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A social-ecological analysis of drinking water risks in coastal Bangladesh

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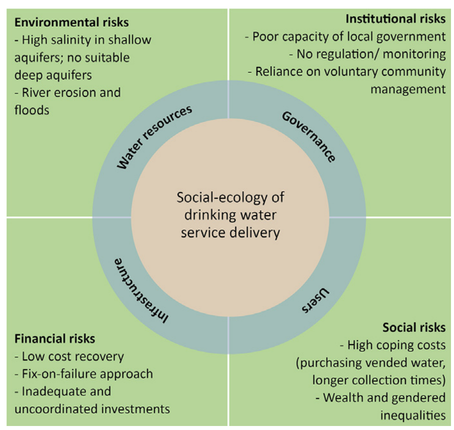
HIGHLIGHTS

- Socio-ecological risks in coastal Asia limit progress to safely-managed drinking water.
- Spatial heterogeneity and severity in groundwater salinity is a major risk.
- Public and private investments increase water 'access' but do not deliver safe 'services'.
- Drinking water tariffs vary by two orders of magnitude by technology and season.
- Wealth and gendered inequalities increase the burden for the most vulnerable.

GRAPHICAL ABSTRACT



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ABSTRACT

Groundwater resources in deltaic regions are vulnerable to contamination by saline seawater, posing significant crisis for drinking water. Current policy and practice of building water supply infrastructure, without adequate hydrogeological analysis and institutional coordination are failing to provide basic drinking water services for millions of poor people in such difficult hydrogeological contexts. We apply a social-ecological systems approach to examine interdisciplinary data from hydrogeological mapping, a water infrastructure audit, 2103 household surveys, focus group discussions and interviews to evaluate the risks to drinking water security in one of 139 polders in coastal Bangladesh. We find that increasing access through public tubewells is common but insufficient to reduce drinking water risks. In response, there has been a four-fold growth in private investments in shallow tubewells with new technologies and entrepreneurial models to mitigate groundwater salinity. Despite these interventions, poor households in water-stressed environments face significant trade-offs in drinking water quality, accessibility and affordability. We argue that institutional coordination and hydrogeological monitoring at a systems level is necessary to mitigate socio-ecological risks for more equitable and efficient outcomes.

1. Introduction

Salinity poses significant drinking water challenges for >25 million coastal inhabitants across the lower reaches of the Ganges-Brahmaputra-Meghna (GBM) delta in South Asia (Mukherjee, 2018;

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Hoque et al., 2016). With 86% of the rural population in South Asia having access to an improved water source (WHO/UNICEF, 2017), the key challenges facing the Sustainable Development Goals (SDGs) are to reach the excluded pockets of unserved populations, improve service levels for those with basic access, and sustain existing and future water infrastructure (World Bank, 2017). Failure of governments to provide basic services in such difficult hydrogeological contexts is largely the result of inadequate and unplanned investments in water supply infrastructure, which often outpaced institutional capacities to manage the water resources and technologies in place (ADB, 2016; Grey and Sadoff, 2007). This is further exacerbated by decentralisation processes that delegate service delivery responsibilities to local governments with limited human and financial resources (JICA, 2015; Singh, 2014). Deficiencies in public provision are partially addressed through siloed interventions by donor agencies and NGOs, informal water markets and self-supply through private investments. However, the result is a waterscape of multiple actors without regulatory oversight and accountability that jeopardises social inclusiveness and equity. Here, we explore the uncoordinated behaviour of public and private water investments in one of 139 polders[1] in coastal Bangladesh and the associated implications for drinking water security for the poor. In doing so, we use a social-ecological systems (SES) approach to conceptualise and analyse the risks to drinking water security.

Water security is characterised by four intersecting risks - environmental, institutional, financial and social (Hope and Rouse, 2013). Environmental risks in coastal deltaic floodplains can manifest in both natural and manmade forms. Although the GBM delta has highly productive aquifers within the thick unconsolidated alluvial sediments, the shallow aquifers are usually contaminated by high levels of salinity and arsenic, with isolated pockets of freshwater in deeper aquifers (Worland et al., 2015). Lateral movement of seawater and tidal flooding, coupled with over extraction of groundwater and reduced upstream flows, are contributing to increased salinisation (Sarker et al., 2018). The literature on water governance have identified various institutional risks, arising from separation of policy-making and service delivery, lack of regulation and accountability, or poor management of water resources and infrastructure (Kayser et al., 2015; Biggs et al., 2013). Experiences from the rural water sector suggest that demand-driven community management often fail to maintain waterpoint functionality, highlighting the need for meaningful participation in decision-making, strong post-construction support from local government or NGOs, and professionalising maintenance services to ensure sustainable service delivery (Whaley and Cleaver, 2017; Whittington et al., 2009; Harvey and Reed, 2007).

Development and sustainability of water infrastructure are often constrained by financial risks, such as shortfall in capital investments and low cost recovery, with studies finding that user payments are influenced by groundwater quality, service reliability, rainfall and payment modes (Thomson et al., 2019; Foster and Hope, 2016). In addition, social risks in the form of gendered and wealth inequalities and perceptions and cultural norms result in inequitable water security outcomes among individuals and groups. Unreliable water services have disproportionate physical and psychological distress on women and girls, who walk long distances, sacrifice schooling or productive work, or jeopardise their health and dignity for accessing water for their families (Sultana, 2011; Wutich and Ragsdale, 2008). Risk perceptions and aversion behaviours are shaped by personal experiences and information on actual risks shared through social networks, as well as the availability of necessary opportunities and resources (Nastiti et al., 2017).

While these environmental, institutional, financial and social risks have been studied across various contexts and scales, there has been insufficient research on their intersection using a unifying framework (Hope and Rouse, 2013). Here, we draw on social-ecological thinking to study the ways in which individuals and households interact with the water resources provided by nature, the infrastructure and institutions that mediate these relationships, and the resulting implications for accessing safe and affordable water services. Despite increasing use of the SES approach in water resource management at regional scales (e.g. Everard, 2019; Lazzari et al., 2019), there are limited examples of its application to drinking water services. The academic contribution of the paper lies in applying the SES approach to explore risks to drinking water security through interdisciplinary research. We combine biophysical evidence from mapping of aquifer salinity and water infrastructure with socioeconomic data from household surveys, focus group discussions and interviews to study water-society challenges. The complex hydrogeology and spatio-temporal heterogeneity in groundwater quality in our study site, along with the rapid and diverse growth of water supply infrastructure in the past half-decade, provides new evidence to exemplify the interplay between socio-ecological risks and the water security outcomes. The paper also advances empirical evidence on the insufficiently explored but significant growth in private investments that emerged to cope with deficiencies in public provision. A critical reflection on the various public and private service delivery models, as illustrated in this paper, is crucial for ensuring sustainable and equitable rural drinking water services.

