UNIVERSITY OF TECHNOLOGY SYDNEY

Investigating groundwater self-supply as a safely managed water service for households in urban Indonesia: Water quality, management and monitoring

by Franziska Genter

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Dr. Tim Foster and Prof. Juliet Willetts

University of Technology Sydney
Institute for Sustainable Futures

September 2023

Certificate of original authorship

I, Franziska Genter, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Institute for Sustainable Futures at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Format of the thesis

The thesis has been prepared as a 'thesis by compilation' as described in the University of Technology Sydney's Graduate Research Candidature Management, Thesis Preparation and Submission Procedures 2022 (Section 10.1.2). A thesis by compilation is structured as a single manuscript that comprises a combination of chapters and published/publishable works.

This PhD thesis manuscript is structured into eight chapters including five published research outputs:

Publication I

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Publication III

Genter, F., Putri, G.L., Maysarah, S., Rolia, E., Pratama, M. A., Priadi, C., Willetts, J., Foster, T. (2023). Associations between seasonality and faecal contamination of self-supply sources in urban Indonesia. Water Sanitation and Hygiene for Development. https://doi.org/10.2166/washdev.2023.060

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Declarations of co-authorship

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Abstract

Self-supply is a widespread response by households to inadequate public water supply. In urban Indonesia, over 40 million people rely on groundwater self-supply for drinking. Self-supply is invested in and managed by an individual household, accessible on-premises, unregulated, and overlooked in policy and regulations. The extent to which self-supply provides a safely managed water service remains unclear. This PhD thesis aims to address the knowledge gap concerning the safety of household self-supply in the Indonesian cities of Bekasi and Metro, using a social-ecological system approach as a conceptual framework and employing quantitative, qualitative, and mixed-methods.

To better understand groundwater self-supply in low- and middle-income countries globally, a systematic review and meta-analysis were conducted. The results revealed that self-supply is commonly contaminated with faecal indicator bacteria and is significantly more likely to be contaminated than piped supply.

To investigate the safety of groundwater self-supply and its faecal contamination risks in urban Indonesia, water quality monitoring campaigns were conducted in Bekasi and Metro alongside household surveys and sanitary inspections. Findings indicated that self-supply commonly contained *Escherichia coli* bacteria, with contamination risks related to infrastructure, proximity to sanitation systems and wealth. Furthermore, the association between seasonality and faecal contamination of self-supply was investigated, demonstrating mixed results.

To understand the use and management of self-supply by households in urban Indonesia, a mixed-methods approach was used. While most households preferred groundwater self-supply, they also relied on alternative water sources to supplement inadequate supply, although trust in these alternatives was low. Boiling water from self-supply was a common household treatment practice, however, the labour involved was tiring for some. Gendered intra-household dynamics varied across households, but showed cooperation between women and men and certain clearly defined roles in terms of responsibilities and decision-making.

Monitoring water service delivery is essential, however there is little guidance on best monitoring practices for self-supply. Therefore, a participatory citizen approach was trialled and evaluated, involving a six-month household-led microbial water quality testing process accompanied by pre- and post-monitoring surveys. This approach provided reliable water quality results and increased awareness of water quality; however, nearly half of the households dropped out of the monitoring and increased awareness did not translate into actions that improved water quality within the study period.

In conclusion, the thesis addresses important gaps in the understanding of self-supply and provides important evidence for developing differentiated strategies to support, regulate and monitor self-supply towards a safely managed water service.

Chapter I

1. Introduction

1.1 Overview

The objective of this PhD research was to investigate self-supply water services in urban Indonesia with regard to the safely managed water service criteria as well as socio-economic and gender dimensions. The research was carried out within the context of the water, sanitation and hygiene (WASH) sector and utilised the criteria for safely managed drinking water criteria established by the World Health Organization (WHO), as well as a modified social-ecological system approach as a conceptual framework to guide the interdisciplinary research. The PhD research was part of a broader project titled 'Transitioning to safely managed water services: Risks and opportunities of self-supply for vulnerable populations', which was conducted in collaboration with the University of Indonesia and funded by the Australian's Department for Foreign Affairs and Trade (DFAT) through the Water for Women Fund (Grant WRA 1004). The introductory chapter of the thesis presents the research context and highlights the relevance of self-supply, as well as gaps in research related to microbial water quality, water quality monitoring, water availability, reliability and usage, and equity aspects such as wealth and gender in the self-supply context. The chapter outlines the research areas and research questions that were addressed in the five journal papers included in the thesis. Finally, the chapter provides an overview of the thesis, which weaves together the research areas and the associated journal publications. The PhD research is justified in terms of how it contributes to expanding upon existing knowledge in the field, by analysing and synthesising previous studies, identifying research gaps, and proposing novel areas of investigation.

1.2 Background and context

Access to water and sanitation is recognised as a human right (UN General Assembly, 2010) and forms a key ambition of the globally agreed Sustainable Development Goal (SDG) framework. The Agenda 2030 contains 17 SDGs, which provide a global framework to jointly solve the world's major challenges, including those related to poverty, inequality, climate change, peace and justice. Safe and reliable WASH is central to sustainable development and is embedded in SDG 6. SDG 6 aims for universal and equitable access to safe and affordable drinking water for all by 2030. To meet the criteria of a safely managed drinking water service, households must use an improved water source that is accessible on-premises, sufficiently available when needed and free from faecal and chemical contamination (WHO, 2022). In addition, the 2030 Agenda commits member states to reduce inequalities within and between countries, which implies progressively reducing and eliminating the gap between advantaged and disadvantaged groups (WHO & UNICEF, 2019) and requires thorough monitoring to ensure that no one is left behind. Although billions of people have gained access to basic WASH services since 2000 and much progress has been made towards reaching SDG 6, there is still a long way to go to fully realise the SDG ambition to achieve universal access for all. The lack of access to safe drinking water is felt disproportionately by disadvantaged community groups (WHO & UNICEF, 2019). In order to achieve the ambitious goal of universal access to safe and affordable drinking water for all, it is essential to consider all potential sources of water, including self-supply services.

1.2.1 Water supply related health risks

Water supply related health risks encompass chemical and microbial contaminants that can affect human health through water consumption. While the great majority of water-related health problems are the result of microbial contamination, an appreciable number of health concerns may also occur as a result of chemical contamination of drinking water (WHO, 2022).

According to the WHO guidelines for drinking water quality (WHO, 2022), most chemical constituents in water supplies are of health concern only after extended exposure of years. Chemical contaminants can be introduced to water supplies from a variety of sources including naturally occurring and anthropogenic due to industrial, agricultural, and other activities. Chemical safety of drinking water focuses on chemical constituents that have been found worldwide such as fluoride, arsenic, selenium, nitrate, iron, manganese, and lead. High-priority chemical parameters at a global level are arsenic and fluoride. Arsenic and fluoride occur naturally and have caused widespread exposure through drinking water and unacceptable chronic health effects in many countries. High concentrations of naturally occurring chemicals are typically found in groundwater in arid and semiarid regions with low groundwater flow rates, where water has been in contact with rocks and soil for long periods under certain conditions. Since natural occurrence is relatively common in water supplies around the world, they should be assumed to be potentially present, and consideration should be given as to whether they are present in concentrations of concern (WHO, 2022).

While chemical contamination poses health risks primarily through long-term exposure, microbial contaminants present immediate public health risks from acute exposure. Based on the WHO guidelines for drinking water quality (WHO, 2022), microbial water quality varies rapidly over a wide range and short-term peaks in pathogen concentration have the potential to significantly increase disease risks and may even trigger outbreaks of waterborne disease. The greatest microbial risks are associated with ingestion of water that is contaminated with faeces from humans or animals, which can be a source of pathogenic bacteria, viruses, protozoa, and helminths causing infectious diseases. Securing the microbial safety of drinking water supplies is based on the use of multiple barriers, including protection of water resources, proper selection and operation of water treatment steps, management of distribution systems to maintain and protect treated water quality, and safe household water treatment and storage (WHO, 2022).

The scope of the PhD research prioritises faecal contamination over chemical contamination due to its immediate and severe impact on public health and its greater relevance in the context of self-supply water services.

1.3 Self-supply water services

Self-supply plays an important role in providing water for households in low- and middle-income countries (LMICs) (Foster et al., 2021). Self-supply has become essential for people who are often beyond the reach of utility- or community managed water supplies, and for those who need to complement an inadequate supply received (Grönwall et al., 2010). Self-supply is a service delivery model usually relying on groundwater or rainwater. It is characterised as a water supply on-premises, self-invested and maintained by the household and therefore based on affordable technologies (Grönwall & Danert, 2020). Self-supply water sources are typically in the form of privately owned wells, boreholes, or rainwater collection systems (Foster et al., 2021). The service delivery model exists all over the world in both rural and urban settings. In rural areas, population density is often too low to warrant municipal or externally funded water supply or the areas are difficult or expensive to reach. Self-supply is found in these areas with widely scattered households, weak or fragmented management, difficult access to maintenance services, a lack of potable water and in areas with households which cannot afford community water services (Sutton, 2009). In urban areas, cities are expanding rapidly so that individual households in outskirts organise their own drinking water access (Grönwall & Danert, 2020). In fast-growing cities, self-supply is found in households which can afford to turn 'off-grid' and take responsibility for the own water supply by drilling boreholes when there is no reliable and convenient public supply (Healy, 2019).

Self-supply has become increasingly common in LMICs and continues to grow as a form of water service delivery. In Asia-Pacific, over 700 million people depend on self-supply across both rural dispersed areas and densely populated urban areas (Foster et al., 2021). For example in rural Bangladesh, groundwater access through privately funded shallow tubewells increased four times in the past decade, comprising 78% of all tubewells in 2018, according to Hoque et al. (2019). Srikanth (2013) observed a higher number of private shallow hand pumps compared to government deep hand pumps to access groundwater in rural India. Elliott et al. (2017) reported the use of multiple water sources in over 90% of the surveyed households in communities of the Republic of the Marshall Islands and the Solomon Islands with private rainwater tanks used as a common water source for drinking and non-consumptive purposes. Rainwater was also observed to be the most common water source in Vietnam, being used for all domestic activities during the rainy season and only for high-value purposes during the dry season (Özdemir et al., 2011). In Indonesia's densely populated settlements, which are the focus of this research project, almost one third of the urban population – approximately 41 million people – rely on groundwater self-supply as their source of drinking water (Foster et al., 2021). In addition, self-supply is frequently used for non-drinking purposes by another 29% of the urban population who consume bottled water but rely on self-supply for non-potable uses, accounting for approximately 43 million people in Indonesia (Foster et al., 2021). It should be noted that self-supply as a form of water service delivery is not unique to LMICs in the Asia-Pacific region. It is prevalent globally, including in urban areas of Africa, in Central and South America, the Middle East, and other regions (Chávez García Silva et al., 2020; Davoodi et al., 2018; Eisenhauer et al., 2016; Gorter et al., 1995; Korfali & Jurdi, 2009; Metwali, 2003).

The unregulated nature of self-supply services and their potential risks to water quality highlight the need for governments to address this issue in order to protect public health and ensure universal access to safe water. Self-supply services are generally unregulated and unmonitored and overlooked in policies and regulations (Grönwall et al., 2010; Grönwall & Danert, 2020). While there are some examples of self-supply being formally supported or recognised by governments in LMICs, such as in Ethiopia (Butterworth et al., 2013), such cases are rare and remain the exception. Typically, self-supply services are often not subject to routine testing for drinking water quality, which instead focus on piped services provided by utilities. Self-supplied water is accessible on-premises and thus may contribute towards a country's safely managed water statistic, as having water supplied on the premises is a key criterion for a water service to be considered safely managed (Foster et al., 2021). However, little is known about the extent to which they provide safely managed water services to poor or vulnerable households in terms of water quality and availability (Grönwall & Danert, 2020). The potential risks to water quality associated with self-supply can be significant since self-supply systems often rely on vulnerable shallow groundwater sources, and infrastructure and maintenance are the households' own responsibility (Sutton & Butterworth, 2021). However, the lack of monitoring and regulation makes it difficult to detect and address contamination and provide support to households, ensuring safe and reliable water sources. This raises the critical question of how governments should respond to self-supply in order to protect public health and ensure universal access to safe water.

Given the high prevalence of self-supply and the lack of monitoring and regulation, it is crucial to study self-supply in research to ensure the provision of safe and reliable water sources for people who depend on it. Self-supply is a reality for millions of people, and it is essential to understand how it functions and the potential risks and benefits it poses. The lack of monitoring and regulation makes it challenging to ensure safe and reliable water sources for people who rely on self-supply services. Therefore, it is crucial to understand the characteristics of self-supply services and their potential to contribute to the SDG 6 targets for universal and equitable access to safe and affordable drinking water for all. Specifically, understanding the extent to which self-supply provides safely managed water services to households in terms of water quality and availability is critical for public health and universal access to safe water. This PhD research specifically focuses on groundwater self-supply in urban areas of Indonesia. It is important to investigate the water quality of groundwater self-supply and potential risk factors for faecal contamination, as well as availability and reliability of water from self-supply services, equity aspects such as socio-economic dimensions of users including wealth and gender, and monitoring of drinking water quality. The following sections (1.3.1 to 1.3.5) deal with these topics in more detail.

1.3.1 Water quality of groundwater self-supply services at the source

Addressing the water quality of groundwater self-supply services is crucial for providing millions of people with safe drinking water, as self-supply often relies on vulnerable shallow groundwater sources and lacks government regulation and monitoring. The main concern regarding self-supply is the potentially poor water quality and its associated health risks (Sutton, 2009). It is a fundamental but as yet unanswered question about the degree to which self-supply attains the safely managed service criteria, being free from contamination (Foster et al., 2021). Many self-supply services rely on shallow groundwater sources that are highly vulnerable to contamination from human activities (Grönwall et al., 2010). Self-supply services face an increased challenge in terms of water quality because they are on-site, often rely on simple construction technologies, are not regulated or monitored by the government, and are operated by users. As such, addressing the issue of water quality in self-supply services is critical to ensuring the provision of safe drinking water for millions of people and requires further investigation.

Understanding and categorising the various contamination factors is crucial for assessing and mitigating the risk of contamination for groundwater supplies. Faecal contamination from various sources including sanitation systems, solid waste dumps, household sullage, stormwater drains and animals poses a risk for groundwater supplies in general (ARGOSS, 2001). Which contamination sources dominate is likely to vary according to the characteristics of the groundwater system, the population density, the type and construction of the water point and the sanitation arrangements and practices in the community (Macdonald et al., 2005). Potential contamination factors can be differentiated into hazard, pathway and indirect factors (Howard, 2002). Hazard factors are referred to as factors from which contamination may be derived and are a measure of sources of faecal matter in the environment. Hazard factors include for example sanitation systems, solid waste dumps and animal husbandry. On the other hand, pathway factors refer to the factors that permit microbiological contamination to enter the water supply, but do not directly provide faecal matter. Pathways are often critical to whether contamination occurs, since the presence of a hazard may not directly correlate to contamination unless there is a pathway for the contamination to enter the water supply. Examples of pathway factors include infrastructure attributes such as leaking pipes or damaged protection works. Lastly, there are indirect factors, which enhance the development of pathway factors but are neither a direct source of faeces nor allow water into the source. An example of an indirect factor is the lack of fencing around or upstream of the water source, which prevents animals from getting close to the water source and possibly contaminating it (Howard, 2002). The PhD research categorises risks based on Howard's (2002) definition of hazard, pathway, and indirect factors (Figure 1), which is discussed in more detail in **Chapter IV**.

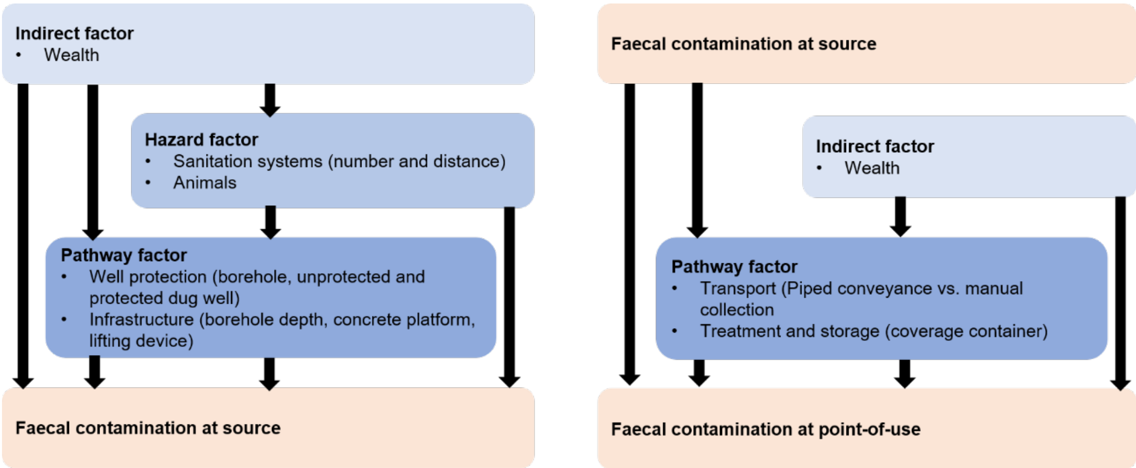

Figure 1: Conceptual model of faecal contamination including hazard factors, pathway factors and indirect factors used in this PhD research. (Adapted from Cronin et al., 2017 and Howard, 2002)

Despite the widespread global use of self-supply water services, a limited number of studies has been found which explicitly examined links between groundwater quality and contamination risks. The risk factors for faecal contamination of groundwater self-supply likely differ across contexts, influenced by various environmental conditions and possible contamination sources. Faecal contamination of groundwater supplies, caused by hazard factors such as on-site sanitation facilities and inadequate spacing to wells, is recognised as a major threat to water quality (Ravenscroft et al., 2017). Several studies on self-supply in peri-urban and urban areas in low-income settings have found significant associations between faecal contamination of self-supplied water and proximity of the well to a sanitation system (Kumpel et al., 2017; Martínez-Santos et al., 2017; Ngasala et al., 2019; Vollaard et al., 2005). Besides contamination caused by hazard factors, several studies suggest that water quality is influenced by pathway factors, such as inadequate well design and construction, and insufficient sanitary protection measures of self-supply (Ali et al., 2019; Butterworth et al., 2013; MacCarthy et al., 2013; Vaccari et al., 2010). However, there is a relative lack of studies that have rigorously assessed the links between groundwater quality and contamination risks in self-supply systems in LMICs. Within the identified studies, the focus is mostly not on self-supply water services and evidence for risk factors is often based on assumptions. Therefore, the PhD research rigorously assesses self-supply water quality and risk factors for faecal contamination.

1.3.2 Drinking water quality of self-supply services at the point-of-use

Considering water quality not only at source but also at point-of-use is important because water can become contaminated during transport, storage, and handling, which can lead to health risks for individuals using the water. Where the water supply is unreliable, temporarily interrupted or not on-premises, households usually store water to ensure that it is available when needed (WHO, 2022). It is known that the quality of water from improved sources deteriorates significantly after collection and is not necessarily safe at point-of-use (Clasen & Bastable, 2003; Ejechi & Ejechi, 2008; Gundry et al., 2006; Meierhofer et al., 2018; Trevett et al., 2005; Wright et al., 2004). Therefore, hygiene and post handling practices of collected water such as the location of water storage vessels, accessing stored water and water treatment methods are crucial for safe water at the point-of-use (McGuinness et al., 2020). In the broader water sector, studies have reported improved drinking water quality by treating water at the point-of-use, resulting in reduced waterborne diseases (Larson et al., 2006; Sobsey et al., 2008). In the context of self-supply, a crucial research gap exists in understanding water management practices and water quality at the point-of-use, as households bear the responsibility of managing their own water supply, and these services might be at risk of contamination at the source.

Only a limited number of studies have been conducted on management practices and water quality at point-of-use in the context of self-supply. For example in East Jakarta, Vollaard et al. (2005) assumed a reduced risk of diarrhoeal disease due to entrenched habits of boiling groundwater before consumption. Groundwater from private boreholes was used as a drinking water source and a source for washing food and dishes in 64% and 74% of the 243 and 286 surveyed households respectively. All respondents reported boiling drinking water before consumption, however non-boiled groundwater was used for food preparation. The study did test the water quality at source, but not at the point-of-use before consumption. Therefore, evidence about the effectiveness of boiling practices remains unclear. Ejechi and Ejechi (2008) detected fewer faecal and total coliforms in water samples obtained directly from the source of private boreholes than in those from the taps connected to private boreholes. Of the 100 samples collected, the number of samples contaminated increased from 10% to 28% for total coliforms and from 0% to 6% for faecal coliforms before and after distribution. The authors reported fieldwork observations such as burst pipes, worn-out sealants and poor pipe fittings as presumed causes of the contamination during pipeline distribution. This study shows that even if self-supply is on-premises, water quality can deteriorate between source and point-of-use.

In the context of self-supply, ensuring water quality at the point-of-use is particularly important since households are responsible for their own water supply, and water can become contaminated during transport, storage, and handling, putting individuals at risk of waterborne diseases. However, studies tend not to specifically consider water quality of self-supply water services and focus on measuring water quality at source, neglecting the point-of-use. There is a lack of information regarding management, storage and treatment practices in households using self-supply water services and how it relates to the water quality at point-of-use. Considering the water quality of self-supply at the point-of-use is crucial, since self-supply is on-premises and transport, distribution and storage practices might be different than for other water supply types. Therefore, the PhD research evaluates water management and treatment practices of self-supply users and assesses the microbial water quality at point-of-use before consumption.

1.3.3 Monitoring of groundwater self-supply quality

In the broader water sector, testing and monitoring water quality is a key element of drinking water safety, because of the widespread exposure to faecal contamination in drinking water (Bain et al., 2014a). The recommended measure of faecal contamination by the WHO is the presence of faecal indicator bacteria such as *Escherichia coli (E. coli)* (WHO, 2022). Thermotolerant coliforms can be used as an alternative faecal indicator to *E. coli* (WHO, 2022). The criteria determined for faecal indicators include that they should not be pathogens themselves, be universally present in faeces of humans and animals in large numbers, not multiply in natural waters, persist in water in a similar manner to faecal pathogens, be present in higher numbers than faecal pathogens, respond to treatment processes in a similar fashion to faecal pathogens and be readily detected by simple, inexpensive culture methods (WHO, 2022). *E. coli* is the most common measure of progress towards universal safe water, but it should be considered that three of the WHO faecal indicator criteria are not met by *E. coli* (Charles et al., 2020). The limitations of *E. coli* as a faecal indicator include that it can multiply in natural waters, be pathogenic, and are less robust than some pathogens (Charles et al., 2020). Despite its limitations, *E. coli* remains a commonly used and important faecal indicator for monitoring drinking water quality, which is why it was chosen for this PhD research.

