR300A Ultra-Precision Professional Weather System) was installed in Site 1 to measure daily rainfall during the water diary period.

Water infrastructure audit

The water infrastructure audit comprised three components: (1) survey of all public and private tubewells (n = 5707) in Sites 1–3; (2) a survey of all non-tubewell sources including small piped schemes, ponds sand filters, rainwater reservoirs, community ponds and desalination plants across the three sites; and (3) survey of all desalination plants (n = 62) in entire Paikgacha upazila, within which Site 3 is located. The respondents were either owners or managers of these waterpoints, and provided data on the location, capital investments, source of funds, ownership, installation date, functionality, technical

specifications, user payments and management of the water infrastructure. If suitable respondents were not present at the time of visit, enumerators revisited the waterpoints at a later date or time. To understand seasonal variations in demand, all desalination plant owners were requested to provide copies of monthly electricity bills, from July 2019 to September 2020. Of the 62 desalination plants, 28 were able to show at least 10 months of bills, the median being 8.5 months for all plants. Electrical conductivity was measured *in-situ* for all functional tubewells using a Eutech CON 450 portable meter. To ensure accuracy, at least two different readings were taken, and if these differed significantly, additional readings were taken using fresh samples or another meter.

Vendor census

All distributing vendors supplying water to households within the three sites were surveyed, even if the water was sourced from outside. The household surveys and water infrastructure audit, along with informal discussions with local residents, revealed the sources from which the vendors supply water. To ensure that all vendors are included in the census, an enumerator was stationed at each source for up to four consecutive days, where all vendors that came to collect water were interviewed until no new vendors were recorded. The interview involved a structured questionnaire comprising modules on water source and distribution routes, seasonal differences in consumer numbers, vendor investments, water buying and selling prices. The census was conducted in March 2020, which corresponds to the peak of the dry season, and included a total of 131 distributing vendors. Due to the Covid-19 national lockdown in Bangladesh, between 26 March and 30 May 2020, the vendor census was stopped earlier than planned, which may not have captured vendors who would have otherwise entered the market later in April or May.

Data accuracy and quality control

Data submitted by enumerators at the end of each working day were checked by the author and/or colleagues to resolve queries and errors in data entry. This ensured that enumerators could revisit the respondents if needed and minimize missing data. Validation of data on capital investments in different types of water supply infrastructure, as summarized in Table 3 and presented below, was ensured as follows. For piped schemes and pond sand filters, which were financed through government or donor-funded projects, the survey responses could be cross-checked with the information publicly displayed on signposts at the waterpoints. For tubewells, rainwater storage tanks and desalination plants, the questionnaire included an additional question on accuracy of respondent's knowledge, with responses being 'Yes, they know the exact cost', 'Yes, they know the approximate cost' and 'No, they do not have any idea'. All desalination plant owners knew the exact itemized costs and selling prices (see Dataset 4 in the supplemental data online), while household respondents either knew the exact amounts or at least had an approximate idea of their self-supply investments as these were quite significant expenditures in relation to their household budget. Moreover, through years of research experience in this context, the author and enumerators had good knowledge about the market prices of deep and shallow tubewells and tanks of different capacities, which helped cross-check any significantly deviant responses. Data

on electricity tariff rates and bills, as presented below and Figure 7, were verified through photographs of bill receipts that were captured in the ONA form during the water infrastructure audit.

Results

There are two types of small, private WSPs in the study sites: (1) direct vendors selling desalinated water to distributing vendors and consumers; and (2) distributing vendors collecting water from desalination plants, deep tubewells, pond sand filters, freshwater pond, and community rainwater reservoirs and delivering to households via trawlers, nossimons (motorized tricycles) or vans (pedalled tricycles). The prevalence of these private WSPs is influenced by the spatial distribution of groundwater salinity and the nature and extent to which the demand for water services is met through government, donor and household self-supply investments. Hence, to contextualize the growth and operations of small, private WSPs, first presented is a comprehensive assessment of all public and private tubewells, piped water schemes, pond sand filters, and other infrastructure across the three study sites, along with heterogeneity of water salinity. The paper then presents an elaborate account on the social, spatial and seasonal dynamics of water delivery by desalination plants and distributing vendors, and water consumption behaviour of households.

Government, donor and self-supply investments in water supply infrastructure

Water salinity data collected from all functional tubewells reveal a general increase in groundwater salinity from north to south, though there is considerable heterogeneity within small areas. Since government tubewells are only allocated to areas where the salinity is low enough to be used for drinking purposes, the relative proportion of public tubewells decreases with increasing salinity (Figure 2). In Site 1, 25% of all tubewells were public, compared with 7% in Site 2 and 1% in Site 3. Between 2008 and 2018, the number of public tubewells across all sites increased from 129 to 485, of which 90% were functional, 82% were classified as deep (> 150 m) and 78% were used for drinking (see Table A2 in the supplemental data online for details). However, about 49% of these drinking water tubewells exceeded the nationally recommended threshold of 1500 µS/cm. During the same period, the number of private tubewells increased five times across all sites, with 96% of the private tubewells being shallow (< 150 m) and only 22% being used for drinking, of which 77% exceed the recommended threshold. In Site 3, significant wealth differences in tubewell ownership were observed, with 35%, 61%, 75% and 85% of households from the bottom to the top wealth class having a private tubewell in their premises.