2. Social-ecological framework of drinking water security

Water security, in the context of drinking and domestic uses, comprises a ‘provision’ and a ‘risk’ perspective (Grey and Sadoff, 2007). Global and national policies during the Millennium Development era focused on the ‘provision’ aspect, aiming to increase coverage of technologically improved sources through infrastructure development. However, ensuing challenges related to service reliability, infrastructure sustainability and social equity in the face of hydro-climatic and socio-political uncertainties have prompted the need to embrace a ‘risk’ perspective in the Sustainable Development era (Bradley and Bartram, 2013). In Bangladesh, where 97% of the population has access to an improved source but only an estimated 39% has safely-managed drinking water services, the challenge is to ensure that the water is free from contaminants, the source is resilient to climatic shocks, and the system is properly managed and regulated (World Bank, 2018b).

A risk is defined as a hazardous event that jeopardises something of human value, including but not limited to physical health, emotional wellbeing, assets and livelihoods (Aven and Renn, 2009). Objective analysis of risks at aggregate levels, based on simplified models of cause-effect relationships or economic principles of rational choice, draw criticisms from social scientists as they mask the diversity in society and can reproduce micro-level inequalities (Zeitoun et al., 2016). Risks and responses to drinking water security can only be understood by studying social actors within the biophysical and socioeconomic contexts in which they operate. Combining a ‘risk’ perspective with a ‘social-ecology’ framework offers a critical, inter- and transdisciplinary approach for understanding societal relationships to nature, and regulating or transforming it in ways that can minimise risks to a tolerable level and produce equitable outcomes (Völker et al., 2017). The core tenets of a SES perspective are that human and natural systems interact, coevolve over time and have substantial impacts upon one another, with causality working in both directions (Fischer-Kowalski and Weisz, 2016). A SES serves as an epistemic object for generating knowledge about real-world phenomena (Liehr et al., 2017). It is defined as “*a bio-geophysical unit with its associated social actors and institutions, which are complex, adaptive and delimited by spatial or functional boundaries surrounding particular ecosystems and their problem context*” (Glaeser et al., 2009: 190).

Several SES frameworks have been developed over the years, varying in terms of their disciplinary origins, their research questions and

[1] The Dutch term ‘polder’ refers to a tract of land, enclosed on all sides by dykes or embankments, in which sluice gates are used to artificially control the discharge and supply of surface water.

the contexts to which they are applied (Binder et al., 2013). Frameworks play a central role in SES research by outlining the interactions between the different components and providing a common language for scholars from different disciplines (Hinkel et al., 2014). One of the most prominent ones is Ostrom's (2009) multi-tier framework which decomposes the SES into resources systems, resource units, governance systems, actors, interactions and outcomes, each of which can be further disaggregated into lower-level attributes and variables. The framework is particularly suited for guiding empirical analysis as it provides a means of organising variables semantically and outlining the process relationships between variables and outcomes (Hinkel et al., 2014). Here, we adapt Ostrom's SES framework to conceptualise the human-nature interactions related to drinking water service delivery (Fig. 1). We outline four core components – water resources, infrastructure, governance and institutions, and users, and link them to the environmental, institutional, financial and social risks that can undermine the robustness of the SES.

Water resources include the quality, quantity and spatio-temporal distribution of rain, surface and groundwater, which are subject to environmental risks posed by natural hydrogeology and climatic shocks and stresses. Environmental risks are particularly high in coastal Bangladesh - an active tidal floodplain crisscrossed by numerous rivers and creeks that extend up to 200 km inland in the south-western region (Brammer, 2014). The region is highly susceptible to tropical cyclones and tidal surges, particularly in the pre- and post-monsoon periods. Intrusion of saline water from the Bay of Bengal poses significant challenges in the dry season when lack of rainfall decreases upstream river flows (Shammi et al., 2017). This seasonal phenomenon has been exacerbated by the withdrawal of water at the Farakka barrage on the Ganges (Padma) River in India and the construction of polders in Bangladesh during the 1960s–70s (Murshed and Kaluarachchi, 2018).

Infrastructure encompass public and private water supply technologies, such as tubewells, piped-systems, and pond sand filters, which enable users to access these water resources. Development and management of these infrastructures are prone to financial risks like inadequate investments, low-cost recovery, and inequitable pricing structures. Tubewells serve as the main source of drinking water in rural Bangladesh, owing to the widespread promotion of groundwater during the 1970s and 1980s as a pathogen free alternative to surface water (Sultana, 2012). There are about 1.5 million publicly-funded tubewells across the country, with an estimated eight times more privately-funded tubewells managed as self-supply (DPHE, 2018; MLGRDC, 2011). However, in coastal areas alternative sources and technologies, such as rainwater harvesting, pond sand filters, reverse osmosis, managed aquifer recharge and small-piped schemes, are widely used as well (Benneyworth et al., 2016; Islam et al., 2013). Rural water infrastructure development is usually financed through publicly and donor-funded projects and implemented by the Department of Public Health and Engineering (DPHE), as well as NGO supported projects that use grants from international development partners. These combined funding sources are, however, not adequate to finance the required infrastructure development, especially in hydrologically difficult areas (Lockwood and Islam, 2016). Moreover, while tariffs are usually affordable for users, they often fail to fully recover operation costs and hardly ever account for maintenance and depreciation of infrastructure. These financial risks have detrimental effects on the sustainability of rural water service delivery.

Governance and institutions refer to the rules, practices and processes that shape the use and management of water resources. Gaps in policy design and enforcement, poor coordination among government and private actors, limited local government capacity, unclear roles and responsibilities, and power dynamics can create institutional risks. In Bangladesh, the provision and maintenance of rural water supplies lies with the Union Parishads, the lowest administrative tier, that often lack the capacity and financial resources to fulfil the mandate set by DPHE at the national level (JICA, 2015). While the local government and private sector have better technical capacity to manage point sources like tubewells, they struggle to with more complex piped water schemes that entail higher levels of coordination and management responsibilities (Lockwood and Islam, 2016). NGOs have a dominant presence in the rural water sector, facilitating awareness and social mobilisation during project implementation phase. More recently, the DPHE with support from the World Bank, are experimenting with private-public partnership models for piped water schemes, as a means of leveraging private sector finance and professionalising management systems (World Bank, 2016, 2018a).