Approaches to testing and monitoring water quality are evolving, however, robust approaches suitable for low-resource settings are lacking. A wide range of tests for faecal indicator bacteria is available, including presence/absence and quantitative tests (Bain et al., 2012). Often, tests rely on culture methods that require basic bacteriology laboratory facilities. Faecal indicator bacteria such as *E. coli* are commonly tested with inexpensive cultural methods that require basic bacteriology laboratory facilities such as membrane filtration with incubation of membranes on selective media and counting colonies after incubation at 35-37°C for 24-48 hours depending on the media (WHO, 2022). Other methods include enzyme-substrate tests, which rely on the combination of an enzyme substrate with a medium that supports selective recovery and growth (Manafi, 1996). A common assay for the detection and quantification of *E. coli* is the IDEXX Colilert with the Quanti-Tray®/2000 system, which quantifies *E. coli* using the most probable number (MPN) method (Chao et al., 2004). Enzyme-substrate tests are sensitive but expensive and require consumables and laboratory materials, such as quantification trays and a sealer, UV light to detect fluorescence and an incubator (Genter et al., 2019; Magro et al., 2014). Few tests are ideal for low-resource settings, and there is a need for simple, reliable and inexpensive microbial tests capable of determining faecal contamination levels (Bain et al., 2012).

To achieve and sustain universal access to safe drinking water, a comprehensive understanding of the water quality of various sources is required, including self-supply. However, monitoring programmes need to expand beyond the single measure of *E. coli*, as highlighted by Charles et al. (2020). Charles et al. (2020) suggested the need to shift from a focus on direct water quality measurements towards a prospective safety perspective to ensure the sustainability and security of water services. For water safety, frequent water testing accompanied by knowledge of the risks from sanitary inspections, systematic management approaches, and routine monitoring is essential (Charles et al., 2020). To effectively identify and manage threats related to *E. coli* contamination, it is essential to comprehend the variability in its occurrence and detection. This understanding entails considering multiple seasons in testing, as opposed to solely relying on data from a single period (Charles et al., 2020; Kostyla et al., 2015). Self-supply is not adequately captured in SDG monitoring, as water quality is currently monitored using routine water quality data from utilities or regulators, or Multiple Cluster Surveys conducted only in certain countries every few years (Foster et al., 2021). To achieve SDG 6 on safely managed drinking water for all, it is crucial to comprehensively assess the water quality of self-supply sources, taking into account the potential risks of contamination and the variability of the water quality over time.

Monitoring the water quality of self-supply services can be challenging due to the informal nature of self-supply arrangements, lack of data, and limited resources. The informal nature of self-supply makes it difficult to collect and analyse water samples on a regular basis, given the involvement of millions of individual water points, as opposed to piped water, where the drinking water of millions of citizens can be monitored by testing a single water supply (Crocker & Bartram, 2014; Foster et al., 2021; Sutton & Butterworth, 2021). Furthermore, self-supply services are the responsibility of households, which may have limited resources and technical expertise to conduct water quality monitoring (Sutton & Butterworth, 2021). Despite the challenges posed by the informal nature of self-supply, it is important to understand and evaluate monitoring options for self-supply services.

There is little guidance and evidence on the most effective methods for monitoring the quality of self-supply services in low-resource settings. The World Health Organization (WHO) guidelines for drinking water quality and the water safety plan manual recommend that common drinking water quality monitoring programmes should include both operational monitoring and independent surveillance (Bartram et al., 2009; WHO, 2022). Operational monitoring provides information for decision-making and corrective actions related to source protection and water treatment. Meanwhile, surveillance of drinking water quality involves an independent third party overseeing the water supply with a specific mandate to protect public health (Crocker & Bartram, 2014). While operational monitoring of piped water supplies using dedicated or shared laboratories and surveillance is common, there is limited operational monitoring of non-piped water sources, such as boreholes (Crocker & Bartram, 2014). Developing and evaluating effective and context-specific monitoring strategies for self-supply services in low-resource settings could be critical for ensuring sustained access to safe water.

Given that self-supply is managed by household themselves, involving them in the self-monitoring of their own water quality could be a promising approach. Participatory citizen monitoring has gained popularity in natural science research but is still scarce in the field of drinking water monitoring. In the water sector, citizen science is most prominent in the field of surface water quality monitoring programmes measuring chemical parameters and biological indicators (Brouwer et al., 2018; Conrad & Hilchey, 2011). Citizen science in the field of drinking water quality monitoring is scarce and is typically limited to the data collection of physical-chemical parameters, excluding microbial parameters (Brouwer et al., 2018; Buytaert et al., 2014; Peckenham et al., 2012). The first citizen science project on drinking water that was documented in academic literature was conducted with citizens of Amsterdam testing the composition and total number of bacterial species in their own tap water, resulting in raised participant awareness about microbial water quality as well as a better understanding of how the bacterial community composition in drinking water changes during transportation in the distribution system (Brouwer et al., 2018). In other fields, citizen science has shown positive impacts on participants, including in public engagement, raising awareness, social learning, knowledge gain or the democratisation of science (Walker et al., 2021). However, there may also be negative impacts of citizen science, such as over-burdening the public (Walker et al., 2021). Incorporating participatory citizen monitoring in drinking water quality monitoring, particularly in self-supply settings, could offer a promising approach that can potentially raise awareness and engagement among households, while also generating valuable scientific knowledge. Therefore, the PhD research established and evaluated a participatory monitoring approach in self-supply settings.

1.3.4 Availability, reliability and usage of water from self-supply services

Self-supply services are accessible on-premises, however it is important to know what role they play in terms of water availability. Generally speaking, in order to be considered a safely managed water service, drinking water should be available in sufficient quantities when needed (WHO, 2022). Availability can be measured by the quantity of water available or used in a given time period, the hours of service per day or the frequency of breakdowns and the time required for repairs (WHO, 2022). Many countries define an amount of water as a minimum norm to cover daily basic water needs, which is around 50-100 litres per capita per day (WHO, 2011). The Joint Monitoring Programme (JMP) measures water availability using survey data based on the amount of time when water is available, rather than quantity of water delivered. The recommended core question on the availability of drinking water assesses sufficiency of water available relative to need (WHO and UNICEF, 2018). When survey data is not available, JMP uses data from regulators or utilities on the number of hours of service per day, usually only for piped networks. An availability of a minimum of 12 hours per day will be used as the global benchmark for 'available when needed' where national or locally relevant standards for hours of service are not available (WHO, 2017). The PhD research uses availability measures based on JMP in household surveys to explore self-supply availability, assessing both the amount of time water is available and the sufficiency of available water relative to need.

A limited number of studies have examined the reliability and availability of self-supply services and found different outcomes, suggesting that the availability and reliability of self-supply varies depending on the source type and context of self-supply. Studies in Ethiopia and Cambodia demonstrate that self-supply water services can be more reliable than communal water systems. In Ethiopia, Butterworth et al. (2013) found that traditional wells with ropes or mechanised pumps were more likely to deliver a reliable supply of water than communal water systems with hand pumps (Butterworth et al., 2013). The study argues that traditional family wells were more reliable due to the possibility of maintaining the facilities themselves. Similarly, a study in Cambodia showed superior operational performance of privately owned handpumps (Foster et al., 2018). Privately owned handpumps had a higher functionality rate and a higher likelihood of repair, but also a greater probability of breakdown compared to communal handpumps. The study discussed factors such as the proximity of the private handpumps, socio-economic characteristics, user perceptions and decision-making authority as reasons for better operation and maintenance of private handpumps. The studies point out that self-supply has potential to provide reliable water supply, however, more evidence is needed for the reasons behind unreliable services of self-supply.

Water from self-supply services is used for different purposes, which needs to be factored in when considering whether it is available in sufficient quantities when needed. A study in Kenya reported that residents use private hand-dug wells for other purposes than drinking and cooking, suggesting that shallow groundwater sources provide poorer urban households with a substantial volume of water for domestic purposes (Okotto et al., 2015). The study estimated daily abstraction rates ranging from $0.02m^3$ to $3m^3$ between the wells. A study by Elliott et al. (2017) in Pacific Islands communities observed seasonal changes in the water sources used and the purpose of use. Rainwater is often used as a supplement rather than a replacement for existing water sources, and there is the opportunity to adapt to local water sources and precipitation patterns by using multiple household water sources. The use and availability of water from self-supply services differs depending on the location and context. It is important to factor in different water uses when considering to what extent self-supply water is available in sufficient quantities when needed. More research is needed, which focuses on the availability and reliability of self-supply services and the purpose of use of these services. Therefore, the PhD research explores the use and factors influencing non-use of self-supply services.

1.3.5 Equity aspects in the self-supply context

The socio-economic dimension is a critical equity aspect that should be considered in the context of self-supply, as it is closely linked to determinants of access to and use of water services. Self-supply systems, which rely on household-level water sources such as boreholes or dug wells, often involve significant investment costs and ongoing maintenance requirements (Sutton & Butterworth, 2021). As a result, socio-economic factors such as income can impact the ability of households to invest in and maintain these systems, and can lead to disparities in access to and usage of water services among different social groups. By considering socio-economic dimensions in the self-supply context, it is possible to identify and address these disparities, promote inclusiveness in water service provision, and ensure that self-supply services are sustainable over the long term. Furthermore, socio-economic dimensions can help to inform the design and implementation of water supply systems that are tailored to the specific needs and contexts of the communities they serve.

The importance of considering socio-economic dimensions in the self-supply context is reflective of a broader trend in the water sector towards a more holistic and equitable approach to water service provision. Traditionally, the water sector has focused primarily on technical solutions such as infrastructure development, without sufficient consideration of the social and economic context. However, it is now widely recognised that water services cannot be sustainable or effective in the absence of broader socio-economic development and support (Yang et al., 2013).

The SDG 6 therefore calls for universal and equitable access to safe drinking water (WHO & UNICEF, 2019). This aligns with efforts to realise the human right to water, which entitles everyone without discrimination to sufficient, safe and accessible water for personal and domestic use (UN Water, 2013). Groups and individuals who are particularly discriminated in accessing WASH are disadvantaged based on sex and gender, race, ethnicity, religion, national origin, birth, caste, language and nationality, disability, age and health status, economic and social status, and others (UN Water, 2013). In the WASH context, equality implies equal access to basic services and demands that everyone benefits from adequate services (UN Water, 2013). Equity is the principle of fairness and is a moral imperative that is open to diverse interpretations (UN Water, 2013). Considering both equity and equality is crucial in ensuring universal access to water services.

The PhD research recognises the importance of both these principles and will investigate their role in the self-supply context. Equity will be explored by identifying and analysing the various factors that lead to disparities in access to and use of safe self-supply systems. This will involve assessing the socio-economic status of households as well as identifying other potential barriers to access, such as gender, age, and disability. On the other hand, equality will be investigated by assessing the quality and availability of self-supply services available to households. This will involve assessing whether the service level provided meets the safely managed water criteria of being ‘free from contamination’ and ‘available when needed’. Understanding and considering both equity and equality in the self-supply context is important in promoting universal access to safe and reliable water services.

There are still knowledge gaps in realising adequate water and sanitation services for everyone and thereby putting the human rights to water and sanitation into practice. Monitoring inequalities in access to drinking water at national and local level is needed. To realise universal and equitable access to water services, disaggregated and higher resolution data is needed to identify inequalities, explore underlying reasons, and develop strategies for improving equality of access (Bartram et al., 2014). To identify discrimination and inequalities, JMP disaggregates data based on wealth quintiles and subnational differences in access to basic services (WHO, 2017). In many countries data on safely managed drinking water services is only available at national level or for certain population groups and is rarely disaggregated by population subgroups. To expand the monitoring of inequalities during SDG, JMP is aiming to prioritise and encourage disaggregation based on informal urban settlements, disadvantaged groups, affordability, and intra-household inequalities such as gender, which are currently not considered (WHO & UNICEF, 2020). More data is needed that provides insight into the local dynamics of inequalities and water access. Seeking to address the data gap on local level water inequality, the PhD research takes into account the socio-economic dimension.

Inequalities by household wealth in terms of water quality, availability and access to safe drinking water have been identified in several studies in the broader water sector. Wealth-based inequalities in WASH are a global issue, with wealthier households generally having greater access to improved drinking water sources (WHO & UNICEF, 2021). For example, a study from Cote d'Ivoire reported that the poorest more often obtained their drinking water from surface waters compared to the wealthier households, who were more likely to access groundwater via a handpump (Schmidlin et al., 2013). Evidence from Ghana indicates that poorer households are less likely to have access to safe water and improved sanitation facilities compared to richer households (Adams et al., 2016). Wealthier households were also in close proximity to the improved water sources compared to the poorest households. It is assumed that these households can afford private water connections or use protected dug wells within close proximity at home. Tucker et al. (2014) illustrated how poorer households in rural Ethiopia use less water for all purposes than wealthier households, which is attributed to labour, water storage and financial constraints. Poorer households owned fewer jerrycans and storage vessels and reported their inability to release labour for water collection as a main constraint in accessing water. They are also more likely to choose an unimproved source over a more expensive protected source. There is need to understand local dynamics of poverty and water access, including reasons for non-uptake of available services, and outcomes associated with different models of service delivery (Carrard et al., 2019). Addressing wealth-based inequalities in access to water services requires understanding the socio-economic dynamics of the local context, as well as exploring strategies that can effectively target and support the most vulnerable and marginalised households.

Wealth-based inequalities in WASH can be measured using a wealth index, which is a key proxy indicator to measure the socio-economic status of households. It uses information about household durable assets collected in standardised household surveys such as the

Demographic and Health Survey (DHS) and Multiple Indicator Cluster Surveys (MICS) (Poirier et al., 2020). The calculation method is usually based on the method developed by Filmer and Pritchett (2001) that summarises multi-dimensional information on ownership of various household assets using principal components analysis (PCA). Despite the ubiquity of use of the wealth index in global health research, debates over which calculation methods results in the best proxy for income or consumption remain open (Poirier et al., 2020). Using the wealth index to monitor inequalities in access to WASH raises the question of whether variables on water and sanitation should be used in the construction of the wealth index when the outcome analysed is water and sanitation coverage (Martel, 2016; Yang et al., 2013). The PhD research will utilise the wealth index as a tool to measure wealth-based inequalities in access to water services, taking into account the potential limitations and considerations in its calculation and interpretation.

The use of self-supply water services is seen as a result of socio-economic inequality in access to WASH by several studies. In Jakarta, studies mention the socio-economic inequalities in access to safe water as a consequence of lack of water service expansion or poor service quality and the subsequent use of expensive or potential low-quality alternative water sources (Furlong & Kooy, 2017; Hadipuro, 2010; Kurniasih, 2008). Kooy et al. (2018) found that the lowest income residents were less likely to have a piped water connection than the highest income residents. Consequently, 70% of the lowest income residents relied on shallow groundwater versus 38% of the highest income residents, with a similar volume of groundwater used for all income groups. Groundwater for drinking was used by 25% and 9.5% of the low and high-income households, respectively. Bottled water was purchased for drinking by 70% of the poorest and 90% of the wealthiest residents. The study reported that residents without access to viable groundwater due to salinisation relied on bottled water, the most expensive water source. In that context, groundwater self-supply provided a cheaper alternative source of drinking water than purchased water. Sutton and Butterworth (2021) observed in Malawi, Ethiopia and Zambia that being poorer reduces the probability of a family having its own well by around 20%, but does not preclude it. In Ethiopia, many families in this situation constructed their own wells. According to wealth surveys, households that own a well tend to experience economic benefits and are often classified in a higher income group, which can mask the fact that their situation was not as good at the time the well was constructed. This creates a situation where having a water supply is easier if a family is better off, but having one also tends to make them better off (Sutton & Butterworth, 2021). The use of self-supply as an alternative source of drinking water may not necessarily improve the equity in access to safe water, as the poorest households may have limited financial resources to invest in constructing and maintaining self-supply facilities, thereby further exacerbating the existing inequalities. Understanding the implications of self-supply on equity in access to safe water is crucial for developing effective and equitable water policies, and will be considered in the PhD research.

Understanding the gendered dynamics of household self-supply is important to promote more equitable and sustainable access to safe water, as it can reveal the unique challenges and opportunities faced by men and women in accessing and managing these services. In the broader WASH sector, the incorporation of a gender perspective has gained importance in literature and practice over the last decade (Carrard et al., 2022; MacArthur et al., 2020; Willetts et al., 2014). In many cases, women and girls are disproportionately affected by WASH issues due to differentiated biological needs, social norms and particular risks (Fisher et al., 2017; Hulland et al., 2015; MacArthur et al., 2020). Furthermore, WASH involves areas of labour inequalities in terms of unpaid care and domestic work due to socially constructed norms, such as the responsibility of women and girls for household water-related tasks (Grant et al., 2017). A meta-analysis across 45 developing countries found that 72% of daily household water-related tasks are done by women and girls (WHO & UNICEF, 2010). It is well recognised that the responsibility for water collection is disproportionately placed on women and girls, resulting in significant impacts on their time, health, and education (Graham et al., 2016). Since self-supply services are privately owned and located on-premises, they provide more convenient access to water and differ from other water sources (Sutton & Butterworth, 2021). However, household members may have different roles and responsibilities in using and managing these services, and gender dynamics may play a significant role in shaping these roles. Therefore, exploring the gendered dynamics of household self-supply is essential to inform policies and practices that address potential inequalities and promote more inclusive and sustainable access to safe water.

Gender equality in water management is crucial for achieving sustainable and inclusive development, as it ensures that both men and women can equally participate in decision-making processes and benefit from improved access to water and sanitation facilities. Studies mainly focus on community water management involving the management and underlying gender dynamics of shared water resources at the community level. Due to social norms, men have generally been the decision-makers in water management and women have only limited influence (Acey, 2010; Carrard et al., 2013; Fisher, 2008; Kilsby, 2012). Although women play significant roles in water-related tasks and family caring roles, gender-related barriers lead to women's exclusion from decision-making forums (Water Governance Facility, 2014). Barriers include being time-poor due to household responsibilities, cultural barriers to women's participation, and inferior education levels and opportunities (Water Governance Facility, 2014).

In the context of self-supply research, understanding the gendered dynamics of household self-supply is essential in shedding light on how gender norms and power relations shape water access and management within households. Self-supply services are typically privately owned and located at the household level, which makes intra-household gender dynamics particularly relevant for understanding access to and management of self-supply services, in contrast to community-level dynamics. In the context of decision-making related to water management, women's voices are more likely to be heard and given weight in their own households (Sutton & Butterworth, 2021). Sutton and Butterworth (2021) posit that the urgency for repair or re-deepening a well is more likely to elicit a positive response when the water source is privately owned. In these situations, decision-making is often simpler and more favourable to women, as they have greater influence in these smaller and more intimate settings compared to the broader community context (Sutton & Butterworth, 2021). While community-level water management is the focus of most studies, household-level dynamics of self-supply water services need to be given more attention. The PhD research therefore investigates gendered power relations and decision-making processes in households, including the barriers faced by women in managing and accessing self-supply services.

The existing research literature on the relationship between gender and self-supply water services has significant gaps. Specifically, no study has been found that explores gender roles in the context of self-supply water access, availability, and use. Self-supply services are unique in that they are privately owned and located on premises, providing convenient access to water, which sets them apart from other water sources. Therefore, it is crucial to understand the intra-household dynamics that shape the use and management of self-supply services. To address these gaps in the existing literature and contribute to a better understanding of gender dynamics in self-supply water services, the PhD research explores the gendered dynamics of household self-supply and the role of gender norms and power relations in shaping access to and management of self-supply services.

1.4 Research questions

This PhD research aims to assess self-supply water services in urban Indonesia considering safely managed water service criteria, with a focus on microbial water quality, management, and monitoring, taking equity aspects such as socio-economic factors and gender dimensions into consideration (Table 1). The identification of research gaps in the literature prompted the development and determination of research questions to be investigated. This PhD research is divided into three main research areas and research questions to address the overarching objective. The first area focuses on the microbial water quality of groundwater self-supply (Section 1.4.1), the second area investigates the use and management of groundwater self-supply at the household level (Section 1.4.2), and the third area examines the monitoring of microbial water quality of groundwater self-supply services (Section 1.4.3).

The PhD research consists of the three main research questions (RQ):

RQ1: To what extent is groundwater self-supply free from faecal contamination at both source and point-of-use and what are potential risk factors of faecal contamination?

RQ2: How is self-supply used and managed by individual households, including intra-household gender dynamics?

RQ3. To what extent is participatory citizen monitoring an appropriate approach to monitor self-supply services in terms of microbial water quality?

The research questions are interlinked in the course of the thesis, using the social-ecological system approach. The PhD research considers equity aspects such as socio-economic factors and gender-dynamics and also discusses the household's responsibility for managing the water supply. The research took place in Kota Bekasi and Kota Metro in urban Indonesia (Section 2.3.2). As such, the focus of the PhD research is specifically on self-supply services based on groundwater in an urban setting.

The PhD research is in the form of 'thesis by compilation' that is structured as a single manuscript that comprises a combination of eight chapters and five published works. The following sections (1.4.1 to 1.4.3) describe the focus areas of the PhD including the research questions and corresponding justification and milestones.

Table 1: PhD objectives including the overarching objective, the focus areas with research questions (RQ), equity aspects and corresponding chapter in the PhD thesis.

Overarching objective	**Investigating self-supply as a safely managed water service in urban Indonesia, with a focus on microbial water quality, management, and monitoring, taking equity aspects into consideration**		
Focus areas	Evaluation of microbial water quality of groundwater self-supply and associated risk factors	Evaluation of use and management of groundwater self-supply at household level	Evaluation of a participatory approach to monitor microbial water quality of groundwater self-supply services
Research Questions (RQ)	**RQ1.** To what extent is groundwater self-supply free from faecal contamination at both source and point-of-use and what are potential risk factors of faecal contamination?	**RQ2.** How is self-supply used and managed by individual households, including intra-household gender dynamics?	**RQ3.** To what extent is participatory citizen monitoring an appropriate approach to monitor self-supply services in terms of microbial water quality?