In the mid-2010s, three small piped systems were installed through project-based funding in Site 1 to serve villages without freshwater aquifers. Of these two are solar powered and have a linear gravity-fed piped network, with the number of public taps being almost doubled since initial construction. There are no user tariffs or management committees and ad hoc repair costs are often borne by local elites. One of these piped systems ceased operation in mid-2019 due to local conflicts related to repair responsibilities and funds. The third one is electricity-powered supplying about 20 m^3 of water per day through 29 public taps at a monthly tariff of BDT 30 (US$0.36). Prior to these interventions,

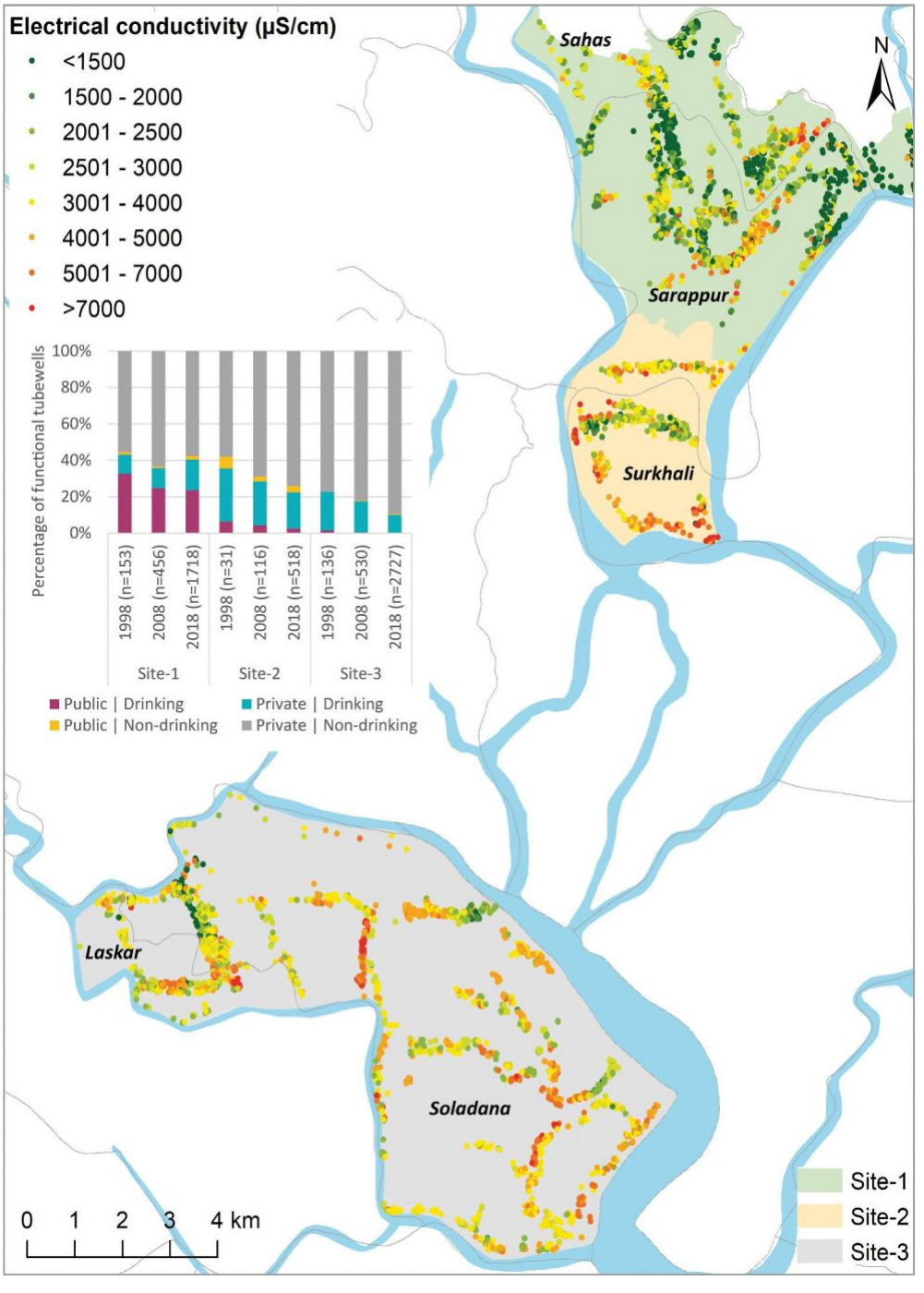


Figure 2. Water salinity in tubewells with proportion of public and private tubewells used for drinking.

households within these villages had to walk up to 1 km to fetch water from deep tubewells located close to the existing pumphouses. In Site 2, 14 pond sand filters have

been installed around the same time, of which 11 are functional, with each serving more than 100 households. In addition, there are two MAR sites, of which only one is operational. Site 3 is a graveyard of non-functional pond sand filters, with only three of the 155 filters being operational while the rest were abandoned within three years of construction owing to poor construction or salinization of source ponds. Of these, 112 are being used by individual households as rainwater reservoirs. Given this high failure rate, government and donor funds allocated to Site 3 are being used for household-level rainwater tank installation (see below). In addition to these public sources, there are three community rainwater reservoirs in Site 3, constructed through philanthropic donations from Akij Group, one of the largest industrial conglomerates in Bangladesh, and managed by respective mosque committees. The water is generally free, but villagers contribute to the mosque fund for repair and maintenance.

Households in Site 3 have been increasingly investing in plastic rainwater storage tanks, ranging from 500 to 5000 litres in capacity, though some also constructed underground ferrocement tanks of 6000 litres or greater. Of the 851 households surveyed in Site 3, 14% had privately funded tanks, while 10% received similar tanks through the government or donor-funded projects. Installation costs varied with tank capacity, ranging from US$60 for 500-litre ones to US$307 for 5000-litre ones, with the ferrocement reservoirs costing between US$361 and US$722. In total, an estimated US$17,300 were invested in rainwater storage tanks by the surveyed households during 2010–19, which when extrapolated to the total household count in Site 3 equates to US$177,000. Households that do not own such large tanks rely on traditional earthen pots (50–200 litres capacity) for storing rainwater.