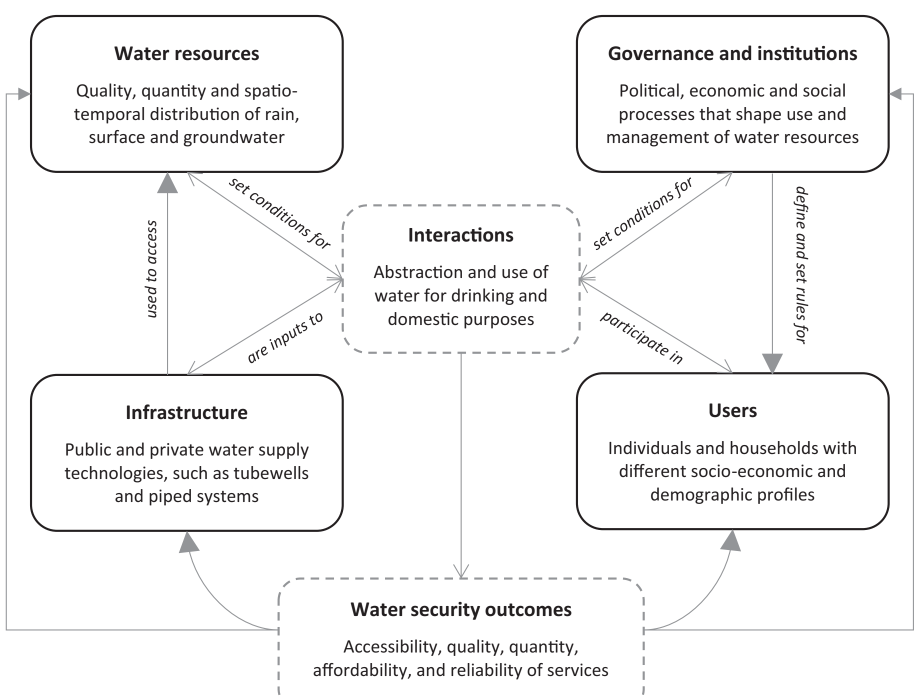

Fig. 1. Social-ecological framework of drinking water services.

Users encompass social actors that derive benefits from the water resources, which in the context of this study focuses on individuals and households, facing social risks in the form of wealth and gendered-inequalities. Research shows that while wealthier households deployed capital-intensive strategies, like drilling wells or increasing storage capacity, that addressed aspects of quality, quantity and convenience more comprehensively in the long-term, poorer ones catered towards more immediate quantity problems by engaging in labour and time-intensive strategies like treating and collecting water from long distances (Majuru et al., 2016). Emotional and physical health impacts of salinity are often disproportionately borne by women and children. High levels of salinity in drinking water can increase the risk of pre (eclampsia) and hypertension in pregnant women (Khan et al., 2014; Khan et al., 2011), with women found to be 1.3 times more likely to be hypertensive than men (Nahian et al., 2018). As prime collectors of water, women are often subjected to physical and emotional sufferings related to walking long distances with heavy containers and negotiating access with those who own or control the water sources (Sultana, 2011).

Interactions among these four components guide the everyday practices of abstracting, collecting, storing and using water for drinking and domestic purposes. In areas with low salinity, households can access freshwater from tubewells installed within or near their premises. However, those in high salinity coastal districts often use two or more sources during the year, with varied implications for quality, quantity, accessibility, reliability and affordability. Recent research show that many households use <35 l of freshwater per day, that too being fetched from pond sand filters or ponds located 1–2 km away (Abedin et al., 2019). Rainwater harvesting is a widespread coping strategy during monsoon, although long term storage is likely to suffer from microbial contamination (Benneyworth et al., 2016).

3. Research design

Our study was conducted in Polder 29 – an embanked area of 80 km^2 covering five unions (Tier-4 administrative boundary) across Dumuria and Batiaghata upazilas (sub-districts) of Khulna district in south-western coastal Bangladesh. The polder is further sub-divided into 77 mouzas (Tier-5 administrative boundary), with a total population of 58,000 and 17,000 households (BBS, 2011). A mixed-methods approach was used to collect empirical evidence relating to the four core components of the polder SES between November 2017 and March 2018. Ethical approval for the study 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.

Data on water resources and infrastructure were collected through a water audit that involved recording the locations, installation dates, technical specifications, ownership, maintenance, and usage patterns of all tubewells, pond sand filters and piped water taps in the south and central regions of the polder. The audit covered 2805 tubewells and 19 pond sand filters, of which 87% and 58% were functional, respectively. Water salinity was measured in-situ for all functional tubewells and pond sand filters using a field kit CLEAN CON30 Tester, 0–20.00mS/cm, with 10% being tested in the lab using an Ohaus ST300CG Portable Conductivity Meter, 0–199.9 mS/cm, for quality control. ArcMap 10.5 was used to illustrate the spatial variation in groundwater salinity in the first and second aquifers using data on water salinity and depth of the tubewells.

The hydrogeological profile of the polder, as shown in the aquifer stratigraphy in Fig. 2, was mapped using DPHE's borelog data at 31 locations in and around the polder. The dataset comprises >3000 borelogs, up to a depth of 330 m, collected from local DPHE offices across the country (DPHE-JICA, 2006, 2010). The lithological logs were analysed and treated in two-dimensional environment using Rockworks 2004 software. Stratigraphic units were defined based on the lithologic logs, and vertical distributions of subsurface formations were determined. Based on the standard practice in coastal Bangladesh, the aquifer system in polder 29 was categorised as: (i) the shallow (or 1st) aquifer extending up to 100 m below the surface; (ii) the main (or 2nd) aquifer ranging from 100 to 300 m and (iii) the deep (or 3rd) aquifer extending to depths >300 m (DPHE-JICA, 2006).

Key informant interviews with owners, managers or representatives of the different drinking water infrastructure were conducted to understand the governance system and institutions. These interviews identified the technical design, institutional and management structure, and financing model of key community drinking water interventions in the polder. These interventions included: three small piped water systems; water vending through truck and vans; pond sand filters; one public rainwater harvesting tank, and one privately funded reverse osmosis plant, leading to a total of 13 interviews.

Focus group discussions (FGDs) and household surveys provided data on the users, that is, the households and individuals. The FGDs provided an overview of the water-related risks within the polder, the diversity of water infrastructure investments, and the day-to-day practices of collecting, storing and using water for different purposes. A total of six FGDs, three male and three female, were conducted across three selected sites, with each FGD comprising 8–10 adult participants. The FGDs were conducted in the local language Bangla and later transcribed and translated for analysis. Data from the FGDs were used to design other research methods, as outlined below.