Equity aspects	Socio-economic equity aspects	Intra-household gender dynamics	Responsibility for water quality monitoring in self-supply
	Chapter III **Chapter IV**	**Chapter V**	**Chapter VI**

1.4.1 Microbial water quality of groundwater self-supply

Despite the importance of self-supply systems, there is a relative lack of studies that have rigorously assessed the links between groundwater quality and contamination risks in self-supply systems in LMICs. There are gaps in evidence about the level of service that self-supply delivers in terms of water quality and to whom. Risks of water contamination and related pathways are site specific and poorly understood. Further, it is unclear to what extent poor and non-poor households are affected differently by the risks of water pollution. Additionally, consideration of point-of-use water quality is crucial in the context of self-supply, as households bear the responsibility of managing their own water supply and self-supply services. However, studies tend not to consider the point-of-use in the context of self-supply. The first research area aims to address the identified gaps by exploring the microbial water quality of self-supply services at both source and point-of-use, while considering various contamination risks.

The first research question (RQ1) asks: **To what extent is groundwater self-supply free from faecal contamination at both source and point-of-use and what are potential risk factors of faecal contamination?** RQ1 aims to investigate the water quality of groundwater self-supply services including the potential hazard and pathway factors of faecal contamination, as well as indirect factors that may contribute to increased risk of contamination. The socio-economic equity aspect is considered as an indirect risk factor for faecal contamination, as the wealth status of households might be associated with different risks of faecal contamination. RQ1 was addressed in five milestones. Firstly, safety and the potential risk of faecal contamination of self-supply services were investigated based on a systematic literature review and meta-analysis using peer-reviewed literature on self-supply and microbial water quality in LMICs (**Chapter III**). Secondly, a household survey was conducted, and microbial water quality was tested at the study sites in urban Indonesia to collect relevant on-site data on water safety (Section 2.3.3). Thirdly, a wealth index was constructed to disaggregate households into different wealth categories (Section 2.3.3.1.1). Fourthly, quantitative analysis, including descriptive and inferential statistics, was used to evaluate potential associations between household wealth status, water quality and contamination risks (**Chapter IV**). Lastly, seasonality was considered by comparing microbial water quality from the wet and dry seasons (**Chapter IV**).

1.4.2 Use and management of groundwater self-supply at household level

Understanding the use and management of groundwater self-supply at household level is crucial, as households bear the responsibility of managing their own water supply. However, only a limited number of studies have been conducted on management practices and water quality at point-of-use in the context of self-supply. Self-supply is accessible on-premises, but there is limited available evidence on the extent to which it provides safe and reliable water for households. It is unclear to what extent and how the availability of self-supply contributes to the coverage of daily basic needs. Further, it is also important to consider the use of multiple water sources in the context of self-supply, as households may rely on various sources for different purposes, which can be influenced by socio-economic factors. Exploring multiple water source use can help identify disparities in access and management practices, which is a yet under-researched topic. Existing research on gender and water supply service delivery has mainly focused on community-level interactions, which has left a gap in understanding how gender dynamics operate within households in the context of self-supply. It is important to explore the gendered intra-household dynamics in access, use, and management of self-supply service to identify potential disparities.

Therefore, the second research question (RQ2) asks: **How is self-supply used and managed by individual households, including intra-household gender dynamics?** This research question sought to understand the use and non-use of self-supply services and alternative water choices and how self-supply is managed by individual households, including intra-household gender dynamics. RQ2 was addressed in two milestones by an explanatory sequential mixed-methods approach comprising a quantitative component followed by a qualitative component. First, the quantitative approach focused on a descriptive assessment of the cross-sectional household survey (Section 2.3.3) providing generalisable insights into the use and management of self-supply. Second, the qualitative approach included in-depth interviews providing detailed and contextualised explanatory insights (Section 2.3.4). The mixed-methods approach allowed for comprehensive findings and provided both broader and deeper insights into the use and management of self-supply (**Chapter V**).

1.4.3 Monitoring microbial water quality of groundwater self-supply

Monitoring water service delivery is essential for government regulation and to contribute towards SDG 6 on safely managed water for all. However, self-supply is often not specifically recognised as a formal service delivery model, placing the responsibility for water safety on households themselves. This creates a challenge as traditional water quality monitoring methods may not be suitable for capturing the diversity of self-supply water sources, resulting in a lack of reliable data on the quality of self-supply sources due to limited monitoring and testing capacity. Consequently, there is a need for research into the feasibility and effectiveness of monitoring approaches for self-supply water quality, particularly participatory monitoring approaches, which are not yet widely used in the field of microbial water quality. Therefore, the third research question (RQ3) asks: **To what extent is participatory citizen monitoring an appropriate approach to monitor self-supply services in terms of microbial water quality?** The research question RQ3 was addressed in three milestones. First, in the preparation and planning phase, households were chosen and equipment was ordered. Second, over a period of six months participants tested self-supplied water every two weeks using field test kits to check for the presence of *E. coli* (Section 2.3.5). The monitoring approach was evaluated based on the feasibility of the participatory monitoring approach, including motivation of participation, awareness and understanding of participants, as well as the water quality results and reliability. A conceptual framework suitable for context analysis, process evaluation and impact assessment (CPI) was used to analyse the functioning of the participatory monitoring approach (**Chapter VI**).

1.5 Research overview

The research is comprised of the three focus areas outlined above (Sections 1.4.1 to 1.4.3), presented in eight chapters (Table 2). Following this introduction (**Chapter I**), **Chapter II** details and justifies the research approach, locating the conceptual framework and research methods across the research areas. **Chapter III** presents a systematic literature review and meta-analysis of faecal contamination of groundwater self-supply in LMICs (Publication I). Three of the chapters within this thesis can be considered as results chapters (**Chapter IV**, **Chapter V** and **Chapter VI**). **Chapter IV** presents and discusses the results on the assessment of risk factors for faecal contamination of groundwater self-supply in urban Indonesia (Publication II). In addition, it also reveals the results on associations between seasonality and faecal contamination (Publication III). **Chapter V** expounds results on household self-supply use and management in urban Indonesia (Publication IV). The next **Chapter VI** discloses the results of a participatory approach to monitor microbial water quality of groundwater self-supply services. Following the results chapters, **Chapter VII** evaluates and discusses self-supply water services in terms of the criteria for a safely managed water service, based on the conceptual framework presented in **Chapter II**. Finally, **Chapter VIII** draws conclusions and implications and summarises future research priorities.

Table 2: PhD overview including focus area with research questions (RQ), milestones (M), research outputs and corresponding chapter in the PhD thesis. The research relates to urban Indonesia expect for M1.1 and Publication I, which refers to LMICs.

	Focus area	Research Question (RQ)	Milestones (M)	Research outputs
Chapter III and IV	Evaluation of microbial water quality of groundwater self-supply and associated risk factors	**RQ1.** To what extent is groundwater self-supply free from faecal contamination at both source and point-of-use and what are potential risk factors of faecal contamination?	M1.1 Assessment of water quality in self-supply sources in LMICs based on the literature M1.2 Water quality testing of self-supply sources in urban Indonesia alongside household surveys M1.3 Wealth index construction M1.4 Evaluation of the potential risks for faecal contamination M1.5 Consideration of seasonality	**Publication I** in Water Research (Genter et al., 2021) **Publication II** in Water Resources Research (Genter et al., 2022) **Publication III** in Water, Sanitation and Hygiene for Development (Genter, Putri, Maysarah, et al., 2023)
Chapter V	Evaluation of use and management of groundwater self-supply at household level	**RQ2**. How is self-supply used and managed by individual households, including intra-household gender dynamics?	M2.1 Quantitative approach including descriptive analysis of structured household survey M2.3 Qualitative approach including preparing, conducting and analysing in-depth interviews	**Publication IV** in PLOS Water (Genter, Putri, Suleeman, et al., 2023)
Chapter VI	Evaluation of a participatory approach to monitor microbial water quality of groundwater self-supply services	**RQ3**. To what extent is participatory citizen monitoring an appropriate approach to monitor self-supply services in terms of microbial water quality?	M3.1 Planning phase including household selection M3.2 Participatory monitoring approach M3.3 Evaluation	**Publication V** in Urban Water (Genter, Putri, Handayani, et al., 2023)

Chapter II

2. Research approach

2.1 Overview

Chapter II describes and justifies the research approach to evaluate self-supply water services as safely managed water services in urban Indonesia. First, the social-ecological system approach that was used as a conceptual framework to combine the interdisciplinary areas of this PhD research is introduced and justified. As an adapted version of the existing social-ecological system approach of Hoque et al. (2019) is proposed as a theoretical perspective for the PhD research, both versions, the existing and adapted, are presented in this chapter. Then, the chapter describes how the PhD research is situated in the social-ecological system approach. The PhD research used quantitative, qualitative and mixed-methods approaches to answer the research questions. This chapter describes the proposed study sites and data collection methods and approaches, which are also discussed in more detail in the individual chapters. Lastly, the chapter clarifies ethical considerations and the influence of the Covid-19 pandemic on the research.

2.2 Social-ecological system approach

With increasing awareness of the interconnectedness between human and natural systems, there has been a growing interest in the social-ecological system approach as a way to study and manage complex environmental issues. Social-ecological system approaches are widely used to generate knowledge on how human and natural systems interact between different components and providing a common language for scholars from different disciplines (McGinnis & Ostrom, 2014).

One of the most widely recognised and used social-ecological system approaches is Ostrom's (2009) framework. Ostrom's framework for analysing the sustainability of social-ecological systems disaggregates natural systems into resource systems, resource units, governance systems, users, interactions and outcomes (Ostrom, 2009). The core subsystems are further subdivided into multiple lower-level variables and attributes.

The social-ecological system approach provides a comprehensive framework that considers the complex interrelationships between social and ecological systems. It is useful in providing a common set of potentially relevant variables to use in the analysis of the findings about the sustainability of complex social-ecological systems (Ostrom, 2009). By providing a holistic and integrated framework for understanding and managing social-ecological systems, the social-ecological system approach can contribute to the development of more sustainable and resilient environmental management policies and practices.

A social-ecological system approach was chosen as a conceptual framework for the PhD research due to its interdisciplinary, comprehensive, and practical nature. Using the social-ecological system approach, the PhD research enables a more holistic understanding of self-supply services. The social-ecological system approach has a sustainability focus, emphasising the need to balance human needs and ecological sustainability (Ostrom, 2009). Furthermore, it is an interdisciplinary framework that draws on multiple fields (McGinnis & Ostrom, 2014). Using this approach can help bridge the gap between different disciplines and facilitate the communication of results across research communities. The social-ecological system approach has a practical and adaptive nature, allowing it to be applied to specific cases and contexts (Folke et al., 2010; McGinnis & Ostrom, 2014). As a result, it can inform practical implications for policy and decision-making.

2.2.1 Social-ecological analysis of drinking water risks

The social-ecological system approach developed by Hoque et al. (2019) focuses on the human-nature interactions related to drinking water service delivery and is therefore relevant for this PhD research. The framework is an adapted version of Ostrom's social-ecological system framework (Ostrom, 2009). As new aspects relative to Ostrom's framework, Hoque et al. (2019) include a separate 'Infrastructure' component as well as a risk perspective, and uses the social-ecological system approach to conceptualise and analyse the risks to drinking water security.

Based on Grey and Sadoff (2007), water security in the context of drinking and domestic uses comprises a provision and risk perspective and is defined as the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies. The provision perspective emphasises the need for universal access to adequate and affordable water services to meet the basic needs of all people (Bradley & Bartram, 2013). Hoque et al. (2019) focused on the risk perspective and defined risk based on Aven and Renn (2009) as a hazardous event that jeopardises something of human value, including but not limited to physical health, emotional wellbeing, assets, and livelihoods. Hoque et al. (2019) outlined 'Water resources', 'Infrastructure', 'Governance and institutions', and 'Users' as the core components (Figure 2), linking them to the environmental, institutional, financial and social water security risks:

- **Water resources** include the quality, quantity and spatio-temporal distribution of rain and groundwater. *Environmental risks* such as hydrogeology and climatic stresses particularly affect water resources.

- **Infrastructure** encompasses different public and private water supply technologies to access the water resources. *Financial risks* like inadequate investments, low-cost recovery and inequitable pricing structures are linked to the 'Infrastructure' component.

- **Governance and institutions** refer to the rules, practices and processes that influence the use and management of water resources. *Institutional risks* can be created through gaps in policy design and enforcement, poor coordination among government and private actors, limited local government capacity, unclear roles and responsibilities, and power dynamics.

- **Users** include social actors who benefit from the water resource and face *social risks* such as for example wealth and gender-inequalities.

- **Interactions** encompass water management practices such as abstracting, collecting, storing and using water for drinking and domestic purposes.

The framework of Hoque et al. (2019) recognises the role of infrastructure in the social-ecological system, which play a crucial role in the provision of water services. As opposed to Ostrom's framework, Hoque et al.'s framework uses 'Infrastructure' as a separate component, while Ostrom's social-ecological system framework includes technology as either 'human constructed facilities' under the 'Resource system' component or 'technology used' under the 'Users' component (Hoque et al., 2019; Ostrom, 2009). Hoque et al.'s framework provides a better fit for the evaluation of water services over Ostrom's framework as it elevates technology and infrastructure and its role in providing resource-based services.

Given the focus on self-supply water services in this PhD research, an adapted version of Hoque et al.'s (2019) social-ecological system approach is proposed as the theoretical perspective. The adapted framework is described in the next section (2.2.2).

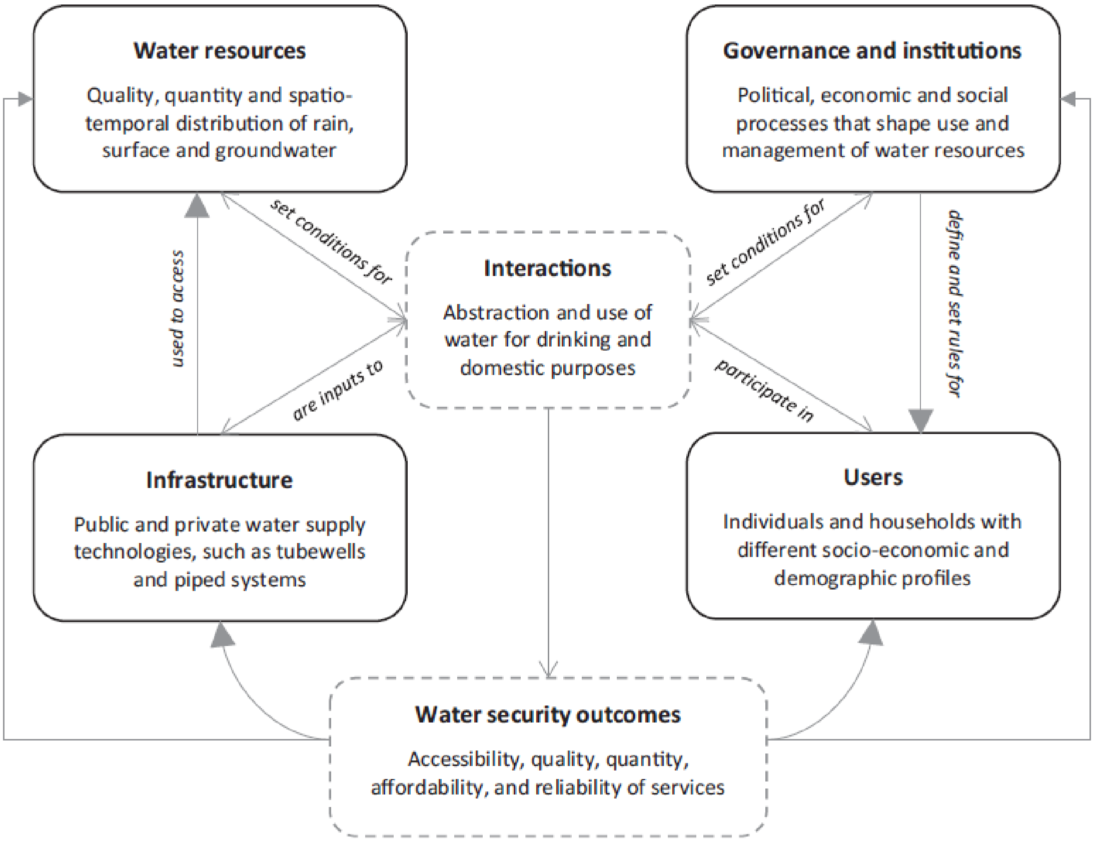

Figure 2: Social-ecological system framework of Hoque et al. (2019), which combines human-nature interactions with water security (Hoque et al., 2019).

2.2.2 Social-ecological system approach of the PhD research

The PhD research will apply an adaption of the social-ecological system approach by Hoque et al. (2019) to examine the research questions and to evaluate water self-supply as safely managed water services. To evaluate and inform water self-supply services, it is necessary to understand interrelated aspects concerning self-supply that cut across both the technical and social domains. Rather than examining water security and associated risks more broadly, the social-ecological system framework of Hoque et al. (2019) has been tailored to specifically address self-supply services within the context of the PhD research. The focus of the research will be on the outcomes of water services related to self-supply. All components of Hoque et al.'s framework cover the PhD research, but were adapted to relate to the PhD research questions (Figure 3):

- **Water resources** include the quality and availability of groundwater sources. All three research questions are situated within this component, with some research questions having greater focus on that component than others.

- **Infrastructure** encompasses self-supply technologies, such as boreholes and dug wells, and water abstraction technologies, such as electric pumps and ropes and buckets. Type and condition of the infrastructure is examined as part of RQ1 and linked to the 'Water resources' component.

- **Governance and institutions** encompass a monitoring focus, which is explored as part of RQ3. In addition, governance also includes management and decision-making processes, which are dealt with in RQ2. In the case of self-supply, these processes are carried out by the users themselves. Overall, the synthesis of self-supply as a safely managed water service and its implications, based on the findings of all three research questions (**Chapter VII**), will provide guidance to governance and institutions on how to respond to self-supply.

- **Users** include individuals and households which benefit from the self-supply water source. The PhD research focuses on socio-economic dimensions including wealth and gender with regard to self-supply use and management. RQ2 emphasises the user's perspective and their interactions with water resources and service outcomes.

- **Interactions** encompass water management practices such as abstracting, collecting, storing and using the self-supply water for drinking and domestic purposes. All three research questions are situated within this component, with some research questions having greater focus on this component than others.

- **Water service outcomes** refer to the quality and availability of self-supply service at household level. The PhD focuses on the microbial quality and availability of the self-supply services. Accessibility in terms of source location is assumed as given since self-supply systems are on-premises. Affordability is considered indirectly as part of the socio-economic characteristics, which are situated in the component ‘Users’. All three research questions are connected to this component, with some research questions having greater focus on this component than others. In contrast to Hoque et al. (2019) the PhD research generally refers to water service rather than security outcomes.

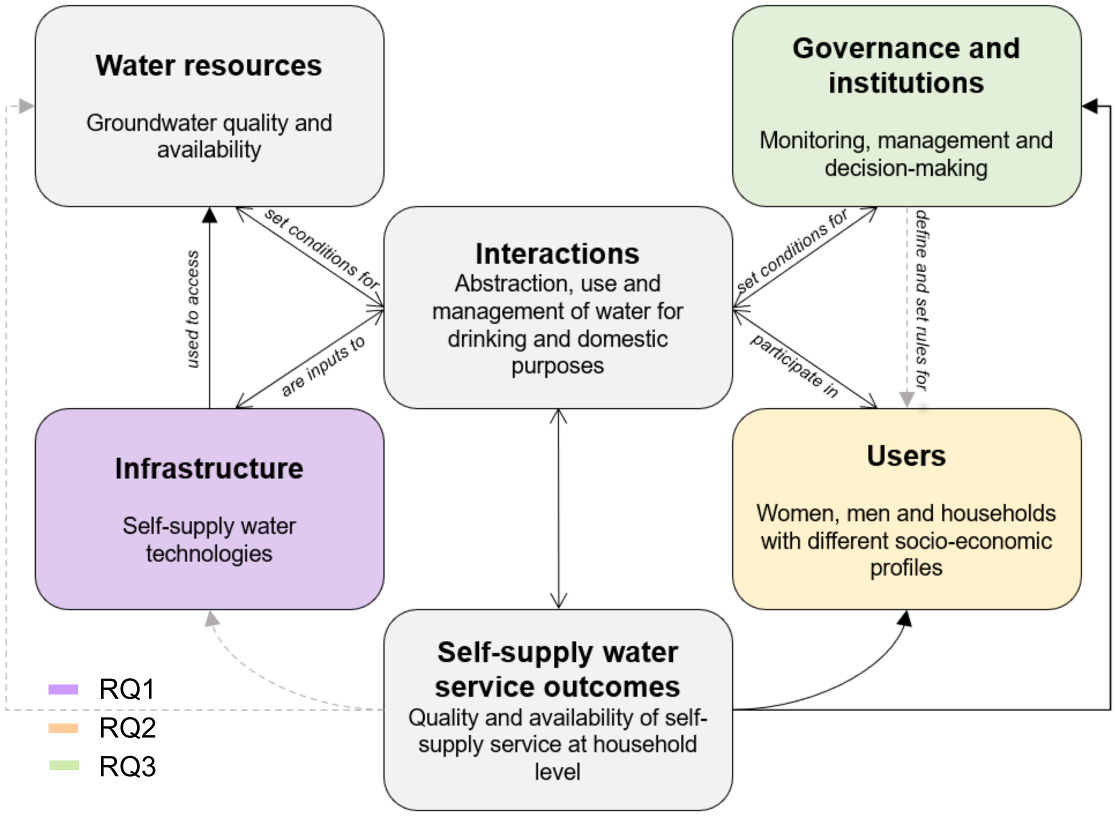

Figure 3: Adapted social-ecological system framework of Hoque et al. (2019), which is used in the PhD research as a conceptual framework. All three research questions (RQ) are situated within the grey shaded components of ‘Water resources’, ‘Interactions’, and ‘Self-supply water service outcomes’, with some research questions having greater focus on these components than others. RQ1 has a focus on ‘Infrastructure’ and how it relates to ‘Water resources’ and ‘Self-supply water service outcomes’. RQ2 on the other hand, emphasises the ‘User’s’ perspective and their interactions with ‘Water resources’ and ‘Self-supply water service outcomes’. RQ3 on self-supply monitoring is situated in the ‘Governance and institutions’ component.

2.2.3 Situating the PhD research

The PhD research questions were situated within the social-ecological framework's components, which cover 'Water resources', 'Infrastructure', 'Governance and institutions', 'Users', 'Interactions', and 'Self-supply water service outcomes'.