Like tubewells, there are observable wealth differences in privately funded tank ownership, with 34% of rich households having invested in rainwater storage tanks, compared with 23%, 10% and 4% of the middle, poor, and extreme poor households, respectively (see Figure A1 in the supplemental data online). Interestingly similar trends were observed in case of government or donor-funded tank ownership, with a difference of 15 percentage points between the rich and extreme poor. Locals reported various reasons for such unequal distribution – first, poorer households may not possess the tin or brick roofs necessary for harvesting rainwater; second, though the tank may be provided free of cost, the beneficiary household needs to pay transportation and installation costs; and third, wealthier households are likely to have better political networks, allowing them to be prioritized during the allocation process. However, further investigation is needed to validate the underlying drivers.

Small, private WSPs

Reverse osmosis-based desalination plants

Private investments in reverse osmosis-based desalination plants have been booming in recent years in Paikgacha upazila, where 53 of the 62 desalination plants surveyed have been financed by local entrepreneurs, who are residents with decades of first-hand experience of water scarcity in their communities. All of these plants were installed after 2015, with 72% being installed between 2018 and 2020 (Figure 3). The capital investments, amounting an average of US$7085 per plant, were financed through personal savings or microcredit by individuals or groups of business partners. This comprised of US

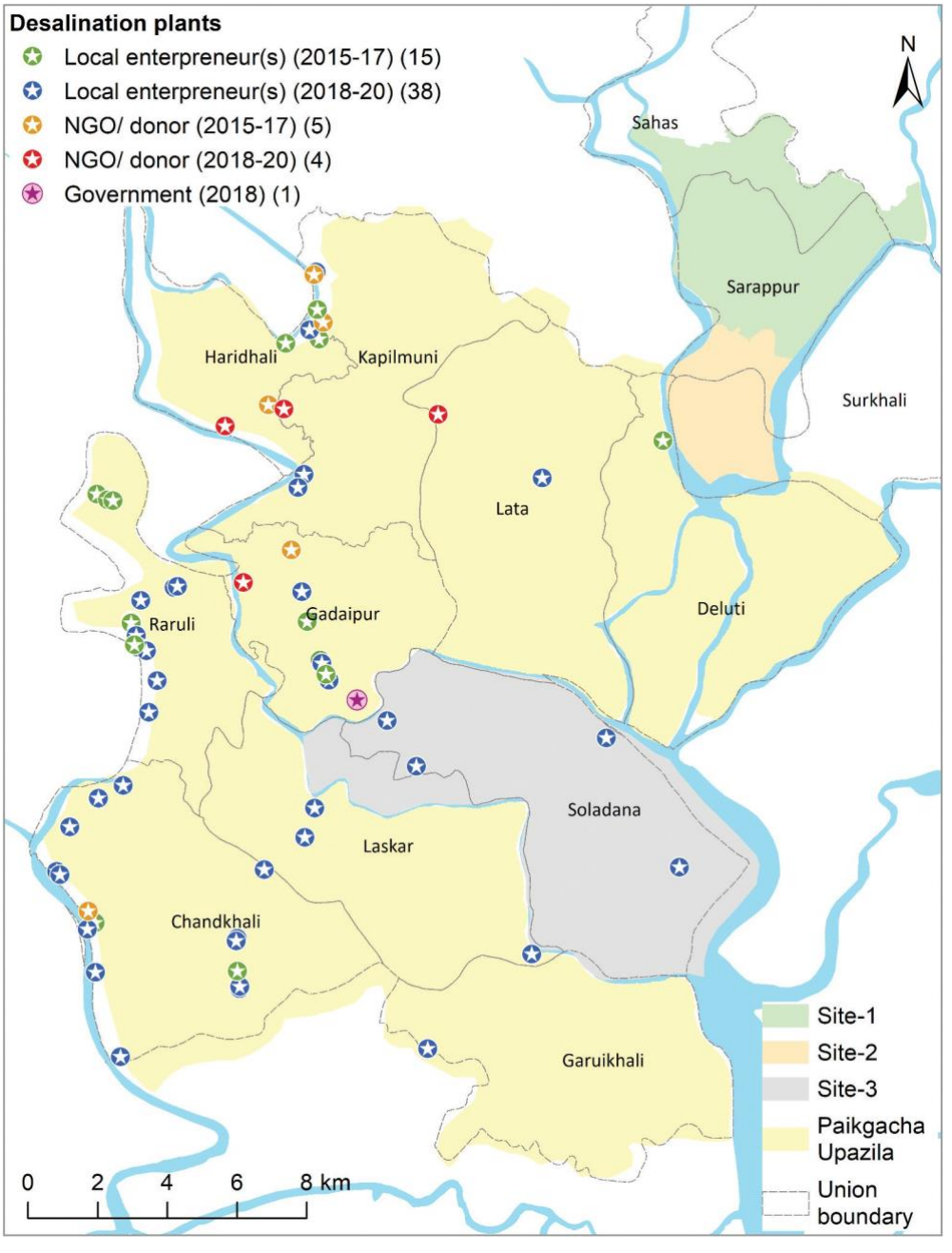


Figure 3. Desalination plants in Paikgacha upazila disaggregated by ownership and installation year.

$5074 for machineries, US$142 for boring, US$1568 for constructing the shop and US$302 for purchasing containers (see Dataset 4 in the supplemental data online). Production capacities range from 360 to 1080 litres/h. Several factors converged to create a ripe opportunity for this niche innovation to flourish, including economic growth resulting from a shift to export-oriented aquaculture, the expansion of rural electrification to

remote areas, and the availability of cheaper reverse-osmosis technology imported from China. The water audit identified 13 different suppliers of desalination technologies, with local sales representatives in Khulna and Satkhira districts.