The household survey collected quantitative data on various indicators of multidimensional poverty and the state of drinking/domestic water services. The survey was administered to 2103 households in two stages: phase 1 involved 978 households spatially distributed across the polder, while phase 2 involved 1125 households within 16 chosen mouzas with relatively higher risk profiles. A stratified random sampling method was used to allocate equal proportions of households from each mouza. 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 survey was administered in Bangla through an electronic form developed in ONA (https://ona.io/), and was conducted by 15 trained local enumerators. The survey data was downloaded as Microsoft Excel files from ONA and later entered into IBM SPSS 25 for calculating wealth indices.

Principal component analysis (PCA) was used to disaggregate households into different wealth categories. 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 (Vyas and Kumaranayake, 2006; Filmer and Pritchett, 2001). We used 10 selected variables (see Table A1 in Appendix) and extracted all components with eigenvalues>1, followed by a k-means cluster analysis of the factor scores of PC_1. The latter segments the data in such a way that the within-cluster variation is minimised, enabling categorisation of households into distinct wealth classes. The wealth classes derived from PCA were further validated with subjective judgments of the enumerators who conducted the survey and correlated with agricultural land ownership, which is an important indicator of wealth in rural Bangladesh.

4. Results

There is a high degree of socio-spatial variation in access to drinking water services in the polder, owing to differences in the availability of good aquifers, infrastructure investments, institutions and management systems, and socio-demographic profiles of the users. Here, we structure our findings according to these four components, as illustrated in the SES framework above, followed by discussion on the interactions and water security outcomes in the next section.

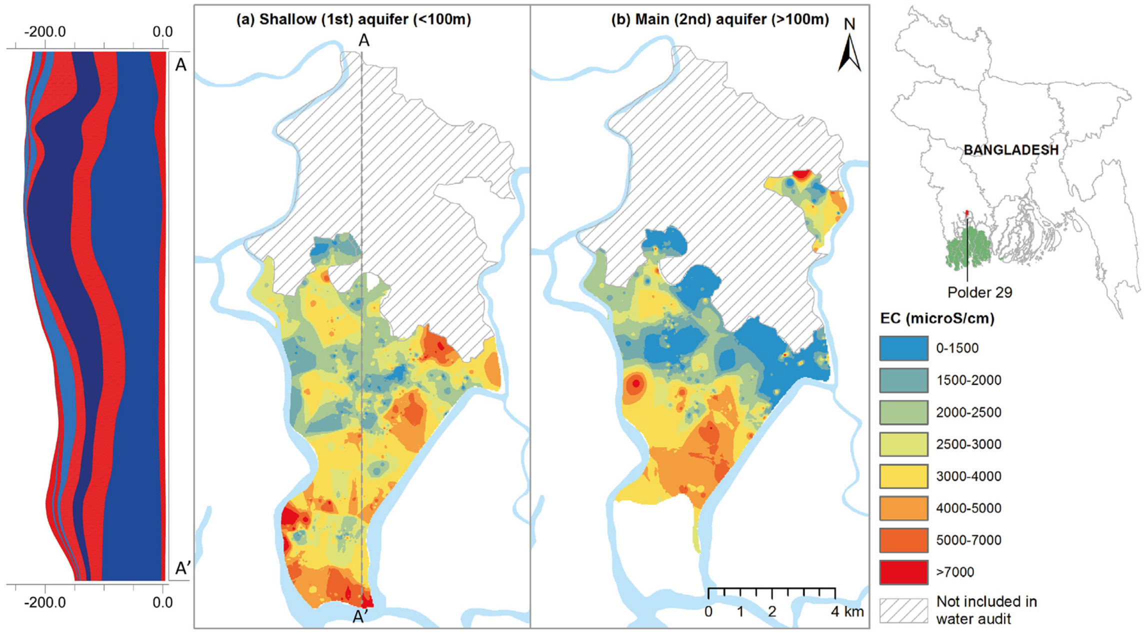

Fig. 2. Groundwater salinity and aquifer stratigraphy of Polder 29 in south-western Bangladesh.

4.1. Water resources

The lithologic analysis exhibited high degree of hydrogeologic complexity and aquifer heterogeneity. The shallow aquifer had a thickness of 50–160 m across the polder; however, the thickness of the second aquifer ranged from 30 to 60 m in the north and decreased substantially in the south. The delineation of the third aquifer was incomplete because of insufficient lithologic information at greater depths. Despite the presence of good shallow aquifers, availability of drinking water was severely constrained due to high levels of salinity. In the north and central parts of the polder, salinity in the shallow and deep aquifers was usually below 1500 μS/cm; however, it increased gradually towards the southern part which lacked suitable deep aquifers as well. The southern part of the polder was highly vulnerable to riverbank erosion, with the latest event occurring in mid-2015, when a section of the embankment collapsed leading to severe flooding. The land remained inundated for up to a month, causing damage to livelihoods and property.

4.2. Infrastructure

In the past decade, there has been a significant growth in the number of tubewells in the polder. This includes three piped water systems, two managed aquifer recharge units, one community rainwater harvesting tank, one formal water vendor, one private reverse osmosis plant, and 19 pond sand filters in the polder (Fig. 3). These interventions involved four types of funding mechanisms – 1) direct provision by local government with funds from annual development budgets or donor-funded projects; 2) NGO supported investments using grants from international development partners; 3) self-supply by households and 4) water markets.

4.2.1. Government-led interventions

A recent inventory published by the DPHE shows that, as of June 2018, there were a total of 4334 and 2714 safe public tubewells in Dumuria and Batiaghata upazilas respectively, with estimated coverages of about 72 and 66 people per tubewell (DPHE, 2018). Our water audit data, which recorded 454 public tubewells, shows similar coverage of about 77 people per tubewell, although the spatial distribution varied based on aquifer availability. Almost all of these were deep tubewells (>100 m) costing an average of Tk. 80,000 (USD 1000), of which 10% came from user contributions.

Two of the three piped-systems were established in 2014 by the local government in Union-3 through the HYSAWA fund[2] (refer to Table A2 in Appendix). Both run on solar energy, with no user tariffs and ad hoc repair costs which are often borne by local elites. Water was pumped continuously with sufficient radiation with the motor automatically disconnected when the overhead tank was full. Prior to these interventions, households within these villages had to walk up to 1 km to fetch water from deep tubewells located close to the existing pumphouses. Locals reported a lot of water wastage, as some people used the public taps for washing clothes and bathing their livestock. Over usage at the nearby taps decreased pressure at ones on the far end, creating longer queues and user dissatisfaction.