- **RQ1** explores the factors affecting the quality of water resources in terms of faecal contamination (**Chapter III** and **Chapter IV**). It examines factors influencing faecal contamination of self-supply services such as the infrastructure's type and condition, the socio-economic profiles of users and the seasonality. RQ1 primarily focuses on the 'Infrastructure', 'Water resource' and 'Self-supply water service outcomes' components, but also considers information from other components, such as socio-economic profiles of the 'Users' component.
- **RQ2** explores the use and water management practices of self-supply users considering intra-household gender dynamics (**Chapter V**). RQ2 primarily focuses on the 'Users' and 'Interactions' components but is also relevant for the 'Governance and Institutions' component. Factors affecting the use and management of self-supply, such as the availability and quality of groundwater sources at household level, form part of the 'Self-supply water service outcomes' component.
- **RQ3** considers the governance and institutional aspects of self-supply, with a focus on a monitoring approach for self-supply services (**Chapter VI**). RQ3 establishes and evaluates a participatory monitoring approach involving self-supply users in water quality monitoring. Findings form the basis for informing approaches to monitoring.

The framework's components and interrelations provide the foundation for the synthesis of self-supply as safely managed water services in **Chapter VII**. The synthesis draws on the findings of the PhD research questions and uses the framework to highlight implications with regard to safely managed water services. Moreover, the synthesis informs support strategies intended to move self-supply services towards a safely managed drinking water service. The findings of this PhD research have significant relevance for policy and practice in urban Indonesia, where more than 40 million people rely on groundwater self-supply.

2.2.4 Adaptions of the social-ecological system approach

The social-ecological system utilised to conceptualise the PhD research is an adapted framework based on the social-ecological system approach developed by Hoque et al. (2019). This section describes two key adaptations made to the framework of Hoque et al. (2019). Firstly, the social-ecological system approach employed in the PhD research places emphasis on water service outcomes rather than water security outcomes. Secondly, while the core components of the social-ecological system approach are addressed, the framework in the PhD research does not explicitly link them to the environmental, institutional, financial, and social water security risks as proposed by Hoque et al. (2019). The section deals with the definitions of “water security” and justifies the focus on “water service outcomes” in the PhD research.

While the PhD research focuses on domestic water services, particularly self-supply, water security is often defined in much broader terms. Numerous definitions and assessment frameworks for water security exist (Allan et al., 2018). The framing of water security varies; some frameworks focus on risks, while others adopt a broad understanding with a focus on the development of water resources to meet human needs (Aboelnga et al., 2019). A widely used definition of water security is that of Grey and Sadoff (2007), who define water security as the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies. The definitions of water security are often holistic and interdisciplinary, capturing all perspectives and dimensions.

The Hoque et al. (2019) framework on water security in the context of domestic water services include a risk and provision perspective, which might not be entirely appropriate for self-supply services, as the acceptability of self-supply as a form of provision could be subject to debate. Hoque et al. (2019) uses the definition of water security in the context of drinking water and domestic uses based on Grey and Sadoff (2007), which include a ‘provision’ and a ‘risk’ perspective. The provision perspective emphasises the need for universal access to adequate and affordable water services to meet the basic needs of all people (Bradley & Bartram, 2013). The framework of Hoque et al. (2019) characterised water security by four intersecting risks based on Hope and Rouse (2013), namely environmental, institutional, financial and social risks. The inclusion of a provision and risk perspective was not considered appropriate in the context of this PhD research, as the acceptability of self-supply as a mode of provision might vary depending on the context and might therefore be arguable. The acceptability of self-supply is dependent on how well these systems achieve the safely managed criteria, like any other model of service delivery.

While the definition of water security of Charles et al. (2020), which includes the aspect of sustainability, would be suitable in the context of self-supply water services, the scope and objectives of the PhD research could not directly assess sustainability. According to Charles et al. (2020), water security entails ensuring the sustained provision of safe services. Sustainability, in this context, refers to the ongoing and reliable functioning of self-supply services (Bradley & Bartram, 2013). Charles et al. (2020) employed the term “security” to encompass long-term considerations and protection against uncertain factors such as demographic change, climate change, and increasing water pollution. They also emphasise the interpretation of water quality measurements and risks as integral components of “water safety”. In the light of these considerations, the framework for the PhD research was adapted accordingly, placing a focus on self-supply water service outcomes rather than water security outcomes. This adjustment aligns with the specific scope and objectives of the PhD research.

In conclusion, the findings of the PhD research primarily inform self-supply water service outcomes rather than water security outcomes. The PhD research defines self-supply water service outcomes as the quality and availability of water at household level provided by the self-supply systems. Water security encompasses broader sustainability considerations that were not directly addressed in the PhD research. The scope of the PhD research did not directly account for uncertain long-term impacts such as climate change or demographic change. Therefore, the component of ‘Water security’ within the social-ecological system approach was adapted in the PhD research to focus on ‘Self-supply water service outcomes’.

2.3 Methods and data collection approach

This section provides information about the study sites, methods, and data collection approaches, which are also detailed in each publication. Data for this PhD research were collected through a range of methods, including household surveys, microbial water quality testing, in-depth interviews, and participatory monitoring (Table 3). The study locations, methods, data collection and analytical approaches are also described in more detail in each publication. As such, this section serves as an overview and overlaps with the more detailed descriptions contained in the publications (**Chapter III**, **Chapter IV**, **Chapter V**, **Chapter VI** and Appendix **A1**).

Table 3: Overview of methods and time of data collection including focus area, milestones (M), and corresponding chapter in the PhD thesis.

	Focus area		Milestones (M)	Methods and data collection approach	Study sites and time of data collection
Chapter III and IV	Evaluation of microbial water quality of groundwater self-supply and associated risk factors	Publication I	M1.1 Assessment of water quality in self-supply sources in LMICs based on the literature *(data collection and analysis fully developed as part of the PhD)*	Systematic literature review and meta-analysis	Including low- and middle-income countries, conducted during 2020-2021
		Publication II	M1.2 Water quality testing of self-supply sources in urban Indonesia alongside household surveys *(in data collection involved as part of the broader project, analysis fully developed as part of the PhD)* M1.3 Wealth index construction *(analysis fully developed as part of the PhD)* M1.4 Evaluation of the potential risks for faecal contamination *(analysis fully developed as part of the PhD)*	Household survey and water quality testing (2.3.2)	Bekasi: R1-B: February-March 2020 (wet season) Metro: R1-M: October-November 2020 (dry season)
		Publication III	M1.5 Consideration of seasonality *(in data collection involved as part of the broader project, analysis fully developed as part of the PhD)*	Household survey and water quality testing (2.3.2)	Bekasi: R1-B: February-March 2020 (wet season) R2-B: October 2021 (dry season) Metro: R1-M: October-November 2020 (dry season) R2-M: February-March 2022 (wet season)
Chapter V	Evaluation of use and management of groundwater self-supply at household level	Publication IV	M2.1 Quantitative approach including descriptive analysis of structured household survey *(in data collection involved as part of the broader project, analysis fully developed as part of the PhD)* M2.3 Qualitative approach including preparing, conducting and analysing in-depth interviews *(data collection and analysis fully developed as part of the PhD)*	Household survey (2.3.2.1) and in-depth interviews (2.3.3)	Household survey: Data from R1-B and R1-M In-depth interviews: Bekasi: December 2020 Metro: August 2021 and November 2021-January 2022

Chapter VI	Evaluation of a participatory approach to monitor microbial water quality of groundwater self-supply services	Publication V	M3.1 Planning phase including household selection M3.2 Participatory monitoring approach M3.3 Evaluation *(whole approach fully developed as part of the PhD)*	Participatory citizen monitoring (2.3.4)	Bekasi: Data collection from April to November 2022

2.3.1 Systematic literature review and meta-analysis

The systematic review of studies including faecal contamination of groundwater self-supply in LMICs was conducted according to the PRISMA guidelines (Moher et al., 2009a). Methods for search strategy, study eligibility and data extraction were adapted from Bain et al., (2014) and are described in the protocol (Appendix **A2**). The PRISMA guidelines stipulate that more than one author is responsible for screening and inclusion of articles. However, for this study, one author was responsible for screening and inclusion of articles, as there was insufficient budget to assign another author to screen all articles. The extracted data of the systematic literature review can be found in the supplementary material of the publication (Appendix **A1**).

2.3.2 Study sites

The study was undertaken in Bekasi and Metro, two densely populated cities in Indonesia. Kota Bekasi and Kota Metro were selected as study sites because of the lack of access to piped water, the widespread use of self-supply and the high population density. These study sites were predetermined as part of the broader research project. Given the context specific nature of self-supply, the inclusion of two study sites offers a more comprehensive view of self-supply water services.

Indonesia's Central Agency for Statistics (Statistics Indonesia) defines urban areas based on population density, the percentage of agriculture-based households, and the number of available urban amenities. After the year 2000, this classification has been measured by a scoring system. Urban areas are characterised by major non-agricultural activities, while rural areas are primarily involved in agricultural activities, including the management of natural resources. Urban areas can be defined as areas that have non-agriculture main activities, with function as urban residential, center and distribution of service delivery, social service and economic activity (Ministry of Public Works et al., 2016).

Kota Bekasi is located in West Java on the eastern border of Jakarta and is divided into 12 districts (*Kecamatan*), three of which were the focus of this research, namely Jatiasih, Bantar Geband, and Jatisampurna (Figure 3). With a population density of 12,085 people/km^2 (2020) and approximately three million inhabitants, it is one of the most populous cities in Indonesia (BPS Kota Bekasi, 2021). Kota Bekasi's local water utility is only able to serve 26.8% of the total population, with the marginal areas of the city remaining unserved (Bappeda Kota Bekasi, 2018). More than 88% of households relied on groundwater as their water source in 2020 (BPS Kota Bekasi, 2021).

Kota Metro is located in the Indonesian province of Lampung on Sumatra Island with a population of 162,976 people and a population density of 2,371 people/km^2 (2018). Metro is an urban settlement and is organised into five districts, namely Metro Barat (West), Pusat (Central), Selatan (South), Timur (East) and Utara (North), all of which were the focus of this research (Figure 4). Only 1.3% of Metro's population (2,134 households) were connected to the piped municipal water system in 2018 (BPS Kota Metro, 2019).

Further detailed information about the study sites is described in the respective publications, including study maps (**Chapter IV**, **Chapter V** and **Chapter VI**).

*Figure 4: Map of the study sites: The PhD research was undertaken in the Indonesian cities of Bekasi and Metro (Genter, Putri, Suleeman, et al., 2023)***.** *Kota Metro is in the Indonesian province Lampung on Sumatra Island, while Kota Bekasi is in West Java on the eastern boarder of Jakarta (A). Metro is organised in five districts, all of which were the focus of this research (B). Bekasi is organised in twelve districts, three of which were the focus of this research (C).*

2.3.3 Household surveys and water quality testing

The data collection for the household surveys and the water quality testing was carried out during both the wet season and dry season in Bekasi and Metro. In Bekasi, data collection was conducted from February to March 2020 (wet season) and October 2021 (dry season). In Metro, data collection took place from October to November 2020 (dry season) and February to March 2022 (wet season). Data were collected from 300 randomly selected households in both Bekasi and Metro. The household survey and water quality testing campaigns were conducted as part of the broader project.

In Bekasi, participating households were randomly selected across three sub-districts (*Kelurahan*), namely Jatiluhur, Sumur Batu and Jatirangga. In Metro, the participating households were randomly selected across five sub-districts, namely Karangrejo, Hadimulyo Barat, Ganjarasri, Iringmulyo, and Rejomulyo. In Bekasi and Metro, districts and sub-districts were selected purposively based on the same criteria, such as self-supply prevalence, lack of access to piped water, and poverty status, with information obtained from secondary data and local government. Although the same selection criteria were applied, all five districts were selected in Metro, while only three were selected in Bekasi.

The hamlets (RW Rukun Warga), which consist of several neighbourhoods (*RT Rukun Tetangga*), were selected in consultation with the heads of the selected sub-districts. After further consultations with the respective head of the selected hamlets, the neighbourhoods to be surveyed were chosen.

All households of the selected neighbourhoods were listed and then randomly selected using the randomisation formula in Microsoft Office Excel 2016. The target number of households to be surveyed in each neighbourhood was determined in proportion to the population size. Based on the randomisation output, households were sorted from smallest to largest randomisation output number and then divided into a priority list and a reserve list. The households in the reserve list were only interviewed if the households on the priority list could not be visited or were not willing to be interviewed.

Data collection included a household questionnaire, sanitary inspection of self-supply sources, and water quality testing. Prior to the data collection, informed consent was obtained in the local language from heads of neighbourhoods and from all participants.

2.3.3.1 Household survey

A structured household survey was conducted in the local language by trained enumerators simultaneously with the water sampling (Appendix **A3**). SurveySolutions software (version 20.01, The World Bank, Washington DC, USA) was used in Kota Bekasi and Qualtrics software (Qualtrics, Provo, UT, USA) in Kota Metro. The software was switched due to changed access rights; however, this switch has no implications for the study. The main household questionnaire covered a range of themes about the household, water sources used and perceptions of water service attributes. Questions about the household included themes on health and socio-economic status, water management and decision-making. Self-supply water sources were defined as groundwater sources (boreholes, protected dug wells, or unprotected dug wells) that were privately owned by a household. Questions on water source usage considered alternative water sources such as public water services, neighbour's water supplies and packaged water (bottled water, refill water) and differentiated between wet and dry season. Questions on water perception included a ranking of attributes that influence households' water choices and reasons for the use and non-use of different water services.

The household survey questionnaire included a sanitary inspection module with observations on water supply and sanitation infrastructure. Observational questions of the WHO sanitary inspection form were adapted to the local context and included questions on the construction of the well, water lifting device, sanitation facilities, and household water storage and treatment (WHO, 2022). The borehole depth (to bottom of borehole) was determined based on the respondent's information. Further observations were made on borehole infrastructure such as the headworks and the presence of a concrete platform. For dug wells it was recorded whether water was delivered through a pump or a rope and bucket. Potential contamination sources were identified such as the number and proximity of sanitation systems and ownership of animals. Number of on-site sanitation facilities within a radius of 20 meters and the lateral distance to the closest sanitation facility were considered and based on surveyed household responses and enumerator estimates. Type and protection of storage container as well as treatment method were recorded for point-of-use water samples.

2.3.3.1.1 Wealth index

In the household survey, 23 indicators were collected to determine the wealth status, including household asset ownership, dwelling structure, type of cooking fuel, and household composition. Using the same approach as the 2017 Indonesian Demographic and Health Survey (DHS), a wealth index was constructed for Bekasi and Metro based on the relevant variables and corresponding indicator values generated from principal component analysis (National Population and Family Planning Board (BKKBN) et al., 2018). The wealth quintiles (Q) were calculated based on the wealth index and the number of household members.

In Bekasi, the wealth index scores ranged from −1.314 to 1.470 and were divided into quintiles Q1 (−1.314-0.019) reflecting poorest households, Q2 (0.026–0.321), Q3 (0.326–0.518), Q4 (0.519–0.702), and Q5 (0.714–1.470) reflecting wealthiest households. In Metro, wealth index scores ranged from −1.478 to 1.611 and were divided into Q1 (−1.478 to −0.224), Q2 (−0.218-0.068), Q3 (0.073–0.330), Q4 (0.351–0.612), and Q5 (0.617–1.611).

Comparison of the wealth index scores shows that households in Metro on average are poorer than the wider urban population in Indonesia, while average wealth status of households in Bekasi is similar to the wider urban Indonesian population. Both cities had narrower wealth distribution than urban national Indonesia (Figure 5).

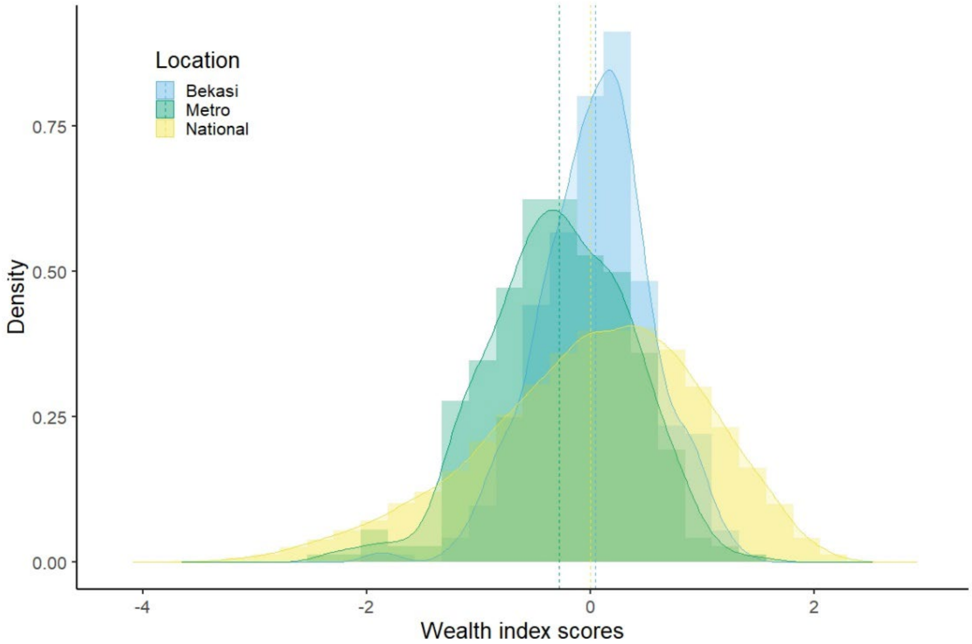

Figure 5: Wealth index scores of households in Bekasi and Metro compared to the wider urban population in Indonesia.

2.3.3.2 Water quality testing

Water samples were collected in sterile Whirl-Pak® bags (120 mL capacity, Nasco, Fort Atkinson, WI, USA) from the randomly selected households in Bekasi and Metro, respectively. Point-of-use samples were collected for every fifth household in the same manner as household members would typically obtain water for consumption (e.g., pouring water into a glass or cup, or directly from the storage container). The samples were stored at 2–8°C and transported to a field laboratory located near the study area, where they were processed within six hours. Sampling collection was conducted according to standard procedures (U.S. EPA, 2009).

Faecal indicator bacteria *E. coli* was quantified with IDEXX Colilert-18 using the IDEXX Quanti-Tray®/2000 system with the Quanti-Tray® sealer model 2X according to manufacturer's instructions (IDEXX Laboratories, 2015). The samples were incubated at

35°C for 18–20 hours, and the *E. coli* cells were enumerated according to the manufacturer's instructions using an ultraviolet source (365 nm) and the Most Probable Number (MPN) table for the Quanti-Tray®/2000 system. The number of *E. coli* was reported as MPN per 100 mL with lower and upper 95% confidence limits. The Quanti-Tray®/2000 system is capable of quantifying the number of *E. coli* in 100 mL water samples over a range of 1–2419.6 MPN per 100 mL.

2.3.3.3 Data analysis

Descriptive analysis was performed using water quality data of self-supply water sources (**Chapter IV**). To understand risk factors for faecal contamination of self-supply, potential predictors were categorized as hazard factors, pathway factors, and indirect factors (Howard, 2002) (Figure 1). Statistical analysis software R (version 1.2.5001, R Foundation for Statistical Computing, Vienna, Austria) was used for analysis. To determine whether microbial water quality differs between source and point-of-use, *E. coli* concentration at source and point-of-use was comparatively assessed using paired samples Wilcoxon and McNemar’s test. The association between wealth and water quality was investigated using Spearman’s rank correlation. To examine the influence of risk factors at source and point-of-use, crude odds ratio (OR) and adjusted odds ratio (aOR) were calculated based on univariate and multivariate analysis.

Water quality data of wet and dry season were matched considering the household ID and water source type using Microsoft Office Excel 2016. To determine whether microbial water quality differs between wet and dry seasons, *E. coli* concentration was comparatively assessed using paired samples Wilcoxon test and McNemar’s test in the statistical analysis software R. To investigate whether single time-point water samples are adequate, logistic regression analysis was performed to predict whether *E. coli* contamination present in dry season increases risk in the wet season using statistical analysis software R.

Data collection and analysis was conducted for Bekasi and Metro, although the research did not aim to compare the two areas.

More detailed information on data analysis can be found in the respective publications (Section 4.2).

2.3.4 In-depth interviews

An explanatory mixed-methods approach was used to understand the use and non-use of self-supply, and to get a deeper insight into the overlooked aspects of purely quantitative or purely qualitative research (**Chapter V**). A question guide for in-depth interviews was developed covering themes on water choice, perception, management and decision-making (Appendix **A4**). The themes were selected following descriptive analysis of the household survey. Descriptive analysis was performed in Microsoft Office Excel 2016 and statistical analysis software R.

Purposive sampling was employed to select 24 households for the interviews based on their characteristics to maximise diversity relevant to the research question. Considered characteristics for household selection included gender of the head of household, gender of responsible person/s for water-related tasks, gender of responsible person/s for decision-making processes, shared or single responsibility and decision-making, household wealth, marital status, and disability. To be eligible for selection, households had to use a self-supply source and own a mobile phone. Owning a mobile phone was a prerequisite for household selection due to Covid-19, as it facilitated remote communication and data collection while minimizing physical contact to ensure the safety of both the participants and the researchers.

Household characteristics were obtained from the household survey responses. Households were listed and categorised based on the gender of the head of household (female/male) and the wealth of household (poor/middle/non-poor). The categorisation of the household wealth was conducted based on the tertiles of the calculated wealth index of households (Section 2.3.3.1.1). The categorisation into poor refers to ownership of 1-4 assets, middle to ownership of 5-10 assets and non-poor to ownership of 11-14 assets. A priority list including 12 households was created for each study site, taking into account shared or sole (female/male) responsibility for water-related tasks and decision-making processes in a way that increases diversity. From the results of the four household survey questions on water-related tasks, we also determined whether the responsibility for water-related tasks was shared or assumed by a sole female or male household member. Priority was given to households where the respondent was the head of household. If a mobile phone number was not available, households were replaced with households from the backup list with similar characteristics. Household characteristics of the purposely selected households can be found in Appendix **A4**.

The 24 in-depth interviews were carried out by phone (due to Covid-19) from the 12 purposively selected households in Bekasi (December 2020) and Metro (August 2021 and November 2021-January 2022), respectively. In-depth interviews were conducted by phone in the local language and responses were recorded, transcribed and translated into English. In-depth interviews were conducted by Linda Darmajanti and Evelyn Suleeman, and translated by Gita Lestari Putri. Challenges arose in interpreting the translations, requiring follow-up questions to the translator to understand the actual meaning. The transcribed information was coded manually in Microsoft Office Word and Excel 2016 using a deductive approach to capture the relevant themes on self-supply water quality (risks, mitigation strategies, perceptions), water availability, water choices (reasons for non-use, perception of alternative water sources), workload (roles, responsibilities, decision-making) and conflicts.

More detailed information on the quantitative and qualitative approach can be found in the respective publication (Section 5.2).