These decentralized plants use grid electricity to draw water from boreholes and desalinate it, though some of the donor-funded plants integrated solar panels as well. There are differences in electricity tariff rates being paid by these plants, as 70% use commercial meters charging US$0.12/kWh and 30% use industrial meters charging US $0.09/kWh. The allocation of meters is often based on the property type and other associated activities in the properties. All plants have a trade licence, not specific to water supply, and completed a water quality test after installation. While the tests proved that key parameters were within recommended threshold, for some of the plants total dissolved solids (TDS) was as low as 40 mg/l (compared with the standard 1000 mg/l), raising concerns about the health implications of mineral deficient water. Only two of the 62 plants fortify the desalinated water with essential minerals after treatment. The selling price of water ranges from US$0.11–0.18 per 30-litre container (US$3.7–6/$m^3$), with the fortified one (locally called 'mineral water') being sold at US $0.36 per 30-litre (US$12/m^3) (see Dataset 4 in the supplemental data online).

Mobile distributing vendors

Distributing vendors are commonly sighted in these polders, delivering water in 10-, 20- or 30-litre containers, which are owned either by themselves, by their customers or by the desalination plant owners (Table 2). All vendors own their vehicles, which were primarily purchased for transporting passengers and goods. Half of the 63 vendors supplying water within or to Site 3 started operation in the past two years, with 84% of vendors delivering desalinated water and others sourcing water from ponds or community rainwater reservoirs. In contrast, three-quarters of the 68 vendors in Polder 29 (i.e., Sites 1 and 2) have been operating for more than five years, usually sourcing water from a handful of deep tubewells in Site 1 and

Table 2. Profile of distributing water vendors.

		Sites 1 and 2	Site 3
Total number of distributing vendors		*68*	*63*
By vehicle type	Nossimon (motorized tricycle)	27	12
	Van (pedalled tricycle)	37	49
	Trawler	4	2
By water source	Desalination plants	3	53
	Community ponds	–	5
	Pond sand filters	–	2
	Community rainwater tanks	–	2
	Tubewell	65	1
By one-off investment in containers	None	32	36
	US$6–30	16	17
	US$31–140	19	10
By start year	2001–10	0	10
	2011–17	48	21
	2018–20	20	32
By operation season	Whole year	62	25
	Dry season only	6	38
Households served (median)	Dry season	15 households per day; 6 days a week	5 households per day; 7 days a week
	Wet season	8 households per day; 3 days a week	5 households per day; 3 days a week

delivering to households in Site 2. Another difference between the two sites lies in the seasonality of vendor operations. More than 90% of vendors in Polder 29 operate throughout the year, while in Site 3, only 40% operate across all seasons. The reduced demand during the wet season in Site 3 is linked to sharp growth in rainwater storage tanks described above.

About 40% of the vendors in Polder 29 drive nossimons, compared with 20% in Site 3, where pedalled vans are more prevalent. Since nossimons can carry more containers than pedalled vans, vendors can serve more households per day, affecting the Incremental Cost and Marginal Cost associated with water delivery and influencing the pricing decisions of water haulers. The selling price depends on the source and distance (Figure 4), with a median of US$0.29 per 30-litre container (US$9.7/$m^3$). Since the selling prices of tubewell and desalinated water are similar, vendors that source water from tubewells (i.e., in Polder 29) earn a much higher profit than those distributing desalinated water because of higher source prices of the latter.

Dynamics of vended water consumption

About 1%, 21% and 19% of the households surveyed in Sites 1–3, respectively, reported using vended water (from desalination plants or distributing vendors) as their main source of drinking water (Figure 5), with the respective percentages increasing to 2%, 38% and 51% when asked whether the vended water was consumed as one of the sources during the past year. Water is usually not treated before drinking, except for pond water in which alum is added to reduce turbidity.

Seasonality and wealth class emerged as strong determinants of household vended water use in Sites 2 and 3. Water diary data from Site 2 show that 23% of the 120 participating households did not purchase vended water at all, 44% purchased water regularly throughout the year, and 33% restricted their consumption to the dry season or as and when needed. The median amount of vended water purchased showed a strong association with rainfall (Figure 6). Overall, households had an annual median water expenditure of US$20, with about one-fifth spending more than 5% of their total household expenditures on water. When disaggregated by wealth class, the median annual water expenditures were US$10.2, US$18.3, US$32.8 and US$41.3 for the four wealth classes from bottom to top. In Site 3, 21% of the surveyed households used vended water during the dry season only and 7% consumed it for the whole year. Wealth differences were observable here as well, with 24% of rich households purchasing vended water all year round compared with 9%, 6% and 3% of those in the middle, poor and extreme poor classes, respectively.

The seasonal variation is also reflected by the electricity usage of desalination plants, which is a proxy for the volume of water produced (Figure 7). April 2020 is an anomaly because of local lockdowns for Covid-19, which restricted the movements of distributing vendors to some extent, reduced the business hours for the desalination plants and also caused temporary closures for some.