The local government in Union-4 established a water vending system in 2015 through funds from the Upazila Governance and Development Project (UGDP)[3] (Table A2). The vending system sourced water from a pumphouse beside DTW1 (Fig. 3) and used a pick-up truck to deliver one 20-l container six days a week (at Tk. 50 (USD 0.6) per month) to registered households in Union-4. The project started operation with 115 households; however, within the first six months, additional households signed up, increasing the total to 350. These households traditionally relied on surface water from a 100-year old community pond or rainwater harvested through their roof catchments, as the nearest groundwater sources with acceptable salinity levels (STW1 and DTW3 in Fig. 3) were located at distances of 3 km and 5 km respectively. The system, however, ceased operation in early 2017 due to institutional failures described below.

4.2.2. NGO and donor-funded projects

An electricity-powered piped-system in Union-3 provided water to households that previously relied on two adjacent public tubewells (DTW2, Fig. 3). The system covered two-thirds of the mouza, supplying

[2] HYSAWA is a multi-donor funding mechanism, established in 2007, to facilitate capacity building of local governments and finance large-scale water and sanitation infrastructure in participating Union Parishads (www.hysawa.org).

[3] The Upazila Governance and Development Project (2015–21) aims to promote needs-based rural infrastructure development by Upazila Parishad and ensure closer linkage between Upazila and Union to provide better service delivery to the local communities (http://www.ugdp-lgd.org).

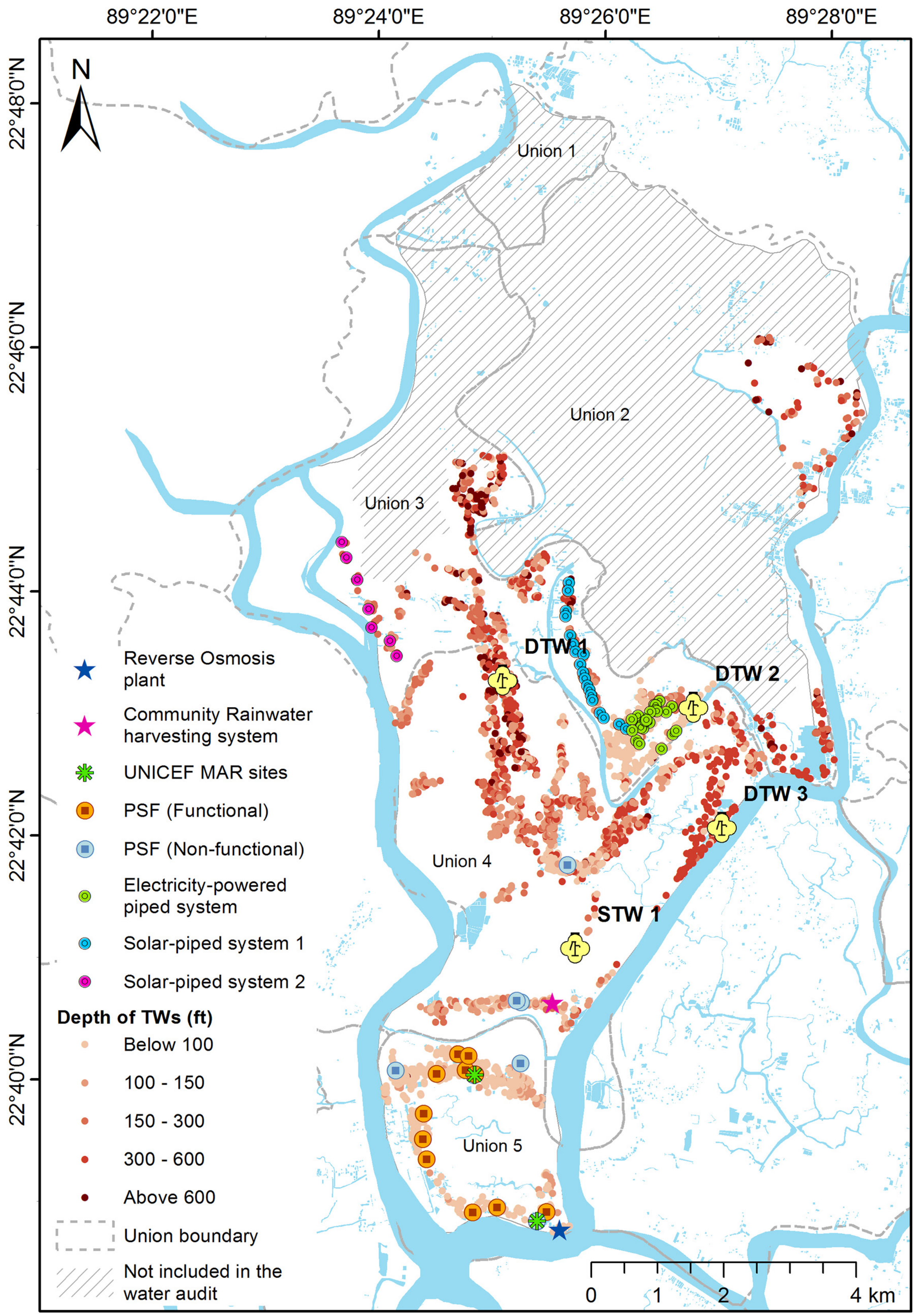

Fig. 3. Water supply infrastructure in Polder 29.

water to about 300 households for a monthly tariff of Tk. 30 (USD 0.04) (Table A2). Those within walking distance of DTW2 continued to use them, while others outside the zone were served through 25 public taps, each allocated to 15 households in the vicinity. Locals reported that compared to the solar systems (described above), this system abstracted water from a considerably smaller aquifer and had a more complex piped network that required installation of the electric pump. As a limited amount of water was supplied at a scheduled time each day, households used the tap water mainly for drinking and sometimes cooking and relied on private shallow tubewells for other domestic purposes.

Such donor-funded projects, implemented by NGOs, provided critical services in high salinity areas where public investments were inadequate. We recorded 19 pond sand filters in the southern part, of which 11 were functional. These are relatively low-cost technologies that use layers of sand and brick chips to filter surface water from ponds filled by rainwater to reduce turbidity, salinity and microbial contamination. Regular maintenance, which involves cleaning and replacing the sand beds about twice a year, and protecting the source pond from contamination, are essential to ensure sustainability of the systems.

> "*Unlike the pond sand filters installed nearby, this one is comparatively better because I took ownership and even invested some money from my pocket. I asked the engineers to improve the type and thickness of brick layer; and insert fine nets in between the sand layers. I also deepened the pond so that it retained water during the dry season as well. Today, most other pond sand filters installed in this polder are not functioning properly; however, mine is running smoothly.*" *–Manager, Union-5*

4.3. Private investments and self-supply

The number of privately-funded tubewells increased four times in the past decade, comprising 78% of all tubewells in 2018 (Fig. 4). In comparison, the population in the polder grew by about 4% during the same period. Most of these were shallow tubewells installed by individual households on their premises, with average costs of Tk. 20,000 (USD 250). Although the combined coverage by public and private tubewells was about 14 people per tubewells, such statistics mask the fact that most of these tubewells exceeded the recommended salinity threshold and were predominantly used for non-drinking purposes. The proportion of public and private tubewells in each mouza was influenced by the aquifer salinity, with 30–40% of tubewells in low salinity mouzas being publicly installed compared to <8% in high salinity mouzas.