2.3.5 Participatory citizen monitoring

A participatory monitoring approach was undertaken in the Indonesian city of Bekasi (**Chapter VI**). Households were advised to test their self-supply water for the presence of *E. coli* every two weeks at both the source and point-of-use. Households were provided with Aquagenx® test kits covering a six-month period between April and November 2022 (a total of 12 sampling rounds). Results were shared with the research team by mobile phone using WhatsApp. Participants received a reward of 15,000 Rupiah (approximately $1.00) after each sampling round.

Participants were trained by two local enumerators at the start of the campaign on how to test water quality. After the initial training, no follow-up trainings on conducting water quality tests were held. After one month and at the end of the campaign, a pre- and post-monitoring survey was conducted by the enumerators during field visit (Appendices **A5** and **A6**). Three quality control samples were collected by the enumerators during the field visit at the start of the campaign (sampling round 1, n=30), after one month (sampling round 3, n=26) and at the end of the campaign (sampling round 12, n=17). Analysed water quality results were shared with participants using WhatsApp.

Rainfall and groundwater levels were measured to provide insight into the temporal variability and as potential factors influencing water quality. Rainfall was measured using a Davis® (0.2 mm) Rain Gauge Smart Sensor at a household in Jatirangga. Groundwater levels were measured using HOBO® MX Bluetooth Water Level Loggers (MX2001) in two private protected dug wells in Jatirangga and in one private protected dug well in Jatiluhur. Measurements were conducted by the research team during five months from June to November, 2022.

The CPI framework proposed by Gharesifard et al. (2019) was used to evaluate the feasibility of the participatory monitoring approach for self-supply water services. The framework encompasses five distinct dimensions, which are categorised into context-related and initiative-related aspects and are suitable for conducting context analysis, process evaluation and impact assessment (CPI) of the monitoring approach.

Statistical analysis software R and Microsoft Office Excel 2016 were used for analysis. Fisher's exact test was calculated to examine the relationship between the socio-economic and demographic characteristics of participants who dropped out and those who completed the full testing. Stuart-Maxwell test was used to compare marginal homogeneity for pre- and post-survey responses of single-select questions for participants who completed monitoring and did not drop out. To examine whether self-testing water quality resulted in improved water quality over time, a generalized estimating equations (GEE) analysis was conducted that accounted for rainfall variability.

More detailed information on the participatory monitoring approach and corresponding data analysis can be found in the respective publication (Section 6.2).

2.4 Ethical considerations

Ethical approval to conduct the research was provided by the Research Ethics Committee of University of Technology Sydney as well as the Universitas Indonesia. This PhD involved primary research with participants in a developing country context, therefore an ethical review was required to respect the participants' rights. A research ethics approval was sought from the University of Technology Human Research Ethics Committee (HREC), as well as the Universitas Indonesia Community Engagement Ethical Committee of the Faculty of Public Health to minimise potential risk and harms to the research participants. Additionally, research permits in Indonesia were requested from the Ministry of Education and Culture at provincial level, district level (*Kecamatan*), sub-district level (*Kelurahan*), hamlet level (*RW Rukun Warga*) and neighbourhood level (*RT Rukun Tetangga*).

Conducting household surveys and interviews in a developing country context has particular ethical requirements given cross-cultural considerations. Potential psychological, physical and legal harms were minimised by informed written and verbal consent obtained from all participants prior to the surveys, in a manner appropriate for their personal circumstances. Participants were informed about the study and the extent of their involvement and reassured that they were free to withdraw or ask questions at any time. To protect the privacy of participants and confidentiality of data, the participants involved in the study were de-identified. Risks of accidentally breaching cultural sensitives or local laws were minimised by working together with local collaborators and trained local enumerators performing the survey and water quality testing. When I was on site, I informed myself early about the culture, respected it and adapted accordingly. To reduce interference with the daily work of household members, surveys were conducted at the available and desired time of the households to be as unobtrusive as possible. Necessary measures were taken to avoid setting unrealistic expectations for participants about potential benefits or outcomes of the research.

For the participatory monitoring approach, private phones and WhatsApp was used as a medium to transfer results, posing several ethical challenges. While the household surveys were conducted using institutional devices, private phones and WhatsApp were used for the participatory approach for simplicity. Privacy and confidentiality are at risk, as personal devices and third-party applications may not provide adequate security, leading to potential data breaches. To mitigate these issues, clear data handling protocols, updated informed consent, and proper training are recommended when it comes to scaling up the participatory monitoring approach. Institutional devices could be made available for enumerators, and a secure data transfer medium, such as Threema, could be used.

Avoiding Covid-19 risks for participants and enumerators while conducting research was a priority. Prior to face-to-face research activities, the University of Technology Sydney COVIDSafe Research Activity Risk Assessment was conducted in order to protect participants and researchers. Alternates to physical face-to-face activities were considered and face-to-face research activities and travel were reduced to the most necessary. General Covid-19 guidance was followed such as hand washing, physical distancing, wearing masks and testing for symptoms. The surveys were not conducted if it was not appropriate, or the area was at high Covid-19 risk.

2.5 Covid-19 considerations

The Covid-19 pandemic had a significant impact on the scope and direction of the PhD research conducted between 2020 and 2023. The travel restrictions and suspension of ethical clearance to conduct in-person research in Indonesia necessitated a shift from in-person collaboration to a remote modality.

I had the opportunity to be on-site in Bekasi for the first round of data collection from February to March 2020. The first data collection had to stop a few days earlier than planned due to the start of the pandemic and travel restrictions. I was just able to fly to Australia before the borders closed. Lockdown in Australia meant not meeting people, which was mentally very difficult in a new country where you don't know anyone. For family reasons, I made an unplanned return trip to Switzerland in early December 2020. Despite receiving the necessary support letters from the Australian government and the university, my applications for entry clearance to Australia were rejected several times. Therefore, I got stuck in Switzerland, which was fraught with financial difficulties.

For more than a year I was unable to meet supervisors in-person. I was working from home and in weekly exchange with UTS Sydney and UI Indonesia. As a result, research questions and schedules were adjusted to account for Covid-19 uncertainties and travel restrictions.

Due to the pre-existing collaboration and on-site training with the partners in Indonesia in January 2020, the data collection campaigns and interviews could be conducted, albeit with delays, in 2021. These delays led to a gap in seasonal data for each location. Consequently, the seasonality aspect was treated as a distinct research output, rather than being incorporated as an integral part of the analysis (Section 4.2).

In addition, due to travel restrictions and delays, the scope of the PhD was limited to a groundwater focus, which prevented the exploration of other study sites with a high prevalence of self-supply based on rainwater. Despite the challenges posed by the Covid-19 pandemic requiring the adoption of alternative methods and causing delays in the data collection process, the research was able to adapt and generate valuable insights into groundwater self-supply in urban Indonesia.

2.6 Summary

Chapter II outlined the rationale for using a social-ecological system approach as the conceptual framework for guiding the PhD research and presented the methods and data collection approach as well as ethical and Covid-19 considerations. The chapter began by presenting the social-ecological system approach and its adapted version used for this research. Subsequently, the chapter situated the PhD research within the adapted version of the social-ecological system framework. Then, the methods employed in the study were described, as they form an integral part of the results chapters. Additionally, the chapter summarised the ethical considerations and the impact of the Covid-19 pandemic on the research. The next chapter presents the literature review on faecal contamination of self-supply services in LMICs underscoring the significance of making self-supply visible.

3. Literature review

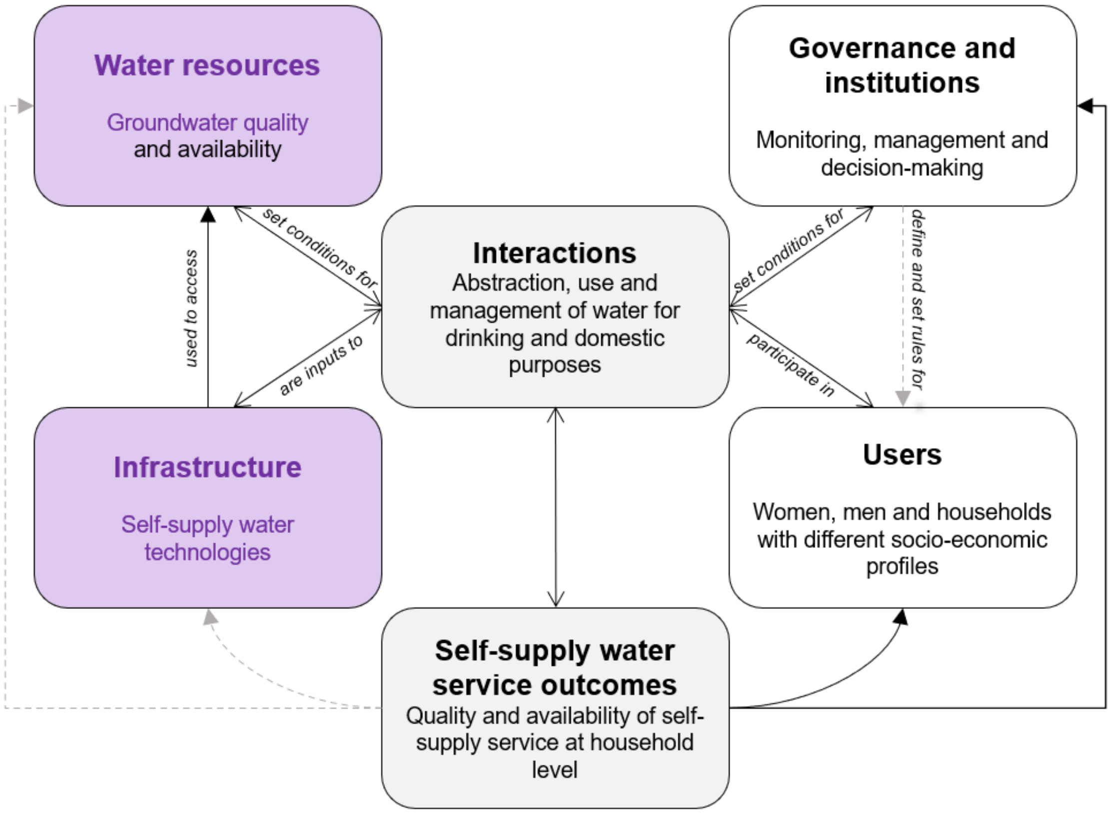

Figure 6: Chapter III contains the systematic literature review and meta-analysis, which provides findings contributing to RQ1, indicating that water obtained from groundwater resources through self-supply is at risk of faecal contamination in LMICs. The literature review included studies focusing on measuring water quality at the source. The findings of the literature review are primarily situated within the 'Water resources' and 'Infrastructure' components, highlighting the need to consider the different components of the social-ecological system framework to understand the complexity of the risk of faecal contamination of self-supply services.

3.1 Overview

Chapter III presents the findings from the systematic review and meta-analysis on faecal contamination of groundwater self-supply in LIMCs. The literature review was published in *Water Research* in 2021 and forms the first of five journal articles included in this thesis by compilation (Publication I). Through the lens of safely managed drinking water criteria, it focuses on the microbial water quality aspect. The findings are primarily situated within the ‘Water Resources’ and ‘Infrastructure’ components of the social-ecological system framework (Figure 6).

This chapter is an integral component of addressing RQ1, which seeks to investigate the extent to which groundwater self-supply is free from faecal contamination at both the source and point-of-use and to examine the potential risk factors of faecal contamination. This chapter refers to self-supply services in LMICs unlike the other chapters, which focus specifically on urban Indonesia. The literature review sheds light on the importance and overlooked aspects of self-supply. Additionally, the chapter emphasises the need for differentiated support to the varying circumstances under which self-supply is present.

3.2 Publication I

Publication I and its supplementary materials are available open access at https://doi.org/10.1016/j.watres.2021.117350 (Genter et al., 2021).

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Review

Faecal contamination of groundwater self-supply in low- and middle income countries: Systematic review and meta-analysis

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ABSTRACT

Self-supply is a ubiquitous response by households to the public water supply inadequacies found worldwide. Self-supply is invested in and managed by an individual household, accessible on-premises and unregulated. Vulnerability to faecal contamination is a concern due to reliance on low-cost technologies and shallow groundwater. This review aims to evaluate the evidence base on the safety of groundwater self-supply in low- and middle income countries in relation to faecal contamination. Differences in microbial water quality between source types, settings, countries and ownership were investigated. A search of peer-reviewed studies in low- and middle income countries was conducted in online databases, including PubMed, Web of Science, ProQuest and Environmental Complete. Studies were included if they had sufficient detail about the water samples to be related to groundwater self-supply, contained extractable data on faecal indicator bacteria (FIB) including thermotolerant coliform or *Escherichia coli* and were published in English between 1990 and April 2020. A total of 30 studies were included, resulting in 100 datasets and 26,981 water samples across the studies. FIB were present in 36% self-supply samples. The odds of FIB being detected was significantly higher for unimproved sources (OR=8.19, 95% CI [4.04–16.59], $p<0.001$) and for sources in low income countries (OR=3.85, 95% CI [1.85–7.69], $p<0.001$). Self-supply was significantly more likely to be contaminated than piped supply (OR=3.45, 95% CI [1.52–7.82], $p=0.003$). However, water quality was highly heterogeneous ($I^2=90.9\%$). Egger's test found no evidence of small study publication bias for self-supply compared to public supply. No evidence of bias due to lack of randomization or season was found, but study design and quality could potentially bias the results. To achieve Sustainable Development Goal 6.1 on safe drinking water for all, more attention is needed from governments to engage with self-supply and formulate balanced policy responses.

1. Introduction

Sustainable Development Goal (SDG) 6.1 calls for universal and equitable access to safe and affordable drinking water for all by 2030. To meet the criteria of a safely-managed drinking water service, households must use an improved water source that is accessible on-premises, sufficiently available when needed and free from faecal and chemical contamination (WHO and UNICEF, 2017). An improved water facility includes sources that are protected from outside contamination by nature of their construction, such as boreholes, protected dug wells or rainwater harvesting (WHO and UNICEF, 2017). Although billions of people have gained access to basic water services and much progress has been made towards reaching SDG 6.1, more extensive efforts are needed to fully realize the SDG ambition to achieve universal access for all. In 2017, more than 2.2 billion people still lacked access to a safely managed water service (WHO and UNICEF, 2021). The lack of access to safe drinking water is felt disproportionately by disadvantaged community groups (WHO and UNICEF, 2019).

Household self-supply has become essential for people who are beyond the reach of utility- or community managed water supplies, and for those who need to complement an inadequate supply (Grönwall et al., 2010). Self-supply is a service delivery model usually relying on groundwater or rainwater. It is characterized as an on-premises water supply that is invested in, and maintained by, a household and therefore based on affordable technologies (Grönwall and Danert, 2020). Self-supply exists all over the world in both rural and urban settings. One third of the total urban population in continental Africa are likely to rely on self-supply (Chávez García Silva et al., 2020). In Asia-Pacific, over 700 million people depend on self-supply across rural and urban areas (Foster et al., 2021). Rural areas with low population density are often

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difficult or expensive to reach with public or centralised water supply systems (Adeniji-Oloukoi et al., 2013; Allen et al., 2006; Sutton, 2009). In urban areas, cities are expanding rapidly so that individual households in outskirts choose to go off-grid and organize their own drinking water access when there is no reliable and convenient public supply (Grönwall, 2016; Grönwall and Danert, 2020; Komakech and de Bont, 2018; Kulabako et al., 2010; Liddle et al., 2016).

Self-supply has the potential to provide a safely managed water service as it is located on the premises of a user household. However, self-supply services are generally unregulated and unmonitored (Grönwall and Danert, 2020; Grönwall et al., 2010). Therefore, little is known about the extent to which self-supply provides drinking water that is free from contamination, and poor water quality and its associated health risks remain a prime concern (Sutton, 2009). Many self-supply services rely on shallow groundwater sources, which are highly vulnerable to contamination from human activities (Grönwall et al., 2010). Moreover, groundwater self-supply often relies on simple construction and lifting technologies. Faecal contamination from various sources such as sanitation systems, solid waste dumps, household sullage, stormwater drains and animals also poses a risk (ARGOSS, 2001).

Contamination of drinking water constitutes a major burden on public health in low-income countries due to water-related disease such as diarrhoeal diseases (Bain et al., 2014b). The World Health Organization (WHO) drinking water guidelines include criteria for assessing health risks and setting targets for improving water safety (WHO, 2011). The recommended measure for assessing faecal contamination by the WHO is the presence of faecal indicator bacteria (FIB) such as *Escherichia coli* (*E. coli*) or alternatively thermotolerant coliform (TTC) (WHO and UNICEF, 2010). The concentration of faecal indicator bacteria is suggested to be an indicator of health risks. However, FIB are imperfect in representing risk and monitoring is required that goes beyond the single measurements of indicators or contaminants to interpreting health hazards (Charles et al., 2020). Nevertheless, even using imperfect methods, there is an urgent need to understand and address the risks and benefits related to self-supply in order to guide policy and practice towards safely-managed services that meet the needs of disadvantaged populations.

This systematic review with meta-analysis aims to provide insight on the safety of groundwater self-supply in LMIC regarding faecal contamination. Amongst selected studies, this study seeks to understand the extent to which groundwater self-supply is free from faecal contamination and addresses three research questions:

1. To what extent is groundwater self-supply contaminated with FIB in LMIC?
2. How does faecal contamination vary between source types, countries, rural and urban areas, seasons and study designs?
3. How does self-supply compare to public supply in terms of faecal contamination?

The focus of the study is self-supply based on groundwater sources. Further, the literature review focuses on microbial water quality as reported by FIB.

2. Methods

The systematic review of studies including faecal contamination of groundwater self-supply in LMICs was conducted according to the PRISMA guidelines (Moher et al., 2009). Methods for search strategy, study eligibility and data extraction were adapted from Bain et al. (2014b) and are described in the protocol (S1).

2.1. Search strategy

Studies were identified from peer-reviewed literature. Online databases were searched including PubMed, Web of Science, ProQuest and Environmental Complete. Search terms regarding water quality were combined with self-supply terms and restricted to LMICs using a list of country names (Bain et al., 2014b). Searches were conducted between April and June 2020.

2.2. Eligibility and selection

Studies were included in the review provided they: (i) had sufficient detail about the water samples to be related to self-supply groundwater sources; (ii) contained extractable data on TTC or *E. coli*; (iii) were published between 1990 and April 2020, (iv) included at least 10 separate water samples; (v) fell into the classification of LMIC (World Bank, 2020) and, (vi) were published in English. Studies were selected by screening of titles and abstracts followed by screening of full texts for selected studies. Duplicates were identified and removed.

2.3. Data extraction and matching

Basic descriptive data from eligible studies (e.g. author, year of publication), water quality information and additional study characteristics thought to influence water quality were extracted into a Microsoft Office Excel 2016 spreadsheet (S2). Where possible, the following water quality information for each source type in the studies were extracted: non-compliance (presence of *E. coli* or TTC); mean, geometric mean and/or median level of contamination (*E. coli* or TTC per 100 ml); standard deviation, variance or standard errors (*E. coli* or TTC per 100 ml); risk categories of microbial contamination (<1, 1–10, 10–100, 10–50, >50 and >100 *E. coli* or TTC per 100 ml); number of samples tested; analytical method used to detect faecal indicator bacteria.

To explore the influence of seasons, those studies that refer to water quality during "wet", "rainy" or "dry" periods or equivalent were recorded. The country income group was identified as "low", "lower-middle" and "upper-middle" income using the World Bank classification (World Bank, 2020). Where possible, level of urbanization was identified as urban or rural. To investigate the influence of source type on water quality, each type of water source was recorded and matched with the corresponding Joint Monitoring Programme (JMP) source definition and classified as improved or unimproved (WHO and UNICEF, 2017). Groundwater sources from studies that did not distinguish between protected and unprotected wells were categorised as unclassified dug well. Groundwater sources that did not distinguish between borehole and dug wells were categorised as unclassified.

2.4. Study quality and risk of bias

Each study was rated for quality based on a quality score between 0 and 10 for specified criteria (Table 1). Quality criteria are based on those used by Bain et al. (2014b). Quality control criteria extracted included information on the selection (selection described, selection randomized, randomized selection described), region described, season reported, quality control, method described, point of sampling defined, handling described, handling minimum criteria met. Higher and lower quality was determined by the median of quality scores of the studies. No study was excluded based on a low quality score. Study designs were identified and categorized as either cross-sectional, longitudinal (study >6 months), cohort, intervention or diagnostic study. The influence of study design and quality on bias between studies was investigated using meta-regression with study design type and quality criteria as subgroups as described in the analysis section (2.5.3 Between study analysis).

2.5. Analysis

2.5.1. Data for analysis

Only studies reporting noncompliance results were used for meta-

Table 1
Quality criteria and description.

Quality Criterion	Description
Selection described	Description of how the water samples were chosen, including how either the types of water source or their users were selected
Selection representative	Description of an approach that provides a representative picture of water quality in a given area
Selection randomized	Randomized sampling over a given study or population
Region described	Description of the geographic region within the country where the study was conducted
Season reported	Report of seasons or months of sampling
Quality control	Specification or reference of quality control procedures
Method described	Description or reference of well-defined and appropriate methods of microbial analysis
Point of sampling	Description of the point at which water was sampled
Handling described	Description of sample handling procedures, including sample collection, transport method and duration
Handling minimum criteria	Fulfilment of handling minimum criteria for sample handling and processing: transport on ice or between 2 and 8 °C, analysis within 6 h of collection, and specified incubation temperature

analysis. Measures of central tendency from studies were not included in the meta-analysis because of limited reporting. For studies reporting both *E. coli* and TTC data, only the *E. coli* results were used. For studies reporting summarised results from sub-results, only the sub-results were used. For studies which assessed water quality at both source and point-of-use, only results from the water source were included in the analysis. For the intervention study, only the dataset several years after the emergency event and intervention was used for analysis (Ali et al., 2019).

2.5.2. Qualitative synthesis

To qualitatively assess the proportion of studies reporting frequent and high levels of microbial contamination, cumulative density functions (CDFs) of the proportion of samples with $\geq$1 FIB per 100 mL and >100 FIB per 100 mL were plotted for each water source type using the "ggplot2" function in the statistical analysis software RStudio (version 1.2.5001, R Foundation for Statistical Computing, Vienna, Austria). Results of unclassified water sources were not included in the CDFs. FIB concentrations from datasets reporting results in risk classification were plotted using Microsoft Office excel 2016. The extent of FIB contamination of self-supply was calculated based on the included datasets used for meta-analysis.