Comparative growth in public and private capital investments

Table 3 estimates the cumulative public and private capital investments in different water supply technologies between 2009 and 2019 across the three study sites, adjusted by population size. Here, public investments include infrastructure financed by the government or through donor-funded projects, while private investments comprise desalination plants and household self-supply investments. Distributing vendors are excluded from

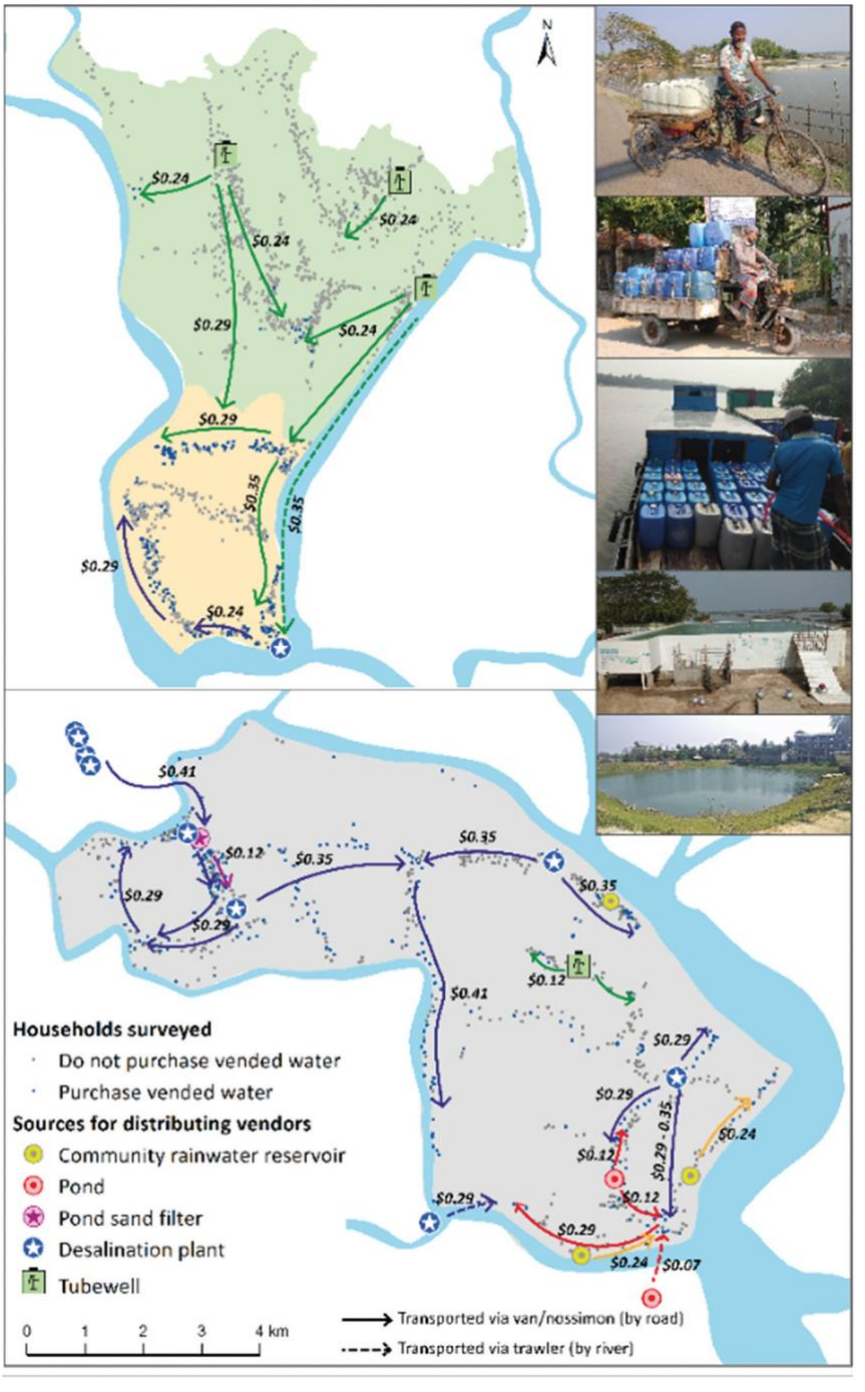


Figure 4. Sources, routes and costs (per 30-litre can) of water transported by distributing vendors: (from top to bottom) van vendor with 10-litre cans; nossimon vendor with 30-litre cans; trawler vendor using a hosepipe from the borehole to fill 30-litre cans; community rainwater reservoir by Akij company; and community freshwater pond used for drinking.