4.3.1. Water markets

More than half of the households in the southern part mentioned purchasing water from informal vendors for varying durations throughout the year. These vendors also sourced water from DTW1 and DTW3 and charged Tk. 20–30 per 30-l (USD 8–10 per m^3) depending on remoteness of the household. Water was delivered via motorised tricycles, locally called 'nossimons', or via the river on trawlers.

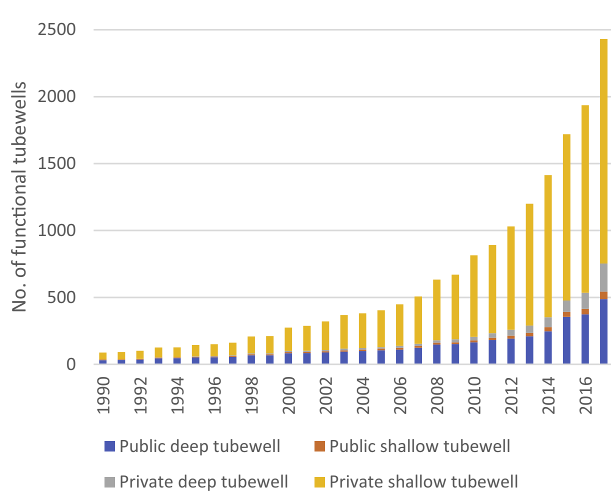

Fig. 4. Growth of public and private tubewells in Polder 29, 1990–2017.

In 2018, one of the households in Union-5 invested his own funds to install a reverse osmosis plant. Knowledge from his previous job at a desalination plant in Dubai encouraged this local entrepreneur to improve water security in his home village where he sold water for Tk. 5 per 10-l (USD 6.25 per m^3). While demand for this desalinated water increased over time, some refrained from purchasing it due to skeptism about its quality. One participant explained, "The vended water [from DTW3] is as natural as coconut water, but this [desalinated] water is treated with chemicals."

4.4. Governance and institutions

The Union Parishads, as government rural water service providers, were installed deep tubewells but struggled with more complex systems that required better coordination, knowledge and post-construction management. One example is the failure of the formal vending system, which faced multiples challenges during its three years of operation. Firstly, the tariff was too low to recover operation costs, which included salaries of the driver and an assistant, fuel and vehicle maintenance cost. Secondly, when the entire southern region was flooded in mid-2015, it supplied free water to all households in Union-4, regardless of their subscription. Thirdly, due to increased requests from an adjacent mouza, which was part Union-5 under a separate upazila, the truck supplied 50 additional households for three months during the summer of 2016. These households were, however, charged higher tariffs of Tk. 150 per month (USD 2.1 per m^3). Such periodic increases in household numbers strained existing resources, increasing the workload of the driver and his assistant, without any salary increments. Moreover, some households refused to pay during the monsoon when they could use rainwater, while others were reluctant to subscribe for the whole year. Decline in revenues during monsoon, without proportional decrease in costs, again jeopardised the sustainability of the system. Finally, the truck was damaged in an accident in early 2017, causing the system to cease operation due to lack of repair funds.

The electric piped-system exemplifies a case of a relatively well-designed community-managed system in a severely water-stressed area. A local NGO, that implemented the project, helped set-up a voluntary management committee, comprising of a chairperson, a treasurer and tariff collectors. There was a high sense of ownership among the committee members. These people had been closely involved with the NGO since the project inception and had played key roles in mobilising community resources, including donating private land for the pumphouse, gathering the funds for community contribution, and suggesting suitable locations for the taps. While the system was running quite effectively at the time of this study, the committee had to resist continuous political pressures from the existing union chairman to expand coverage to the unserved communities, which was likely to jeopardise the sustainability of the system built by his predecessor.

> "*The newly elected chairman told the villagers that he would make the water free for all, and that he had paid additional money to clear the backlogs. But in reality, the management committee only received a nominal amount, that too, in instalments via a third person. The problem is that now when we ask people to pay their tariff, they think that we are keeping the money for ourselves.*" *– Management committee member*

4.5. Users

Most households across the northern part of the polder expressed no concerns about their drinking water services and relied on communal or private deep tubewells for drinking and domestic purposes throughout the year (Fig. 5). Water security was, however, a major issue across the