2.5.3. Between study analysis

To investigate heterogeneity between studies in faecal contamination, random effects meta-regression was used to test *a priori* defined subgroups such as setting, season, source type and other study characteristics as possible explanations. Continuity correction of 0.5 was employed in Microsoft Office Excel 2016 for proportions of 0 or 1 (Sweeting et al., 2004). For studies with zero positive samples, 0.5 was substituted for the number of positive samples and for studies where all samples were positive, 0.5 was subtracted from the total number of positive samples. The "metafor" package in the statistical analysis software R (version 1.2.5001, R Foundation for Statistical Computing, Vienna, Austria) was used for meta-regression (Viechtbauer, 2010). A logit transformation for the analysis of proportion was applied to the proportion of samples with >1 FIB per 100 mL and >100 FIB per 100 mL using the "escalc" function. To compare the faecal contamination with the defined subgroups, random effects pooled odds ratio were calculated using the "rma" function. The DerSimonian-Laird estimator was used to estimate the amount of heterogeneity (DerSimonian and Laird, 1986).

2.5.4. Within study analysis

Studies that included extractable water quality data from both self-supply and public water sources were combined using meta-analysis with the odds ratio as the effect measure to compare the faecal contamination based on the proportion of samples >1 FIB per 100 mL. Pooled estimates were calculated using the "escalc" and "rma" function in the R "metafor" package. Heterogeneity was estimated using Higgins I^2 (Higgins and Thompson, 2002). Here, heterogeneity refers to the variation in faecal contamination levels between the studies. Forest plots were created using the "forest" function for self-supply compared to public water sources, self-supply compared to public piped water sources and improved self-supply water sources compared to improved public water sources. The influence of small study bias was assessed with the funnel plot method and Egger's regression test for odds ratio and standard error using the "funnel.rma" and "regtest" functions (Egger et al., 1997).

3. Results

3.1. Search results

In total 677 records were identified through database searches and additional three reports through snowball searching (Fig. 1). Most studies were excluded because water sources were not related to self-supply or there were no extractable *E. coli* or TTC data. Several studies did not mention the ownership of the water source or did not differentiate the FIB results between public and self-owned water sources. An adequate description of the water source to allow them to be matched to the JMP source was missing in numerous studies. For example, some studies described water sources as "wells" but did not provide information about the construction (e.g. protected or unprotected dug well). In total 30 studies were incorporated in the review resulting in 100 datasets and 26,981 water samples (Tables 2 and S2).

3.2. Study characteristics

Characteristics of the included studies are presented in Table 3. Studies report water quality information from self-supply sources in urban (n = 15, 50%), rural (n = 12, 40%) or both (n = 2, 7%) settings. One study described the region but did not classify the level of urbanization (Ali et al., 2019). In half of the selected studies, self-supply sources were classified as boreholes (n = 15) and less commonly as protected and unprotected dug wells (n = 6 and n = 2). In 40% (n = 12) of the selected studies, the self-supply source type was not clearly described and could not be classified. The majority of the studies described the season, with reported water sample collection during wet (n = 11, 37%), dry (n = 14, 47%) and both (n = 5, 17%) season. Some studies (n = 4, 13%) did not describe the season or not differentiate between wet and dry season (n = 6, 20%).

The review was dominated by cross-sectional studies (n = 24, 80%) with fewer longitudinal surveys (n = 5, 17%). Sample size of the datasets ranged from three to 4834 samples with a median of 43 samples. Randomized water source or household selection was reported in a minority of studies (n = 12, 40%). The majority of the studies reported FIB results as noncompliance (n = 27%, 90%) using *E. coli* (n = 16, 53%) and TTC (n = 16, 53%) as parameters. One intervention study took place after an emergency (Ali et al., 2019). In addition to the water quality testing, household and sanitary surveys were conducted in 30% (n = 9) and 37% (n = 11) of the selected studies, respectively.

Study quality ranged from a quality score of 4 to 10 with an interquartile range of 7 to 8 and a median of 7 (Fig. S3). In all studies the region was specified where it was conducted. Most studies described the method (n = 28, 93%), the handling (n = 28, 93%) and specified the point of sampling (n = 22, 73%). Fewer studies met the handling minimum criteria (n = 19, 63%), described the selection (n = 18, 60%) or randomized selection (n = 12, 40%) and the minority specified quality control procedures (n = 5, 17%) (Fig. S4).

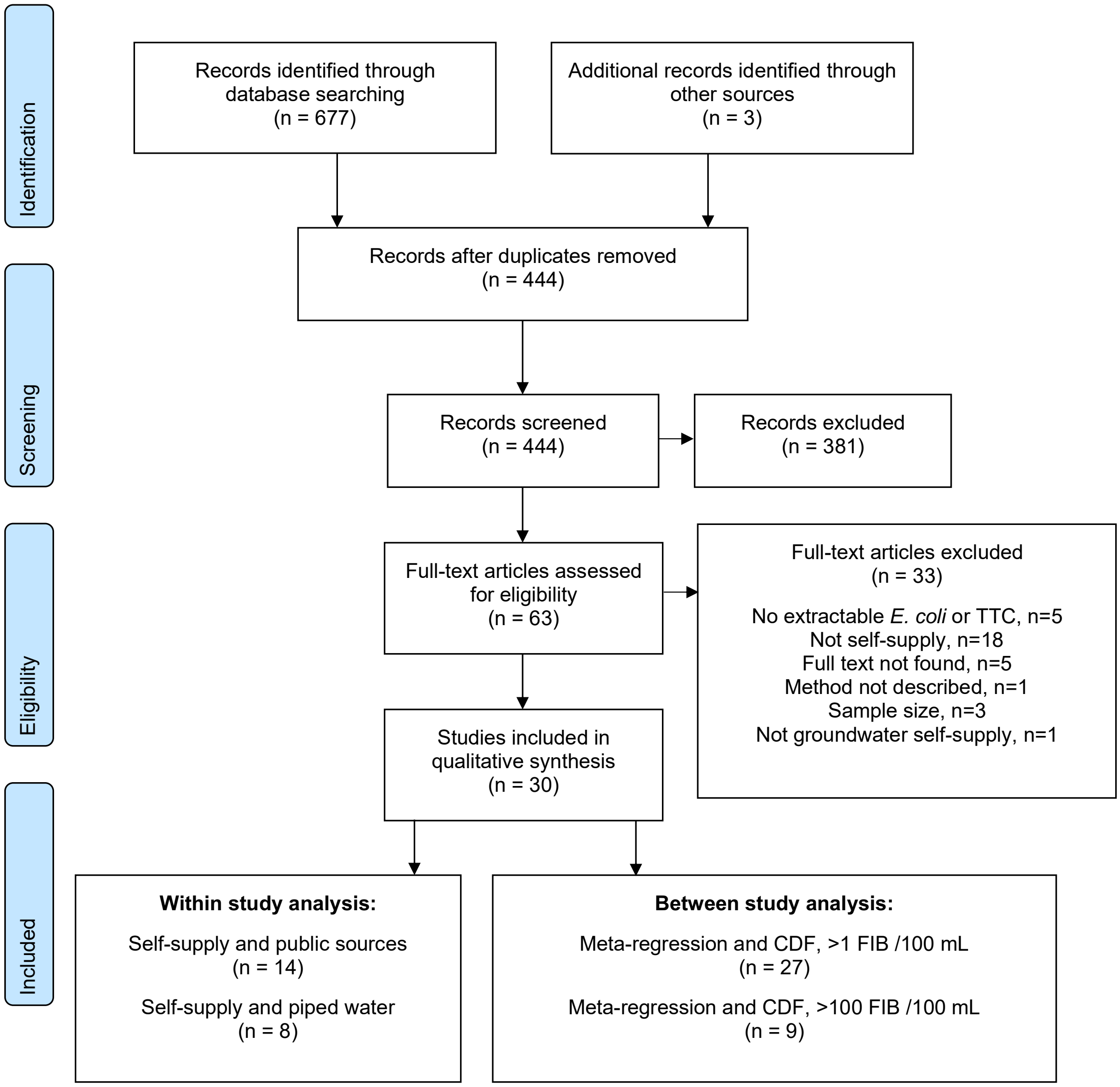

Fig. 1. Flowchart for a review of microbial water quality from self-supply sources.

3.3. Qualitative synthesis

Likelihood and level of microbial contamination varied between study and source type (Fig. S5). FIB were detected in 36% samples (n_{pos} = 5066) from self-supply sources, including 28% of samples (n_{pos} = 1973) from boreholes, 77% of samples (n_{pos} = 143) from protected dug wells, and 81% of samples (n_{pos} = 777) from unprotected wells. Studies reporting results in FIB risk classifications showed that FIB were detected in all datasets (n = 22) and exceeded levels of 50 and 100 FIB per 100 mL in 95% of the datasets. Although the proportion of samples in which FIB were detected were higher for unimproved sources such as unprotected dug wells, samples from improved sources such as boreholes still exceeded levels of 100 FIB per 100 mL in nine of ten datasets. Samples from protected dug wells exceeded levels of 50 FIB per 100 mL in both of the datasets. The results are in agreement with a comparison to CDFs by source type showing a similar pattern to those from the FIB risk classification (Figs. 2 and S6). FIB were detected in a lower proportion of samples from boreholes and in a higher proportion of samples in unprotected and protected dug wells.

3.4. Between study analysis

The likelihood of self-supply contamination was significantly higher when sources were unimproved and for low-income settings. Meta-regression showed that self-supply sources classified as unimproved were significantly more likely to be contaminated with FIB than improved sources (OR = 8.19, 95% CI [4.04–16.59], p<0.001) (Table 4). The odds of microbial contamination were 9.18 times (95% CI [5.00–16.84], p<0.001) higher for dug wells compared with boreholes. Similarly, the likelihood of a high level of microbial contamination (>100 FIB per 100 mL) was significantly greater in unimproved compared to improved sources (OR = 27.72, 95% CI [3.80–202.12], p = 0.001) and in dug wells compared to boreholes (OR = 19.31, 95% CI [3.26–114.23], p = 0.001). Protected dug wells were significantly more frequently contaminated with >1 FIB per 100 mL than boreholes (OR = 9.68, 95% CI [2.92, 32.04], p<0.001). Country-level of income status was a significant predictor of microbial contamination, with odds of contamination (>1 FIB per 100 mL) being 3.85 (95% CI [1.85–7.69], p<0.001) higher for low-income countries compared with wealthier countries. Odds of a high level contamination (>100 FIB per 100 mL) were 5.26 (95% CI [1.30–33.33], p = 0.092) higher for low-income countries. No statistically significant results were found comparing FIB

Table 2
Self-supply studies incorporated in the systematic literature review.

Study	Region	Setting	Self-supply type	FIB parameter
Korfali and Jurdi (2009)	Lebanon	Urban	Borehole	*E. coli*
Korfali and Jurdi (2007)	Lebanon	Urban	Borehole	*E. coli*
Nogueira et al. (2003)	Brazil	Urban and rural	Unclassified well	TTC
Kumpel et al. (2017)	Nigeria	Urban	Borehole	*E. coli* and TTC
Kumpel et al. (2016)	Nigeria	Urban	Borehole	TTC
Ngasala et al. (2019)	Tanzania	Urban	Unclassified	*E. coli*
Knappett et al. (2013)	Bangladesh	Rural	Borehole	*E. coli*
Mukhopadhyay et al. (2012)	India	Urban and rural	Unclassified dug well	*E. coli*
Potgieter et al. (2006)	South Africa	Rural	Borehole	TTC
Martínez-Santos et al. (2017)	Mali	Rural	Unclassified dug well	TTC
MacCarthy et al. (2013)	Madagascar	Urban	Borehole	TTC
Ejechi and Ejechi (2008)	Nigeria	Urban	Borehole	TTC
Gorter et al. (1995)	Nicaragua	Rural	Unprotected and protected dug well	TTC
Vaccari et al. (2010)	Thailand	Rural	Unclassified dug well	*E. coli* and TTC
Metwali (2003)	Yemen	Urban	Unclassified	TTC
Ebner et al. (2018)	Afghanistan	Urban	Unclassified	*E. coli*
Maran et al. (2016)	Brazil	Urban	Borehole and unclassified	*E. coli*
Ali et al. (2019)	Pakistan	Unclassified	Unprotected dug well	TTC
Schram and Wampler (2018)	Haiti	Rural	Unclassified dug well	*E. coli*
Butterworth et al. (2013)	Ethiopia	Rural	Unprotected and protected dug well	TTC
Ravenscroft et al. (2017)	Bangladesh	Rural	Borehole	TTC
Vollaard et al. (2005)	Indonesia	Urban	Borehole and unprotected dug well	TTC
Díaz-Alcaide and Martínez-Santos (2019)	Mali	Rural	Unprotected and protected dug well	TTC
Adams et al. (2016)	Nigeria	Urban	Borehole	*E. coli*
Baloyi and Diamond (2019)	South Africa	Rural	Borehole and unclassified dug well	*E. coli*
Davoodi et al. (2018)	Iran	Urban	Unclassified	*E. coli*
Eisenhauer et al. (2016)	Guatemala	Rural	Unprotected dug well	*E. coli*
Van Geen et al. (2011)	Bangladesh	Rural	Borehole	*E. coli*
Pujari et al. (2012)	India	Urban	Unclassified	TTC
Luby et al. (2008)	Bangladesh	Urban	Borehole	*E. coli* and TTC

contamination in urban versus rural settings and in wet versus dry season.

3.5. Within study analysis

Significantly higher likelihood of FIB contamination was found for self-supply water sources compared to public water sources. Meta-analysis of studies containing water quality FIB data from both self-supply and alternative public sources showed that self-supply is more likely to be contaminated (pooled OR = 3.29, 95% CI [1.79–6.04], $p<0.001$) (Fig. 3 and Table 5). Heterogeneity was high ($I^2 = 90.9\%$), indicating that contamination varies across settings. Similarly, comparing self-supply with piped public sources indicated that self-supply was more likely to be contaminated than public piped sources (pooled OR = 3.45, 95% CI [1.52–7.82], $p = 0.003$). Heterogeneity was relatively high with $I^2 = 83.1\%$. Self-supply source types included both improved and unimproved sources. Public source types were dominated by piped water followed by other improved public sources and included only one unimproved water source. For a small number of studies the OR was smaller than one, indicating that in some settings self-supplied water is less likely to contain FIB than the public water sources (Ejechi and Ejechi, 2008). When comparing improved self-supply sources with improved public sources, odds of faecal contamination were again higher for self-supply (OR = 3.55, 95% CI [1.46–8.66], $p = 0.005$, $I^2 = 77.8\%$) (Fig. 3).

Table 3
Characteristics of included studies.

Characteristics	Studies	Datasets	Samples
	Number (%)	Number (%)	Number (%)
Setting			
Urban	15 (50.0)	28 (28)	7694 (28.5)
Rural	12 (40.0)	65 (65)	9370 (34.7)
Urban and rural	2 (6.7)	2 (2)	430 (1.6)
Unclassified setting	1 (3.3)	5 (5)	9561 (35.4)
Income group			
Upper-middle	8 (26.7)	20 (20)	7006 (26.0)
Lower-middle	15 (50.0)	72 (72)	19,313 (71.6)
Low	7 (23.3)	8 (8)	662 (2.5)
Source type			
Borehole	15 (50.0)	35 (35)	8953 (33.2)
Protected dug well	2 (6.7)	9 (9)	468 (1.7)
Unprotected dug well	6 (20.0)	36 (36)	11,662 (43.2)
Unclassified dug well	5 (16.7)	8 (8)	297 (1.1)
Unclassified	7 (23.3)	12 (12)	5601 (20.8)
Design			
Cross-sectional survey	24 (80.0)	50 (50)	8038 (29.8)
Longitudinal survey	5 (16.7)	18 (18)	10,248 (38.0)
Cohort study	1 (3.3)	27 (27)	1523 (5.6)
Intervention	1 (3.3)	5 (5)	9561 (35.4)
Randomized	12 (40.0)	47 (47)	13,512 (50.1)
Parameter			
E. coli	16 (53.3)	29 (29)	8878 (32.9)
TTC	16 (53.3)	72 (72)	18,103 (67.1)
Results FIB			
Noncompliance	27 (90.0)	70 (70)	24,266 (89.9)
Risk classification	13 (43.3)	31 (31)	12,311 (45.6)
Other (Mean, Median, Range)	13 (43.3)	71 (71)	6709 (24.9)
Surveys			
Household survey	9 (30.0)	49 (49)	3456 (12.8)
Sanitary survey	12 (40.0)	33 (33)	12,159 (45.1)
Seasons			
All (differentiated)	5 (16.7)	NA	NA
All (not differentiated)	6 (20.0)	19 (19)	10,885 (40.3)
Wet	11 (36.7)	20 (20)	2467 (9.1)
Dry	14 (46.7)	51 (51)	3828 (14.2)
Not mentioned	4 (13.3)	10 (10)	9801 (36.3)
Sample size[a]			
Smaller (n = 3–43)	NA	50 (50)	1018 (3.8)
Larger (n = 44–4834)	NA	50 (50)	25,963 (96.2)
Quality[b]			
Lower (1–6)	15 (50.0)	30 (30)	7908 (29.3)
Higher (7–10)	15 (50.0)	70 (70)	19,073(70.7)
Total	30 (100.0)	100 (100.0)	26,981 (100)

[a] Median by datasets of the total sample number.
[b] Median by studies of the total quality score.

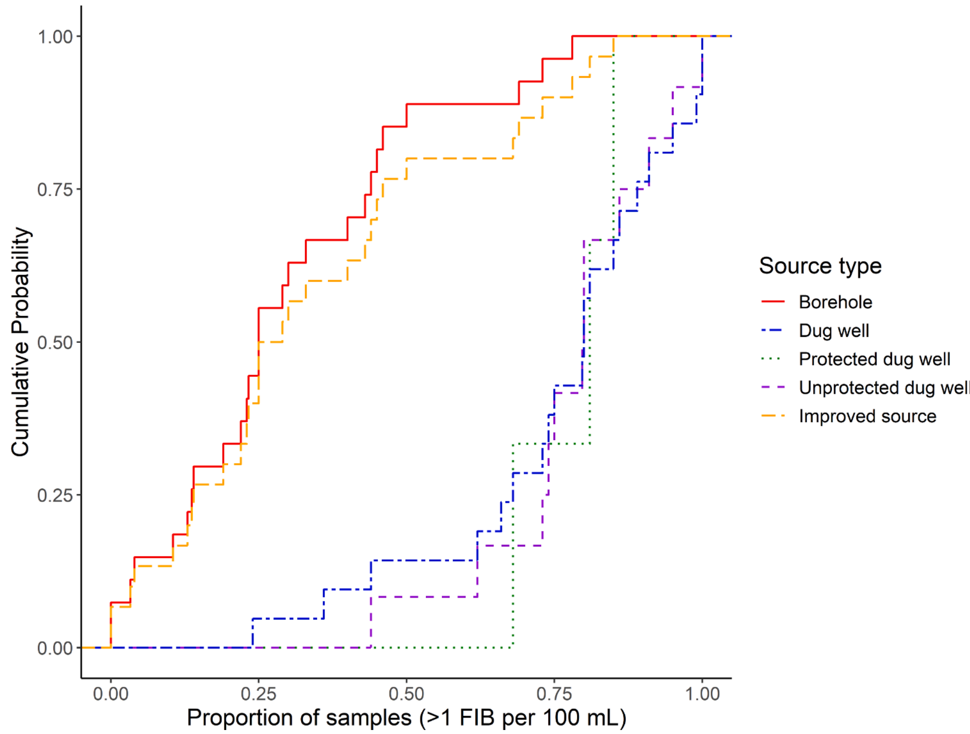

Fig. 2. CDF shows higher proportion of samples with >1 FIB per 100 mL for dug wells.

Table 4
Between study meta-regression.

Variables	Proportion of Samples > 1 FIB per 100 mL			Proportion of samples > 100 FIB per 100 mL		
	Obs.	OR [95% CI]	p-Value	Obs.	OR [95% CI]	p-Value
Setting						
Urban versus rural	54	0.64 [0.33–1.24]	0.184	15	2.25 [0.53, 9.62]	0.275
Low-income versus Other (Upper-middle and lower-middle)	57	**3.85 [1.85–7.69]**	**<0.001**	15	5.26 [1.30, 33.33]	0.092
Source type						
Dug well versus Borehole	48	**9.18 [5.00–16.84]**	**<0.001**	12	**19.31 [3.26, 114.23]**	**0.001**
Protected versus Unprotected dug well	15	0.93 [0.32–2.75]	0.901	–	–	–
Unimproved versus Improved	42	**8.19 [4.04–16.59]**	**<0.001**	11	**27.72 [3.80, 202.12]**	**0.001**
Protected dug well versus Borehole	30	**9.68 [2.92–32.04]**	**<0.001**	–	–	–
Study characteristics						
Wet versus dry	34	1.34 [0.50, 3.54]	0.562	7	1.02 [0.07, 13.94]	0.987
TTC versus *E. coli*	57	**1.92 [1.09, 3.38]**	**0.025**	15	1.08 [0.22, 5.37]	0.929
Random versus non-random selection	57	1.19 [0.63, 2.25]	0.588	15	0.71 [0.19, 2.61]	0.610

3.6. Assessment of bias

Egger's test found no evidence of small study publication bias for the meta-analysis of self-supply compared to alternative public water sources (p = 0.964, Figs. S7 and S8), self-supply compared to public piped water sources (p = 0.293, Fig. S9) or improved self-supply compared to improved public sources (p = 0.170, Fig. S10). Meta-regression did not find significant evidence of bias due to lack of randomization or season (Table 4). TTCs were significantly more likely to be reported as a FIB parameter in studies where water was more contaminated (OR = 1.92, 95% CI [1.09–3.38], p = 0.025) and therefore may exaggerate comparisons between studies reporting results in *E. coli* and TTC. Studies classified with lower quality ranking scores below 7 were significantly more likely to report faecal contamination (OR = 3.19, 95% CI [1.75–5.80], $p<0.001$) than higher ranked studies. Studies which did not describe selection or handling and did not meet handling minimum criteria reported were significantly more likely to report presence of FIB per 100 mL (Table S11). Study design might also influence bias in estimates of non-compliance, with significantly higher odds of FIB detection for cross-sectional studies (OR = 4.22, 95% CI [2.43–7.34], $p<0.001$).