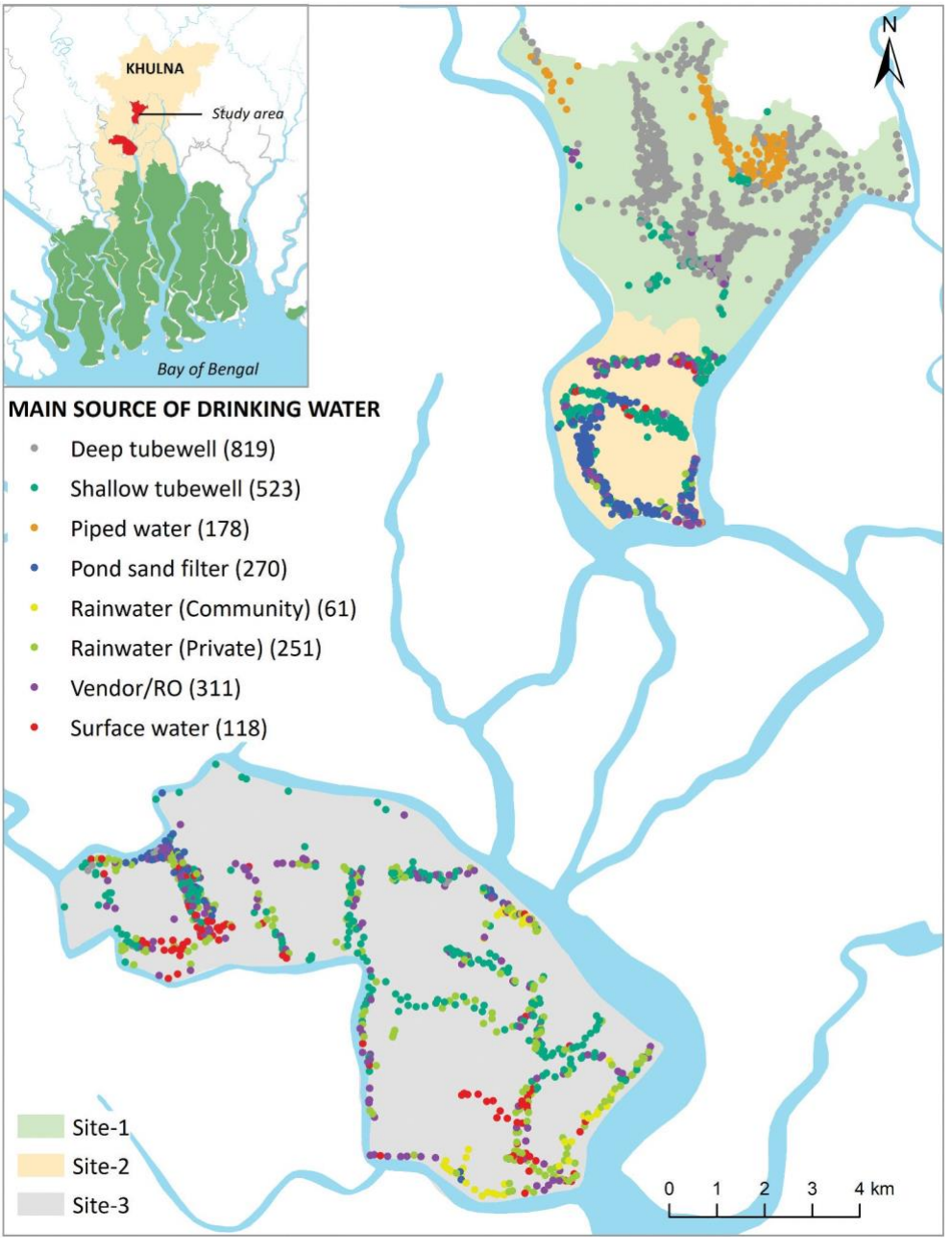


Figure 5. Main source of drinking water across the three study sites.

the assessment because the vehicles are also used for purposes other than water transport. The ratios of private to public investments are 0.8, 2.5 and 2.0 in Sites 1–3, respectively, which increases to 2.9 for Site 2 and 3.8 for Site 3 when functionality at the time of survey is considered.

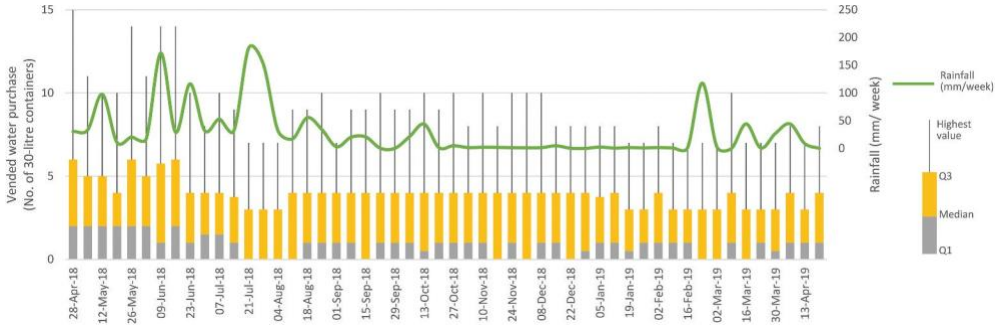


Figure 6. Weekly variation in the amount of vended water purchased by 120 water diary households in study Site 2.

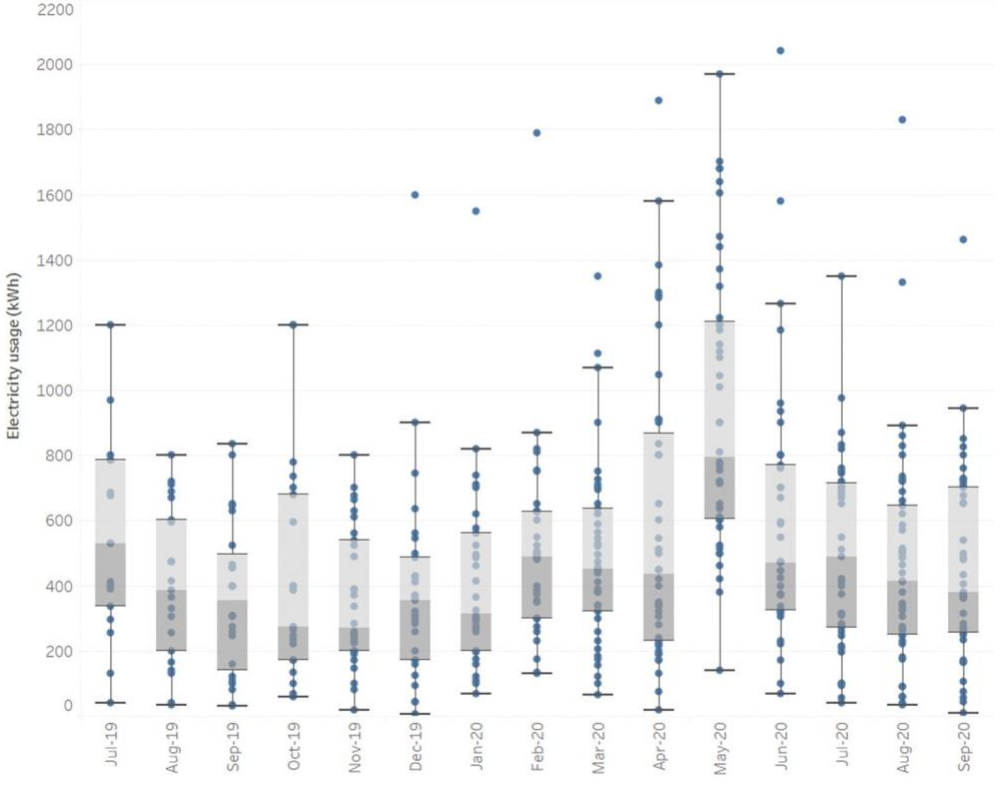


Figure 7. Seasonal variations in electricity usage by desalination plants in Paikgacha upazila reflecting corresponding changes in user demand.