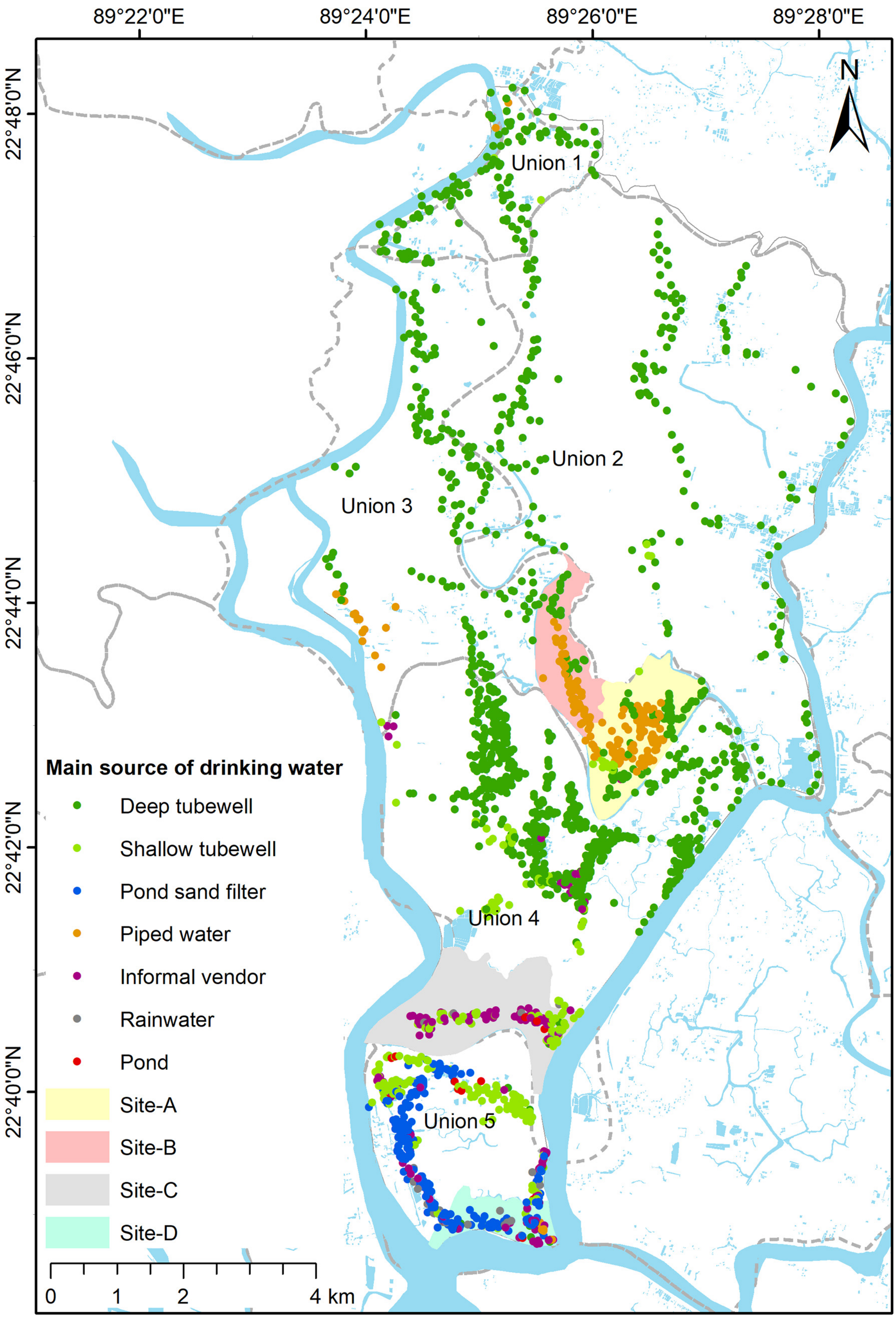

Fig. 5. Main sources of drinking water used in polder 29.

southern end of the polder, where households depended on multiple sources, including shallow tubewells, pond sand filters, rainwater and informal vendors.

To highlight the differential water security outcomes, we illustrate the variations in sources, collection time and responsibilities in four selected sites within the polder (Figs. 5 and 6). About 58% of the surveyed

Fig. 6. (a) Main sources of drinking water; (b) gendered responsibilities [Men/women >16 years; boys and girls <16 years] and (c) collection times.

households in Site-A used the electric piped-system as their main source, with another 37% depending on the two deep tubewells next to the pumphouse. While collection times including queuing were usually <30 min, it was higher for those outside the coverage area of the piped system. The situation was comparatively better in Site-B, where 71% households used the piped-system while others shared deep tubewells usually within 15 min of their dwellings. Moreover, since tap water was available for longer periods during the day in Site-B, fewer households reported using alternative sources for drinking or cooking. During the FGDs, users in these two sites reflected that before construction of the piped-systems, higher proportions of men were involved in fetching water owing to the longer walking distances.

In Site-C and Site-D, we observed significant wealth differences in main source, with 60% of rich households using vended water compared to 15% of extreme poor ones. Since poorer households could not afford vended water, they resorted to pond sand filters or walked 1–3 km to fetch water from tubewells in distant mouzas, which created greater physical burden. Interestingly, we observed higher proportions of men involved in water collection in these sites due to two main reasons. In some households men used their own/hired vehicles to fetch water from tubewells in other mouzas; while in others, men helped in bringing the water containers left by the vendors near main roads. The choice to purchase vended water was also determined individual preferences, presence of able-bodied members to fetch water, and presence of individuals with special needs, like children or members with ill-health.

"*It rained about 10 days ago, and we still have some rainwater stored at home. My daughter doesn't drink rainwater as she it doesn't suit her. So we have to buy vended water for her. When we were younger, we used to drink pond water without any treatment. People were not aware at that time. But due to continuous river erosion, we have lost all the ponds in our village.*" *- Female FGD, Union-5*

Most households in Union-5 used more than one source, particularly shifting to rainwater during the monsoon. While 69% and 80% of households in Site-C and Site-D harvested rainwater, only 7% and 9% in Site-A and Site-B did the same. Poorer households considered a lack of storage capacity as a significant constraint, and perceived investments in large-scale community systems as the optimal solution in the short-term. Whether the rainwater was used for both drinking and cooking or for cooking only depended on how well individuals tolerated it. While some cited it as their most preferred source, others complained about coughs, bloating or diarrhoea resulting from drinking rainwater.

5. Discussion

Water security is determined by the complex interactions between water resources, governance systems, infrastructure development and user needs and values. Application of a SES lens bridges disciplinary divides and draws attention to these interdependent biophysical and social processes. Here, we elaborate the various environmental, institutional, financial and social risks affecting the SES and discuss ways to minimise them to facilitate sustainable and equitable rural water service delivery.

Environmental risks posed by inorganic contaminants have been extensively studied by hydrogeologists, particularly with reference to the source, transport and spatial distribution of arsenic and salts in the GBM delta, and the future implications of rising sea-levels and increased storm surges (Sarker et al., 2018; Shammi et al., 2017; Worland et al., 2015; Zahid et al., 2013). However, these studies usually adopted a regional scale that mask the local variations in freshwater availability, knowledge of which is essential for determining the types and scale of investments required for providing drinking water. With respect to arsenic, van Geen et al. (2003) highlighted the spatial heterogeneity in contamination of 6000 tubewells within a small area of 25 km^2 in Bangladesh, with a larger study of 30,000 tubewells in India and Pakistan showing that majority of households with a high arsenic tubewell lived within 100 m of a safe one (van Geen et al., 2019). Same is true for salinity, as demonstrated by the complex heterogeneity in availability and quality of aquifers in the polder. However, such information is only available post-construction of tubewells, that too based on taste perceptions, as location decisions are based on convenience of access and expert opinion from hydrogeologists are neither available nor sought prior to installation. van Geen et al. (2016) found that nepotism and elite capture often result in inequitable allocation of deep tubewells. In this study, we also observe disproportionate allocation of government funds, with Union-4 having higher number of public tubewells per person than Union-5. In this case, the differential allocation is mainly due to differences in aquifer availability, as it is relatively easier to improve access by installing more tubewells in areas with favourable aquifers than dealing with complex systems required for difficult contexts.