4. Discussion

This systematic review of studies shows groundwater self-supply in LMICs is commonly contaminated with FIB. Meta-analysis between studies demonstrated that unimproved groundwater self-supply (i.e. unprotected dug wells) was more likely to be contaminated with FIB than improved sources such as boreholes or protected dug wells (OR = 8.19, 95% CI [4.04–16.59], $p<0.001$). Likewise, CDFs and FIB risk classification showed more frequent FIB contamination for unimproved self-supply sources. These findings are consistent with previous analysis of microbial contamination in groundwater sources more broadly (Bain et al., 2014b). Nonetheless, faecal contamination was still frequently reported for self-supply in the form of boreholes (28% of samples) and protected dug wells (77% of samples), suggesting well protection alone does not fully address water quality problems for self-supply sources. Even with protection, self-supply systems often rely on low-cost technologies and construction techniques, and draw on shallow groundwater sources, which may make them vulnerable to contamination from

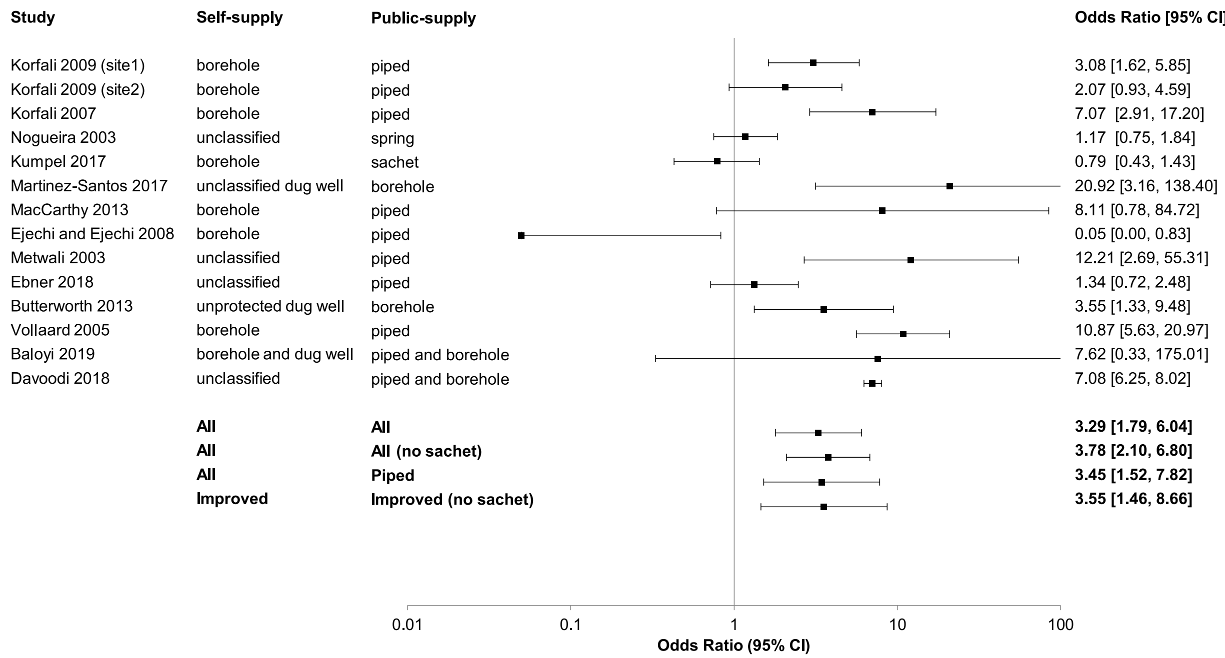

Fig. 3. Forest plot showing higher odds of faecal contamination for self-supply versus public sources.

Table 5
Meta-analysis for self-supply versus public water sources with higher odds ratio for FIB contamination for self-supply sources.

Study	Proportion of Samples > 1 FIB per 100 mL		
	Obs.	OR [95% CI]	p-Value
Self-supply versus public (excluding sachet water)	13	**3.78 [2.10–6.80]**	**<0.001**
Self-supply versus public (including sachet water)	14	**3.29 [1.79–6.04]**	**<0.001**
Self-supply versus piped	8	**3.45 [1.52–7.82]**	**0.003**
Self-supply improved versus public improved	7	**3.55 [1.46–8.66]**	**0.005**

human activities (Grönwall and Danert, 2020). However, previous studies have found similarly widespread FIB contamination for boreholes and protected wells generally (Bain et al., 2014b), and so these water quality risks are not necessarily unique to self-supply.

The reviewed studies reported a range faecal contamination risks including on-site sanitation systems and poor well condition, however few studies rigorously assessed contamination pathways. Sanitary risk inspections are recommended by the WHO drinking water guidelines as a technique to identify poor hygiene and inadequate sanitation as potential risks of faecal contamination (WHO, 2011). Less than half of the reviewed studies conducted sanitary inspections ($n = 12$, 40%), and only three of the reviewed studies conducted sanitary risk inspections according to the WHO guidelines (Kumpel et al., 2017; Luby et al., 2008; Vaccari et al., 2010). Limited data are available on the relationship between contamination of self-supply and sanitary score, suggesting more research is needed to identify important sanitary risk factors.

This study provides evidence that risk of faecal contamination of groundwater self-supply varies across contexts. Microbial water quality was highly heterogeneous ($I^2 = 90.9\%$) between studies, with higher risk of faecal contamination in low-income settings (OR = 3.85, 95% CI [1.85–7.69], p<0.001). While Bain et al. (2014a) found rural water sources were at higher risk of contamination, between study analysis of self-supply sources did not find a significant difference in the odds of contamination for rural versus urban locations. The heterogeneity observed may reflect a diversity of environmental conditions and possible contamination sources, including on-site sanitation (Díaz-Alcaide and Martínez-Santos, 2019; Kumpel et al., 2017, 2016; Martínez-Santos et al., 2017; Ngasala et al., 2019) or poor condition of wells and inadequate protection (Ali et al., 2019; Butterworth et al., 2013; Knappett et al., 2013; MacCarthy et al., 2013; Vaccari et al., 2010). The variety of self-supply sources in purpose and form, along with the different risks and benefits in different contexts, means that government policies, regulation and support need to be designed to meet a range of local conditions (Sutton and Butterworth, 2021).

Meta-analysis demonstrated that faecal contamination was less common in piped water. Even when self-supply was improved, piped water was still less likely to be contaminated (Fig. 3). These results suggest that, in general, households should be encouraged and supported to switch to piped supply where possible. However, this differential does not always hold, with Ejechi and Ejechi (2008) reporting significantly lower odds of *E. coli* contamination in borehole water as compared to piped water in urban Nigeria. It should be considered that faecal contamination affects all types of water sources, including piped water (Bain et al., 2014a, 2014b). Due to the limited number of studies that included both self-supply and communal groundwater sources, it was not possible to draw conclusions from the meta-analysis on whether the likelihood of contamination differs between self-supplied and communal groundwater sources. Notably, some studies showed that in areas where piped systems provide safer water, there were households that still preferred to self-supply their drinking water. Further research is needed to understand why in some contexts households might prefer self-supply over piped water, and how these preferences vary across different contexts. Possible reasons why people may prefer self-supply over piped water include convenience and reduced travel time to collect water (compared with public taps), increased water availability (where piped systems provide an intermittent supply), organoleptic properties, and enhanced status and reputation (Capstick et al., 2017; Sutton and Butterworth, 2021).

In areas where piped networks are not possible, supporting households to invest in safer forms of self-supply could reduce the risk of faecal contamination. Piped systems are not always feasible, particularly in sparsely populated rural areas, and self-supply may provide a critical stepping stone or stopgap for households. The meta-analysis indicated significantly lower risk of contamination for improved sources compared with unimproved sources. Similarly, boreholes were significantly less likely to be contaminated than both protected dug wells and unprotected wells. Where piped services remain infeasible, policy and practice should look to support investments in safer forms of self-supply. For example, an incremental approach to self-supply source protection has been implemented in parts of rural Africa (Butterworth et al., 2013; Sutton, 2011).

The results of the meta-analysis may reflect socio-economic inequalities. On a broad scale, the meta-analysis reveals that the risk of contaminated self-supply is higher in low-income countries. On a local scale, self-supply is often seen as a result of socio-economic inequality linked to a lack of water service expansion or poor service quality for the poorest (Furlong and Kooy, 2017; Hadipuro, 2010; Kooy et al., 2018; Kurniasih, 2008). Moreover, the poorest may be less able to invest in safer forms of self-supply, and may be more reliant on shallow groundwater that is vulnerable to contamination. Thus there is a need for reliable provision of piped services and inclusive approaches to increase equity of access. Financing strategies for water quality improvements through source protection and household water treatment could also help address these inequalities (Sutton and Butterworth, 2021).

Notwithstanding water quality concerns, availability and reliability of water is an important consideration when evaluating the role of self-supply in securing water for domestic needs. Water from self-supply can be used for different purposes beyond just drinking – including productive uses – and can supplement other sources that might provide higher quality water for drinking. For example, a study in Kenya reports that residents use private hand-dug wells that provide substantial volumes of water for purposes other than drinking and cooking (Okotto et al., 2015). When considering to what extent self-supply water is available in sufficient quantities when needed, it is important to factor in different water uses. There is also evidence to suggest in certain contexts self-supply can be more reliable than public sources (Butterworth et al., 2013; Foster et al., 2018). Investing in self-supply and being the primary beneficiary are seen as powerful motivators to ensure systems are sustained (Sutton and Butterworth, 2021).

A limitation of the meta-analysis is the variability in study design reported by the included papers. Studies were combined that used *E. coli* and TTC as a faecal indicator, and studies reported different handling and microbiological analytical methods. Meta-analysis showed significantly higher odds of faecal contamination for studies measuring TTC as compared to *E. coli* (OR = 1.92, 95% CI [1.09, 3.38], p = 0.025). Moreover, FIB - whether TTC or *E. coli* – are an indicator for faecal contamination and the presence or absence of FIB does not definitively confirm the presence or absence of pathogens (Charles et al., 2020). Further, only one-third of the reviewed studies (n = 11) tested the water quality considering both seasons. To ensure water safety, infrequent testing of water for FIB and subsequent interpretation of the health hazard is not sufficient to identify and manage risks.

The quality of the included studies was mixed. In the included studies, sample selection was often not described, representative or randomized, and quality control was not often mentioned. Method and sampling was mostly described, however handling minimum criteria was only reported to be met by 63% of the studies. Studies with a lower quality ranking score reported significantly higher odds of faecal contamination and thus might have caused bias. Meta-analysis resulted in significantly higher odds for FIB positive samples in cross-sectional studies (OR = 4.22, 95% CI [2.43–7.34], p<0.001). One possible explanation is that cross-sectional studies were more likely to be conducted in low-income countries. It is also important to note that study sites may have been biased towards locations where faecal contamination of groundwater supplies is perceived to be a problem. This could lead to an overestimation of the extent of faecal contamination in self-supply sources.

The review revealed a relatively small number of studies that have examined microbial quality of self-supplied groundwater in low- and middle-income countries. Within those studies that were identified, very few have rigorously assessed the links between groundwater quality and contamination risks. There is a need to understand water quality and associated contamination risks of self-supply services specifically. Further, studies included in this review focused on measuring water quality at source, neglecting the point-of-use. There is also a lack of information regarding management, storage and treatment practices in households using groundwater self-supply water services and how it relates to the water quality at point-of-use. It is known that the quality of water from improved sources deteriorates significantly after collection, due to different factors such as water storage conditions and post handling practices, and is not necessarily safe at point-of-use (Clasen and Bastable, 2003; Gundry et al., 2006; Lechevallier et al., 1996; McGuinness et al., 2020; Meierhofer et al., 2018; Shaheed et al., 2014; Shields et al., 2015; Trevett et al., 2005; Wright et al., 2004). Considering water quality of self-supply at point-of-use is crucial, since self-supply is on-premises and transport, distribution and storage practices might differ from other water supply types. There is a need to understand water management and treatment practices of self-supply users as well as assessing the microbial water quality at point-of-use during distribution, storage and before consumption. Studies also rarely compared self-supply sources with alternative public service delivery models, which is crucial to evaluate risk and benefits of self-supply as a potential service delivery model. More research is needed in different contexts to understand how self-supply compares to public water sources.

Self-supply is largely unmonitored and unregulated and hence the quality of self-supplied water has been rarely if ever systematically tracked. This has direct implications for monitoring progress towards SDG target 6.1 (universal access to safely managed water services). Self-supplied water is accessible on-premises and hence may contribute to one part of a country's 'safely-managed water' statistic. However, in many countries the data used to inform the 'free from contamination' dimension are derived from utilities providing a treated piped supply to households (WHO/UNICEF, 2018). According to WHO and UNICEF (2018), water quality data for piped supplies is applied towards the entire population using improved supplies as long as the population to which the data relate is at least 80% of the population of interest . When deriving national estimates, the Joint Monitoring Programme treats the safely managed water criteria independently, with the minimum value across the three indicators used to estimate the proportion of the population using a safely managed water service (WHO, 2017). Thus if self-supply counts towards the 'on premises' criterion, but is excluded from the 'free from contamination' calculation, it could lead to an overestimation in the proportion of households that truly have access to safely managed water services. The incorporation of water quality testing into nationally representative surveys (e.g. Multiple Indicator Cluster Surveys) that cover all types of water sources, including self-supply, is one way in which this bias can be addressed.

Policy and practice need to respond to water quality concerns of self-supply. Government and non-governmental support for household investment in safer forms of self-supply can improve the quality and sustainability of self-supply (Sutton and Butterworth, 2021). Self-supply should be considered in water safety planning, including necessary parts such as promotion of household water treatment and hygienic practices. Where piped networks are feasible, governments need to weigh the cost-benefit of supporting self-supply improvements with expansion and improvement of piped water supplies. The scale of continued investment in self-supply highlights the need for policy-makers to consider regulatory and monitoring systems for self-supply (Fischer et al., 2020).

5. Conclusion

This literature review and meta-analysis demonstrated that groundwater self-supply in LMICs often contains FIB, with contamination in 36% of samples across the included studies. Unimproved self-supply sources had more frequent and higher levels of faecal contamination than improved sources, while faecal contamination was more likely in self-supply than in piped water sources. Where piped systems are not feasible, supporting households to invest in safer forms of self-supply could reduce the risk of faecal contamination. Self-supply as a service delivery model needs government recognition and differentiated support for the different circumstances in which it is present.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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References

Adams, G.O., Ogedegbe, P.E., Tawari-Fufeyin, P., 2016. Assessment of presence of heavy metals and other pollution burden parameters and their effect on water quality in Benin City, Edo State. Environ. Qual. Manag. 26, 65–87. https://doi.org/10.1002/tqem.21485.

Adeniji-Oloukoi, G., Urmilla, B., Vadi, M., 2013. Households' coping strategies for climate variability related water shortages in Oke-Ogun region, Nigeria. Environ. Dev. 5, 23–38. https://doi.org/10.1016/j.envdev.2012.11.005.

Ali, R., Bünzli, M.A., Colombo, L., Khattak, S.A., Pera, S., Riaz, M., Valsangiacomo, C., 2019. Water quality before and after a campaign of cleaning and disinfecting shallow wells: a study conducted during and after floods in Khyber Pakhtunkhwa, Pakistan. J. Water Sanit. Hyg. Dev. 9, 28–37. https://doi.org/10.2166/WASHDEV.2018.272.

Allen, A., Dávila, J.D., Hofmann, P., 2006. The peri-urban water poor: citizens or consumers? Environ. Urban. 18, 333–351. https://doi.org/10.1177/0956247806069608.

ARGOSS, 2001. Guidelines for assessing the risk to groundwater from on-site sanitation. Br. Geol. Surv. 01, 97.

Bain, R., Cronk, R., Hossain, R., Bonjour, S., Onda, K., Wright, J., Yang, H., Slaymaker, T., Hunter, P., Prüss-Ustün, A., Bartram, J., 2014a. Global assessment of exposure to faecal contamination through drinking water based on a systematic review. Trop. Med. Int. Health. https://doi.org/10.1111/tmi.12334.

Bain, R., Cronk, R., Wright, J., Yang, H., Slaymaker, T., Bartram, J., 2014b. Fecal contamination of drinking-water in low- and middle-income countries: a systematic review and meta-analysis. PLoS Med. 11 https://doi.org/10.1371/journal.pmed.1001644.

Baloyi, R.S., Diamond, R.E., 2019. Variable water quality of domestic wells emphasizes the need for groundwater quality monitoring and protection: stinkwater, hammanskraal, Gauteng. Water SA 45, 216–224. https://doi.org/10.4314/wsa.v45i2.08.

Butterworth, J., Sutton, S., Mekonta, L., 2013. Self-supply as a complementary water services delivery model in Ethiopia. Water Altern. 6, 405–423.

Capstick, S., Whitmarsh, L., Healy, A., Bristow, G., 2017. Resilience in goundwater supply systems: findings from a survey of private households in Lagos, Nigeria., RIGSS working paper.

Charles, K.J., Nowicki, S., Bartram, J.K., 2020. A framework for monitoring the safety of water services: from measurements to security. NPJ Clean Water 3, 1–6. https://doi.org/10.1038/s41545-020-00083-1.

Chávez García Silva, R., Grönwall, J., Van Der Kwast, J., Danert, K., Foppen, J.W., 2020. Estimating domestic self-supply groundwater use in urban continental Africa. Environ. Res. Lett. 15 https://doi.org/10.1088/1748-9326/ab9af9.

Clasen, T.F., Bastable, A., 2003. Faecal contamination of drinking water during collection and household storage: the need to extend protection to the point of use. J. Water Health 1, 109–115. https://doi.org/10.2166/wh.2003.0013.

Davoodi, R., Pirsaheb, M., Karimyan, K., Gupta, V.K., Takhtshahi, A.R., Sharafi, H., Moradi, M., 2018. Data for distribution of various species of fecal coliforms in urban, rural and private drinking water sources in ten years period-a case study: kermanshah, Iran. Data Br. 18, 1544–1550. https://doi.org/10.1016/j.dib.2018.04.053.

DerSimonian, R., Laird, N., 1986. Meta-analysis in clinical trials. Controll. Clin. Trials. https://doi.org/10.1016/0197-2456(86)90046-2.

Díaz-Alcaide, S., Martínez-Santos, P., 2019. Mapping fecal pollution in rural groundwater supplies by means of artificial intelligence classifiers. J. Hydrol. 577 https://doi.org/10.1016/j.jhydrol.2019.124006.

Ebner, P.D., Deering, A., Mojadady, M., Rahimi, Z., Amini, R., Popal, M., Eshaqzai, N., Barak, S., Amini, S., Azizi, E., Morshid, E., Mohammadi, N., Rahimi, M., McNamara, K., Oliver, H.F., 2018. Capacity building through water quality and safety analyses in herat, Afghanistan. J. Food Prot. 81, 1467–1471. https://doi.org/10.4315/0362-028X.JFP-18-051.

Egger, M., Smith, G.D., Schneider, M., Minder, C., 1997. Bias in meta-analysis detected by a simple, graphical test. Br. Med. J. https://doi.org/10.1136/bmj.315.7109.629.

Eisenhauer, I.F., Hoover, C.M., Remais, J.V., Monaghan, A., Celada, M., Carlton, E.J., 2016. Estimating the risk of domestic water source contamination following precipitation events. Am. J. Trop. Med. Hyg. 94, 1403–1406. https://doi.org/10.4269/ajtmh.15-0600.

Ejechi, E.O., Ejechi, B.O., 2008. Safe drinking water and satisfaction with environmental quality of life in some oil and gas industry impacted cities of Nigeria. Soc. Indic. Res. 85, 211–222. https://doi.org/10.1007/s11205-007-9086-6.

Fischer, A., Hope, R., Manandhar, A., Hoque, S., Foster, T., Hakim, A., Islam, M.S., Bradley, D., 2020. Risky responsibilities for rural drinking water institutions: the case of unregulated self-supply in Bangladesh. Glob. Environ. Chang. 65, 102152 https://doi.org/10.1016/j.gloenvcha.2020.102152.

Foster, T., Priadi, C., Kotra, K.K., Odagiri, M., Rand, E., Willetts, J., 2021. Self-supplied drinking in low- and middle-income countries in the Asia-Pacific. NPJ Clean Water. https://doi.org/10.1038/s41545-021-00121-6. In press.

Foster, T., Shantz, A., Lala, S., Willetts, J., 2018. Factors associated with operational sustainability of rural water supplies in Cambodia. Environ. Sci. Water Res. Technol. 4, 1577–1588. https://doi.org/10.1039/c8ew00087e.

Furlong, K., Kooy, M., 2017. Worlding water supply: thinking beyond the network in Jakarta. Int. J. Urban Reg. Res. 41, 888–903. https://doi.org/10.1111/1468-2427.12582.

Gorter, A.C., Alberts, J.H., Gago, J.F., Sandiford, P., 1995. A randomized trial of the impact of rope-pumps on water quality. J. Trop. Med. Hyg. 98, 247–255.

Grönwall, J., 2016. Self-supply and accountability: to govern or not to govern groundwater for the (peri-) urban poor in Accra, Ghana. Environ. Earth Sci. 75 https://doi.org/10.1007/s12665-016-5978-6.

Grönwall, J., Danert, K., 2020. Regarding groundwater and drinking water access through a human rights lens : self-supply as a norm. Water 12, 21 (Basel).

Grönwall, J.T., Mulenga, M., McGranahan, G., 2010. Groundwater, self-supply and poor urban dwellers-a review with case studies of Bangalore and Lusaka. Human Settlements Working Paper Series - Water and Sanitation 26, 87.

Gundry, S.W., Wright, J.A., Conroy, R., Du Preez, M., Genthe, B., Moyo, S., Mutisi, C., Ndamba, J., Potgieter, N., 2006. Contamination of drinking water between source and point-of-use in rural households of South Africa and Zimbabwe: implications for monitoring the millennium development goal for water. Water Pract. Technol. 1 https://doi.org/10.2166/wpt.2006.032.

Hadipuro, W., 2010. Indonesia's water supply regulatory framework: between commercialisation and public service? Water Altern. 3, 475–491.

Higgins, J.P.T., Thompson, S.G., 2002. Quantifying heterogeneity in a meta-analysis. Stat. Med. https://doi.org/10.1002/sim.1186.

Knappett, P.S.K., McKay, L.D., Layton, A., Williams, D.E., Alam, M.J., Mailloux, B.J., Ferguson, A.S., Culligan, P.J., Serre, M.L., Emch, M., Ahmed, K.M., Sayler, G.S., Van Geen, A., 2013. Unsealed tubewells lead to increased fecal cotamination of drinking water. J. Water Health 10, 565–578. https://doi.org/10.1038/jid.2014.371.

Komakech, H.C., de Bont, C., 2018. Differentiated access: challenges of equitable and sustainable groundwater exploitation in Tanzania. Water Altern. 11, 623–637.

Kooy, M., Walter, C.T., Prabaharyaka, I., 2018. Inclusive development of urban water services in Jakarta: the role of groundwater. Habitat Int. 73, 109–118. https://doi.org/10.1016/j.habitatint.2016.10.006.