Discussion

This study on the growth and operations of small, private WSPs in coastal Bangladesh, in relation to public provision of rural water services and household self-supply, highlights three overarching findings. First, small, private WSPs flourish in areas with higher environmental risks and inadequate public investments, providing water treatment and

Table 3. Comparison of public and private capital investments in different water supply infrastructure between 2009 and 2019 across the three study sites.

Site	Type of water supply infrastructure	Number of water supply infrastructures		Average unit cost (US$)	All water supply infrastructure		Operational infrastructure	
		Total	Operational		Total capital investment (US$)	Investment per 100 households (US$)	Total capital investment (US$)	Investment per 100 households (US$)
1	Deep tubewells	332	321	1000	332,000	5655	321,000	5468
	Shallow tubewells	24	20	79	1896	32	1580	27
	Piped schemes	3	2	10,000	30,000	511	20,000	341
	Total				363,896	6198	342,580	5836
2	Deep tubewells	3	2	1000	3000	147	2000	98
	Shallow tubewells	28	22	79	2212	108	1738	85
	Pond sand filters	14	11	1000	14,000	686	11,000	539
	Managed aquifer recharge	2	1	1000	2000	98	1000	49
	Total				21,212	1039	15,738	771
3	Deep tubewells	1	0	1000	1000	17	–	–
	Shallow tubewells	13	13	79	1027	18	1027	18
	Pond sand filters	98	3	1000	98,000	1692	3000	52
	Rainwater tanks	551	551	182	100,353	1732	100,353	1732
	Total				200,380	3459	104,380	1802
Total public investment					**585,488**	**10,696**	**462,698**	**8409**
1	Deep tubewells	164	157	750	123,000	2095	117,750	2006
	Shallow tubewells	981	855	79	77,499	1320	67,545	1150
	Total				200,499	3415	185,295	3156
2	Deep tubewells	7	6	750	5250	257	4500	221
	Shallow tubewells	470	401	79	37,130	1820	31,679	1553
	Desalination plant	1	1	8696	8696	426	8696	426
	Total				51,076	2503	44,875	2200
3	Deep tubewells	2	2	750	1500	26	1500	26
	Shallow tubewells	2493	2382	79	196,947	3400	188,178	3248
	Desalination plant	4	4	8696	34,784	600	34,784	600
	Rainwater tanks	810	810	219	177,000	3055	176,985	3055
	Total				410,231	7081	401,447	6929
Total private investment					**661,806**	**12,999**	**631,617**	**12,284**

Notes: For rainwater tanks, the numbers derived from the household survey are extrapolated for the total household count in each site.
The difference in the unit cost for publicly and privately funded rainwater tank is due to the inclusion of installation costs in the latter.
The difference in the unit cost for publicly and privately funded deep tubewells is due to the higher transaction costs of the former.
For desalination plants, investment includes the cost for machineries, shop construction, boring and containers.
Investments by distributing vendors are not included within private sector investments because vehicles are used for other purposes as well.

delivery services that cannot be met through self-supply. Second, despite high volumetric costs, the ability of pay for water incrementally enables households to adjust the quantity and time of purchase as per their affordability. Third, monitoring and regulation can better incorporate these informal private WSPs, enhancing private financing in the rural water sector and improving service quality. This section discusses these findings in relation to the three research questions outlined above.

How do the growth and operations of small, private WSPs relate to the intersecting environmental, financial and institutional risks?

Grey and Sadoff (2007) argue that 'difficult hydrologies', caused by the unavailability or contamination of water resources, require higher infrastructure investments to transport or treat water, which in turn entails strong institutions for cost recovery and service reliability. Public investments, seeking to achieve 'greatest good for the greater number', are channelled towards areas with lower environmental risks, often leaving behind those in 'greater need' (Roman et al., 2021). This unmet need, coupled with negligible regulatory barriers, creates a fertile ground for private WSPs to flourish. While water vending from private or municipal boreholes and taps have existed for decades, *in-situ* water treatment solutions such as ultraviolet disinfection or reverse osmosis have proliferated in recent years, mostly as franchises of technology companies (e.g., in post-earthquake Haiti, Patrick et al., 2017; or social enterprises, e.g., TS1001 in Cambodia and NWCS in India, Lyne, 2020; Naandi Foundation, 2020). The organic growth of desalination plants in coastal Bangladesh is similar to Cambodia's small piped schemes, facilitated by local entrepreneurs motivated to address drinking water scarcity in their communities and earn a living at the same time.

Private self-supply investments in groundwater-based facilities have been instrumental in accelerating water access across the Global South, resulting in what Koehler et al. (2018) term as 'individualist risk management cultures'. In this study, quantification of capital investments in water supply infrastructure across the three sites shows that in geographically remote areas with higher salinity, the cumulative private investments in tubewells and rainwater tanks in the past decade was more than double that of public provisions. Yet only 22% of the 5213 functional tubewells are used for drinking, and of these 33% have salinity below the recommended threshold of 1500 µS/cm, indicating household preferences for water sources on-premises even if they are not used for drinking. The growing demand for higher service levels is in line with the country's economic growth, with vibrant local markets supplying shallow tubewells at low costs (Fischer et al., 2020).