This inertia to move beyond the trusted model of community-managed handpumps/tubewells is seen across rural Asia and Africa. A study on responses to groundwater salinity in rural Malawi reveals a similar scenario, whereby aid-driven handpump installation has resulted in a landscape of 'poor water quality' boreholes and wastage of funds (Rivett et al., 2019). In Bangladesh, the government-led agenda of shifting from surface to groundwater is also fuelled by exponential growth in private shallow tubewells, which in turn is facilitated by availability of cheap spare parts and drillers. A provisional estimate suggests that more than Tk. 28 million (USD 350,000) have been invested by households in the polder in the past decade,[4] which is more than double the combined investments on all other systems, and close to half of the public investment for deep tubewells during the same period. Despite the dominance of self-supply, it is not recognised nor regulated as a formal service delivery model. The water audit is the first attempt to create an inventory of private tubewells. While the government has taken some initiatives to map, code and test public waterpoints across the country (DPHE, 2014, 2018), systematic mapping of all public and private water supply infrastructure is essential to facilitate planning, regulation and monitoring.

While tubewells still dominate the rural water sector in Bangladesh, alternative sources and technologies are increasingly installed and used, particularly in the coastal region (Islam et al., 2017; Sultana et al., 2014; Harun and Kabir, 2013). Within the polder, we observed small-scale piped-systems that were deemed as appropriate solutions for areas within 1–2 km of a suitable aquifer. As these investments were beyond the scope of the limited funds channelled to local governments from the annual development budget, they were largely financed through separate donor-supported projects like HYSAWA and UGDP and transferred to the community for operation and maintenance. Areas with severe water stress, that is, without suitable aquifers within a 4–5 km radius, necessitated transfer and selling of water from other areas. In the absence of infrastructure investments, the gaps in service delivery were filled by informal vendors – a situation commonly encountered in rural and urban centres in the developing world (Garrick et al., 2019).

Inadequate investments in drinking water systems and low-cost recovery pose significant challenges in areas with poor aquifers. According to a recent multi-country review (World Bank, 2017), Bangladesh scored the lowest in rural water service delivery compared to 16 other countries in Asia and Africa. Apart from the consistent shortfall in public capital investment, a common challenge is the absence of sustainable financing mechanisms for recurrent costs, capital maintenance and replacement, with the latter being done on 'fix-on-failure' basis (World Bank, 2017, 2018b). This is exemplified by the piped-systems and pond sand filters, as well as the failed formal vending system in the polder. The lack of tariffs in the solar piped-system is a missed opportunity to fund feasible system upgrades that can serve additional households or increase service levels for existing ones. Tariff design is driven by the notion that rural households are reluctant or unable to pay, often keeping initial charges even lower than operation costs. This further reinforces community expectations of free/cheap services, which act as a barrier for any subsequent tariff revisions. The traditional strategy of involving nominal community contributions as a means of gauging demand and sense of ownership is largely ineffective because, firstly, the upfront contributions are usually made by a few local elites, and secondly, those making these financial contributions later feel entitled to (mis)use the system.

The lack of monitoring and regulation, resulting from limited capacity of the Union Parishads, is one of the key institutional challenges (JICA, 2015). As observed in polder 29, even the government-led solar piped-systems were unsupervised and except for anecdotal evidence, current ward members had little knowledge about them. In comparison, the management committee of the electric piped-system had an active presence, which can be attributed to intensive engagement with residents during project design and implementation phases, as well as support from the NGO during the first year of operation. Except for one-off water quality tests in the beginning, there were no further attempts by the Union Parishad to monitor or maintain these projects. Private entrepreneurs, like the reverse osmosis system and informal vendors, lacked regulatory oversight and relied on market forces for setting prices. Separation of administrative and hydrological boundaries posed further institutional risks. Since Union-5 was under the jurisdiction of a different upazila altogether, the area struggled to be benefitted from water sources in the rest of the polder through government arrangements, as exemplified by the formal vending system that charged twice as much for emergency supply to residents in this upazila.

Wealth differences in coping behaviour was observed in Site-C and Site-D, where proportion of households purchasing vended water increased with wealth class, while poorer households used pond sand filters and relatively saline shallow tubewells, thus, compromising quality to maintain affordability. On a similar note, Cook et al. (2016) notes that in rural Kenya, households with piped connection or private wells, which also had relatively higher incomes, incurred lower day-to-day coping costs in terms of collection times than those travelling outside home to fetch water. Wealthier households, however, as also observed by Gurung et al. (2017) in Kathmandu and Amit and Sasidharan (2019) in Chennai, incurred higher one-off capital expenditures for drilling their own private wells. Such wealth inequalities in coping strategies were not observed in Site-A or Site-B, where installation of the piped-systems improved accessibility without putting additional strain on the household budget. This has implications of achieving SDG 6.1 which requires joint achievement in all dimensions - quality, quantity, accessibility, affordability, and reliability.

Groundwater salinity and infrastructure investments also influenced gender differences in collection responsibilities in the polder. While our findings align to the well-established fact that women and girls disproportionately bear the burden of fetching water, we also observe a large proportion of men getting involved in water-stressed areas, particularly in absence of suitable infrastructure. In rural Brazil, Aleixo et al. (2019) similarly found that infrastructure interventions led to significant decline in children and adolescents fetching water, and slight decrease for men, noting that men did participate when the collection involved a vehicle. However, in contrast to other contexts, where children fetch water often on their own, such instances were fewer in the polder where children usually accompanied elders.

[4] 1400 private shallow tubewells installed since 2008, costing Tk. 20,000 on average.

6. Conclusion

Coastal polders in south Asia are dynamic and complex social-ecological systems where many of the world's poorest and most vulnerable people live. In coastal Bangladesh, chronic risks from salinity and flooding hazards present enormous governance challenges to ensure safe drinking water for populations with high and enduring levels of poverty. Private responses to these social-ecological risks have revealed unexpected and significant investment in shallow tubewells and market entrepreneurship over the last decade. In the absence of institutional coordination and water quality regulation, this wave of investment has outstripped government infrastructure spending and poses fundamental questions and opportunities on reforming policy and practice which is acceptable and equitable. With improved environmental monitoring the risks associated with salinity can inform more targeted water infrastructure investments to benefit the poor. A simplistic infrastructure agenda of building public tubewells is shown to be ineffective and failed to target the most at risk. Without independent regulation and monitoring at a system level, here the polder, the pathways to drinking water security will remain elusive. The demand for improved and accessible water services revealed by significant private investment suggests new opportunities to pool public and private finance to optimise betters for all, potentially at lower costs. Emerging vending and entrepreneurial models which provide safe water on demand indicate the opportunity and need for an institutional model working to identify and mitigate risks which maximise benefits for the most vulnerable. Coordinated public action is feasible if appropriate and acceptable institutional models can be designed based on the outcome of safely-managed water for all. This would require reform of the infrastructure-led approach that has dominated government and donor behaviour in ensuring high-levels of coverage without ensuring safe and reliable services for the poor.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.04.359.

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