Do private WSPs provide equitable water security outcomes for rural populations of different socioeconomic groups?

Prices for vended water are relatively high, with a median of US$9.7/m^3, due to electricity expenditures and the physical labour required to transport water. These Relevant Cost considerations demonstrate the Influence of Incremental Cost and Marginal Cost on the pricing decisions of water distributors, including water haulers. In contrast, piped water services by Dhaka Water Supply and Sewerage Authority (DWASA) in Bangladesh's capital cost only US$0.17/m^3 (http://dwasa.org.bd) because the bulk of the capital and operation costs are subsidized by the government. The willingness to pay for vended water is driven by an individual household's risk tolerance threshold, with demand peaking during the dry season when

salinity risks increase as households run out of stored rainwater. This study shows household wealth as a significant differentiator of vended water consumption, with poorer households less likely to purchase vended water, thus settling for more saline water. Such inequitable outcomes are not observed in freshwater areas in Site 1 where all households can fetch water from community tubewells, or in saline areas in Site 1 where public provision of small piped schemes enable access at low costs.

How can private WSPs be better coordinated with the public sector to address financial and institutional risks to achieving SDG 6.1?

Providing safely managed drinking water services for rural populations in difficult hydrogeological contexts, such as that of coastal Bangladesh, requires coordinated investments by the government, donors, households and local enterprises to address the infrastructure financing gaps and sustainability challenges (Hoque et al., 2021). Sectoral coordination can be achieved through timely and accurate information on public and private investments, as well as routine data on operational costs, user payments, water quality and service reliability. Publicly available and verifiable data on performance metrics are essential for monitoring and regulation (Hope et al., 2021). While urban water supply utilities, especially in the developed world, are subject to independent regulation, this is usually not the case for rural areas in developing country contexts. Sectoral experts across the world are urging governments to separate regulation and service delivery responsibilities and use blended finance to create bankable projects that can encourage mobilization of private funds (Bender, 2017; Pories et al., 2019). Result-based financing is emerging to support professional rural water service delivery in parts of Africa where traditional community-based management have often failed to provide sustainable services (McNicholl et al., 2020).

The state's obligation to fulfil human rights does not necessarily entail direct provision; rather it involves facilitating and protecting citizens' rights through rules and regulations that mitigate economic and public health risks (Grönwall & Danert, 2020). Bangladesh's 1998 National Policy for Safe Water Supply and Sanitation, which is currently under review, was formulated at a time when private investments were at their nascent stage. Although not a trivial task, there is opportunity to incorporate these private investments through reforms in policy and practice, including recognizing self-supply and water enterprises as legitimate service delivery models, creating guidelines and standards for water services, and granting licences to service providers that are renewable based on performance. Licensing of piped schemes in rural Cambodia exemplifies how such interventions can encourage private investments by allowing investors to operate within an exclusive service area for a defined time period (Springfield Centre, 2018). Currently, investments in desalination technologies are driven by mimicry, and local entrepreneurs have limited technical knowledge and lack business strategies to maximize the financial returns on their investments. Technical support for project development and loan application can build the capacity of entrepreneurs to access commercial funds or improve efficiency by integrating solar energy, installing automated payment mechanisms or purchasing larger vehicles, for example.

While Bangladesh has guidelines for drinking water quality, these focus on the 'absence' of pathogens and inorganic contaminants, not on the health risks from lack of essential minerals in desalinated water. A recent study in coastal Bangladesh by Naser et al. (2020) found that a lower intake of calcium, magnesium and potassium among

rainwater drinkers increased the risks of cardiometabolic diseases when compared with groundwater drinkers. In India, for example, concerns with the lack of essential minerals in desalinated water has led the National Green Tribunal to issue a directive in May 2019 asking the Ministry of Forest, Environment and Climate Change to prohibit the use of desalinated water with a TDS < 500 mg/l (*The Hindu*, 2020). This may involve requiring manufacturers to maintain minimum levels of calcium and magnesium, raising public awareness about the health implications of demineralized water, and ensuring regulatory bodies regularly test the quality of reverse-osmosis-treated drinking water.

Conclusions

The rural water policies across the Global South have predominantly focused on maximizing access to improved water sources through publicly financed and communally managed water supply infrastructure. In Bangladesh, where 98.5% of 160 million people have access to improved water sources, this infrastructure-led approach has inevitably skewed public investments away from high-salinity areas, where the provision of safe drinking water services requires costly water treatment and distribution technologies such as desalination plants and piped schemes. Gaps in public provision are being addressed by a growing network of water enterprises, including desalination technologies and mobile-distributing vendors. Their delivery activities demonstrate how Relevant Cost considerations, particularly Incremental Cost and Marginal Cost, influence the pricing decisions of water haulers. However, these informal private investments remain outside the formal sectoral narrative, with very limited data on the extent to which they complement or compete with public investments. This is the first study to systematically document the nature and scale of these small, private WSPs in Bangladesh, albeit in a selected study area, within the broader social–ecological system of public and self-supply investments, highlighting the social and spatial inequalities in household water access. Rather than perceiving these WSPs as residuals that need to be eliminated once public provision has caught up, there is potential to better integrate these private investments with progressive reforms in policy and practice, including greater consideration of the costs that influence water distributors' pricing decisions.

Data availability statement

Data used in this paper can be found in the supplemental data online: Dataset S1 (Household survey), Dataset S2 (Water Diary), Dataset S3 (Tubewell audit) and Dataset S4 (Desalination plant audit). The household survey and tubewell audit data for Polder 29 (Sites 1 and 2) are also available at ReShare UK Data Service: Hoque et al. (2021) and Salehin et al. (2021).

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