Korfali, S.I., Jurdi, M., 2009. Provision of safe domestic water for the promotion and protection of public health: a case study of the city of Beirut, Lebanon. Environ. Geochem. Health 31, 283–295. https://doi.org/10.1007/s10653-008-9218-1.

Korfali, S.I., Jurdi, M., 2007. Assessment of domestic water quality: case study, Beirut, Lebanon. Environ. Monit. Assess. 135, 241–251. https://doi.org/10.1007/s10661-007-9646-x.

Kulabako, R.N., Nalubega, M., Wozei, E., Thunvik, R., 2010. Environmental health practices, constraints and possible interventions in peri-urban settlements in developing countries - a review of Kampala, Uganda. Int. J. Environ. Health Res. 20, 231–257. https://doi.org/10.1080/09603120903545745.

Kumpel, E., Albert, J., Peletz, R., De Waal, D., Hirn, M., Danilenko, A., Uhl, V., Daw, A., Khush, R., 2016. Urban water services in Fragile States: an analysis of drinking water sources and quality in port harcourt, Nigeria, and Monrovia, Liberia. Am. J. Trop. Med. Hyg. 95, 229–238. https://doi.org/10.4269/ajtmh.15-0766.

Kumpel, E., Cock-Esteb, A., Duret, M., Waal, O.De, Khush, R., 2017. Seasonal variation in drinking and domestic water sources and quality in port harcourt, Nigeria. Am. J. Trop. Med. Hyg. 96, 437–445. https://doi.org/10.4269/ajtmh.16-0175.

Kurniasih, H., 2008. Water not for all: the concequences of water privitisation in Jakarta, Indonesia.. In: Proceedings of the 17th Biennial Conference Asian Studies Association of Australia, pp. 1–19.

Lechevallier, M.W., Welch, N.J., Smith, D.B., 1996. Full-scale studies of factors related to coliform regrowth in drinking water. Appl. Environ. Microbiol. 62, 2201–2211. https://doi.org/10.1128/aem.62.7.2201-2211.1996.

Liddle, E.S., Mager, S.M., Nel, E.L., 2016. The importance of community-based informal water supply systems in the developing world and the need for formal sector support. Geogr. J. 182, 85–96. https://doi.org/10.1111/geoj.12117.

Luby, S.P., Gupta, S.K., Sheikh, M.A., Johnston, R.B., Ram, P.K., Islam, M.S., 2008. Tubewell water quality and predictors of contamination in three flood-prone areas in Bangladesh. J. Appl. Microbiol. 105, 1002–1008. https://doi.org/10.1111/j.1365-2672.2008.03826.x.

MacCarthy, M.F., Annis, J.E., Mihelcic, J.R., 2013. Unsubsidised self-supply in eastern Madagascar. Water Altern. 6, 424–438.

Maran, N.H., Crispim, B.D.A., Iahnn, S.R., de Araújo, R.P., Grisolia, A.B., de Oliveira, K. M.P., 2016. Depth and well type related to groundwater microbiological contamination. Int. J. Environ. Res. Public Health 13. https://doi.org/10.3390/ijerph13101036.

Martínez-Santos, P., Martín-Loeches, M., García-Castro, N., Solera, D., Díaz-Alcaide, S., Montero, E., García-Rincón, J., 2017. A survey of domestic wells and pit latrines in rural settlements of mali: implications of on-site sanitation on the quality of water supplies. Int. J. Hyg. Environ. Health 220, 1179–1189. https://doi.org/10.1016/j.ijheh.2017.08.001.

McGuinness, S.L., O'Toole, J., Barker, S.F., Forbes, A.B., Boving, T.B., Giriyan, A., Patil, K., D'Souza, F., Vhaval, R., Cheng, A.C., Leder, K., 2020. Household water storage management, hygiene practices, and associated drinking water quality in Rural India. Environ. Sci. Technol. 54, 4963–4973. https://doi.org/10.1021/acs.est.9b04818.

Meierhofer, R., Bänziger, C., Deppeler, S., Kunwar, B.M., Bhatta, M., 2018. From water source to tap of ceramic filters-Factors that influence water quality between collection and consumption in rural households in Nepal. Int. J. Environ. Res. Public Health 15. https://doi.org/10.3390/ijerph15112439.

Metwali, R.M., 2003. Water quality of some wells in Taiz city (Yemen republic) and its surroundings. Folia Microbiol. 48, 90–94. https://doi.org/10.1007/BF02931282. Praha.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., 2009. Preferred Reporting Items for Systematic Reviews and Meta- Analyses: The PRISMA Statement. PloS Med 6 (7). https://doi.org/10.1371/journal.pmed.1000097.

Mukhopadhyay, C., Vishwanath, S., Eshwara, V.K., Shankaranarayana, S.A., Sagir, A., 2012. Microbial quality of well water from rural and urban households in Karnataka, India: a cross-sectional study. J. Infect. Public Health 5, 257–262. https://doi.org/10.1016/j.jiph.2012.03.004.

Ngasala, T.M., Masten, S.J., Phanikumar, M.S., 2019. Impact of domestic wells and hydrogeologic setting on water quality in peri-urban Dar es Salaam, Tanzania. Sci. Total Environ. 686, 1238–1250. https://doi.org/10.1016/j.scitotenv.2019.05.202.

Nogueira, G., Nakamura, C.V., Tognim, M.C.B., Abreu Filho, B.A., Dias Filho, B.P., 2003. Microbiological quality of drinking water of urban and rural communities, Brazil. Rev. Saude Publica 37, 232–236. https://doi.org/10.1590/S0034-89102003000200011.

Okotto, L., Okotto-Okotto, J., Price, H., Pedley, S., Wright, J., 2015. Socio-economic aspects of domestic groundwater consumption, vending and use in Kisumu, Kenya. Appl. Geogr. 58, 189–197. https://doi.org/10.1016/j.apgeog.2015.02.009.

Potgieter, N., Mudau, L.S., Maluleke, F.R.S., 2006. Microbiological quality of groundwater sources used by rural communities in Limpopo province, South Africa. Water Sci. Technol. 54, 371–377. https://doi.org/10.2166/wst.2006.890.

Pujari, P.R., Padmakar, C., Labhasetwar, P.K., Mahore, P., Ganguly, A.K., 2012. Assessment of the impact of on-site sanitation systems on groundwater pollution in two diverse geological settings-a case study from India. Environ. Monit. Assess. 184, 251–263. https://doi.org/10.1007/s10661-011-1965-2.

Ravenscroft, P., Mahmud, Z.H., Islam, M.S., Hossain, A.K.M.Z., Zahid, A., Saha, G.C., Zulfiquar Ali, A.H.M., Islam, K., Cairncross, S., Clemens, J.D., Islam, M.S., 2017. The public health significance of latrines discharging to groundwater used for drinking. Water Res. 124, 192–201. https://doi.org/10.1016/j.watres.2017.07.049.

Schram, H.E., Wampler, P.J., 2018. Evaluation of hand-dug wells in rural haiti. Int. J. Environ. Res. Public Health 15. https://doi.org/10.3390/ijerph15091891.

Shaheed, A., Orgill, J., Ratana, C., Montgomery, M.A., Jeuland, M.A., Brown, J., 2014. Water quality risks of "improved" water sources: evidence from Cambodia. Trop. Med. Int. Health 19, 186–194. https://doi.org/10.1111/tmi.12229.

Shields, K.F., Bain, R.E.S., Cronk, R., Wright, J.A., Bartram, J., 2015. Association of supply type with fecal contamination of source water and household stored drinking water in developing countries: a bivariate meta-analysis. Environ. Health Perspect. 123, 1222–1231. https://doi.org/10.1289/ehp.1409002.

Sutton, S., 2011. Accelerating Self Supply: a Case Study from Uganda.

Sutton, S., 2009. An Introduction to Self Supply: putting the user first - Incremental improvements and private investment in rural water supply. Rural Water Supply Ser. 1–12.

Sutton, S., Butterworth, J., 2021. Self-Supply: Filling the Gaps in Public Water Supply provision. Practical Action Publishing, Rugby. https://doi.org/10.3362/9781780448190.

Sweeting, M.J., Sutton, A.J., Lambert, P.C., 2004. What to add to nothing? Use and avoidance of continuity corrections in meta-analysis of sparse data. Stat. Med. https://doi.org/10.1002/sim.1761.

Trevett, A.F., Carter, R.C., Tyrrel, S.F., 2005. The importance of domestic water quality management in the context of faecal-oral disease transmission. J. Water Health 3, 259–270. https://doi.org/10.2166/wh.2005.037.

Vaccari, M., Collivignarelli, C., Tharnpoophasiam, P., Vitali, F., 2010. Wells sanitary inspection and water quality monitoring in Ban Nam Khem (Thailand) 30 months after 2004 Indian Ocean tsunami. Environ. Monit. Assess. 161, 123–133. https://doi.org/10.1007/s10661-008-0732-5.

Van Geen, A., Ahmed, K.M., Akita, Y., Alam, M.J., Culligan, P.J., Emch, M., Escamilla, V., Feighery, J., Ferguson, A.S., Knappett, P., Layton, A.C., Mailloux, B.J., McKay, L.D., Mey, J.L., Serre, M.L., Streatfield, P.K., Wu, J., Yunus, M., 2011. Fecal contamination of shallow tubewells in Bangladesh inversely related to arsenic. Environ. Sci. Technol. 45, 1199–1205. https://doi.org/10.1021/es103192b.

Viechtbauer, W., 2010. Conducting meta-analyses in R with the metafor package. J. Stat. Softw. 36, 1–48.

Vollaard, A.M., Ali, S., Smet, J., Van Asten, H., Widjaja, S., Visser, L.G., Surjadi, C., Van Dissel, J.T., 2005. A survey of the supply and bacteriologic quality of drinking water and sanitation in Jakarta, Indonesia. Southeast Asian J. Trop. Med. Public Health 36, 1552–1561.

WHO/UNICEF, 2018. JMP Methodology: 2017 Update & SDG baselines 1–23.

WHO, 2017. Safely managed drinking water - thematic report on drinking water 2017. ISBN 978 92 4 156542 4.

WHO, 2011. Guidelines for drinking-water quality. World Heal. Organ.

WHO, UNICEF, 2021. JMP WASH data [WWW Document]. URL https://washdata.org/ (accessed 1.21.20).

WHO, UNICEF, 2019. Progress on household drinking water, sanitation and hygiene 2000-2017. Special focus on inequalities 140.

WHO, UNICEF, 2017. Guidelines for drinking-water quality: fourth edition incorporating the first addendum. doi:10.1017/CBO9781107415324.004.

WHO, UNICEF, 2010. Progress on sanitation and drinking water - 2010 update.

World Bank, 2020. World Bank Country and Lending Groups [WWW Document]. URL https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-group (accessed 4.1.20).

Wright, J., Gundry, S., Conroy, R., 2004. Household drinking water in developing countries: a systematic review of microbiological contamination between source and point-of-use. Trop. Med. Int. Health 9, 1. https://doi.org/10.1046/j.1365-3156.2003.01160.x.

3.3 Summary

Chapter III, including the systematic literature review and meta-analysis, contributes to answering RQ1 of the PhD research by demonstrating that groundwater self-supply in LMICs is at risk of faecal contamination. The literature review found that self-supply services were commonly contaminated at different frequencies and levels depending on the type of self-supply technology. Furthermore, faecal contamination was more likely in self-supply than in piped water sources.

This chapter has also highlighted the importance of RQ1 by showing that while groundwater self-supply is widely practised in many parts of the world, there is still a significant lack of understanding regarding water quality concerns and the associated contamination risks. Existing studies tend to overlook critical aspects such as water quality at point-of-use and related management, treatment, and storage practices. Therefore, a comprehensive and holistic understanding of the risks and benefits associated with self-supply is needed to identify ways to improve the safety and reliability of this practice as a source of water. This highlights the importance of considering the different components of the social-ecological system framework to understand risks and benefits associated with self-supply water quality.

Further, groundwater self-supply practices can vary widely depending on the social, economic, and environmental contexts in which they are used. Understanding the contextual factors that shape groundwater self-supply practices is essential for developing effective strategies aimed at improving access to safe and reliable drinking water. Although this literature review offers a valuable overview of the topic and concerns surrounding groundwater self-supply in LMICs, it is important to note that the PhD research focuses specifically on self-supply settings in urban Indonesia.

The PhD research will address the identified gaps in the literature review by assessing the water quality of self-supply services at both the source and point-of-use in urban Indonesia (**Chapter IV**). Additionally, self-supply practices, usage, and management will be evaluated (**Chapter V**).

Chapter IV

4. Microbial water quality of self-supply in urban Indonesia

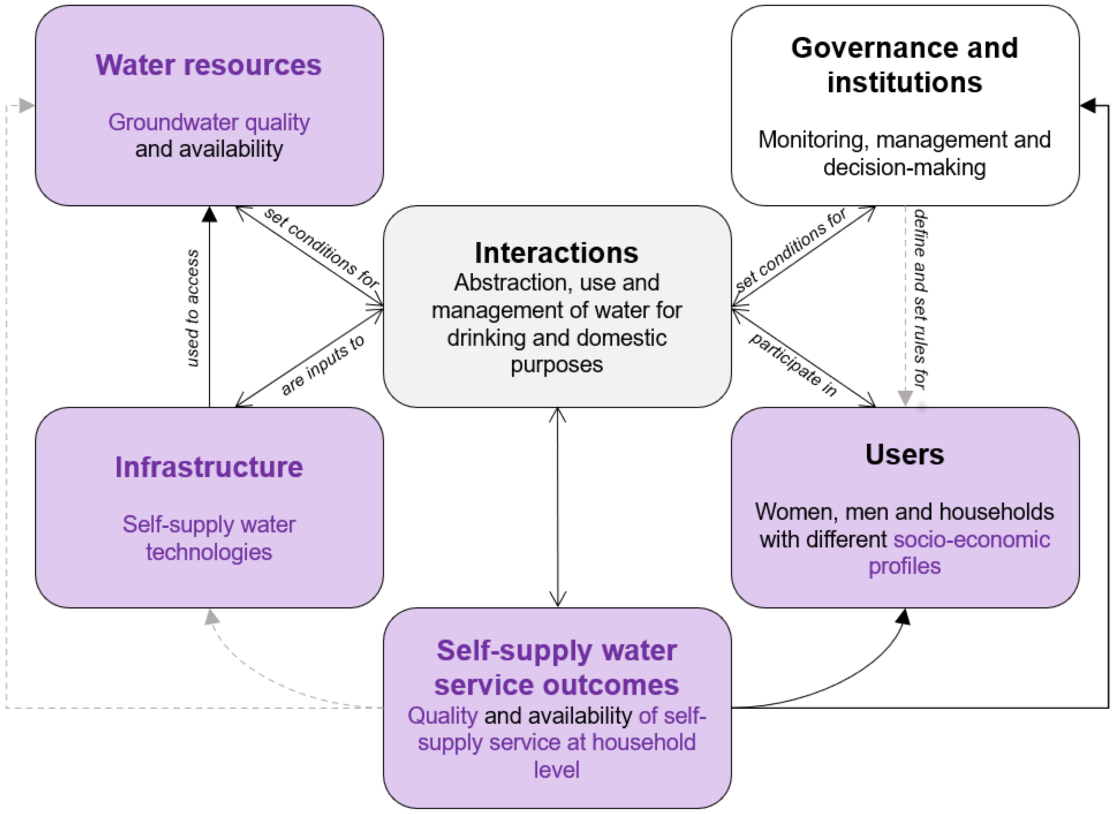

Figure 7: Chapter IV focuses on the microbial water quality of self-supply services in the urban Indonesia context and contributes to RQ1 by investigating the risk factors of faecal contamination for self-supply services. The assessment considers water quality both at the source and at the point-of-use at household level. The assessment and findings are primarily situated within the components of 'Water resource', 'Infrastructure' and 'Self-supply water service outcomes', but also consider other components such as 'Users' and 'Interactions'.

4.1 Overview

Chapter IV addresses RQ1, which seeks to investigate the extent to which groundwater self-supply is free from faecal contamination at both the source and point-of-use and examine the potential risk factors of faecal contamination. This chapter focuses on the urban Indonesia context.

The chapter consists of two publications. The first publication in this chapter, the assessment of sanitary and socio-economic risk factors of microbial contamination of groundwater self-supply in urban Indonesia, was published in *Water Resources Research* in 2022 (Publication II). The second publication in this chapter, which examines the associations between seasonality and faecal contamination of self-supply sources in urban Indonesia, was published in *Water, Sanitation and Hygiene for Development* in 2023 (Publication III).

The findings are primarily situated within the 'Water Resources', 'Infrastructure' and 'Self-supply water service outcomes' components of the social-ecological system framework. However, the findings of the study also take into account information from other components, such as socio-economic profiles of 'Users' or 'Interactions' such as water treatment practices (Figure 7).

The assessment (Publication II) considers the socio-economic dimensions and sheds light on equity aspects in access to safe water. The study identifies several factors associated with faecal contamination of groundwater self-supply and also provides valuable insights into the potential impact of socio-economic factors on water quality. Publication III accounts for seasonality and associations with *E. coli* contamination, which were not yet considered in Publication II.

4.2 Publications II and III

Publication II and its supplementary materials are available open access at https://doi.org/10.1029/2021WR031843 (Genter et al., 2022).

Publication III and its supplementary materials are available open access at https://doi.org/10.2166/washdev.2023.060 (Genter, Putri, Maysarah, et al., 2023).

ADVANCING EARTH AND SPACE SCIENCE

Water Resources Research

RESEARCH ARTICLE
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Key Points:

- Risk factors for fecal contamination of groundwater self-supply assessed in two Indonesian cities
- Contamination associated with lower socio-economic status, proximity to sanitation, and lack of well protection
- Widespread boiling of self-supplied water significantly improves microbial quality between source and point-of-use

Supporting Information:

Supporting Information may be found in the online version of this article.

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Microbial Contamination of Groundwater Self-Supply in Urban Indonesia: Assessment of Sanitary and Socio-Economic Risk Factors

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Abstract In urban Indonesia, more than 40 million people rely on groundwater self-supply, but the extent to which self-supply delivers safe water and the associated risk factors for fecal contamination remain unclear. This study quantified *Escherichia coli* (*E. coli*) for 511 self-supply sources and at point-of-use for 173 households in the Indonesian cities of Bekasi and Metro. A structured questionnaire collected information about the household, water sources, and potential contamination sources. Univariate and multivariate logistic regression analysis examined risk factors for fecal contamination. *E. coli* was detected in 66% of sources, including 55% of boreholes, 64% of protected dug wells, and 82% of unprotected dug wells. Widespread boiling of water meant microbial quality improved significantly between source and point-of-use, with *E. coli* detected in 30% of self-supply samples at point-of-use. Unprotected dug wells were significantly more likely to be contaminated than boreholes. In Bekasi, the analysis found a significant association between presence of *E. coli* and sanitation systems located within 10 m of the groundwater source. In Metro, poorer households had significantly higher odds of contamination than wealthier households. Other significant factors included shallower borehole depths in Bekasi, use of a rope and bucket, and absence of a concrete platform in Metro. In Bekasi, *E. coli* concentration at source was significantly associated with water quality at point-of-use. Risk of fecal contamination could be reduced by supporting households to invest in improved protection, and by facilitating promotion for safe household water treatment. Support for self-supply improvements should be weighed against the expansion and improvement of piped water services.

1. Introduction

Many countries are facing challenges in extending water services to poor and vulnerable communities that are most at risk of being left behind (WHO & UNICEF, 2021). The world is not on track to achieve the Sustainable Development Goal (SDG) target 6.1, which calls for universal and equitable access to safe and affordable drinking water for all by 2030 (WHO & UNICEF, 2021). To meet the criteria of a safely managed drinking water service, households must use an improved water source that is accessible on-premises, available in sufficient quantities when needed and free from fecal and chemical contamination (WHO & UNICEF, 2017). An improved water facility includes sources that are protected from outside contamination by nature of their construction, such as boreholes, protected dug wells, or rainwater harvesting (WHO & UNICEF, 2017). In 2020, two billion people still lacked access to a safely managed water service (WHO & UNICEF, 2021). The lack of access to safe drinking water is felt disproportionately by disadvantaged households (Ezbakhe et al., 2019; Flores Baquero et al., 2016; WHO & UNICEF, 2019).

Self-supply plays an important role in providing water for households in low- and middle-income countries (LMIC) and has implications for progress toward SDG target 6.1 (T. Foster et al., 2021). Household self-supply commonly refers to an on-premises water source, usually relying on groundwater or rainwater, that is privately owned and managed by an individual household or family (Grönwall & Danert, 2020). Self-supply exists in a range of contexts in urban and rural settings and can be found in households which are beyond the reach of utility- or community managed water supplies or in households that need to complement an inadequate supply (Adeniji-Oloukoi et al., 2013; Allen et al., 2006; Grönwall, 2016; Grönwall & Danert, 2020; Komakech & de Bont, 2018; Kulabako et al., 2010; Liddle et al., 2016; Sutton, 2009). Self-supply services are generally unregulated and unmonitored (S. Foster et al., 2022; Grönwall & Danert, 2020; Grönwall et al., 2010). In the

Asia-Pacific, it is estimated that over 700 million people depended on self-supply across rural and urban areas in 2018 (T. Foster et al., 2021).

In urban Indonesia, nearly one third of the urban population—or more than 40 million people—self-supply their drinking water (T. Foster et al., 2021). Self-supply has the potential to provide a safely managed water service as it is located on the premises of a user household. However, in Indonesia little is known about the extent to which self-supply provides drinking water that is free from contamination (Genter et al., 2021). In 2020, 57% of the Indonesian population were living in urban regions, which corresponds to a population of 156 million people. Indonesia is in the bottom 15 countries globally in terms of urban use of piped water for drinking, with a coverage of 12% (National Population and Family Planning Board (BKKBN) 2018). Yet 72% were using improved water supplies accessible on premises in 2020 (WHO & UNICEF, 2021), a statistic which is largely driven by widespread reliance on self-supply. Self-supply in Indonesia is often seen as a result of socio-economic inequality linked to a lack of water service expansion or poor service quality for the poorest (Cronin et al., 2017; Furlong & Kooy, 2017; Hadipuro, 2010; Kooy et al., 2018; Kurniasih, 2008). Despite the ubiquity of self-supply in urban Indonesia, data on the "free from contamination" criterion for safely managed water are lacking (WHO & UNICEF, 2021), and there is an urgent need to address this evidence gap.

Few studies have rigorously assessed fecal contamination risks of groundwater self-supply. Risk factors for fecal contamination of groundwater self-supply likely vary across contexts, influenced by a diversity of environmental conditions and possible contamination sources (Genter et al., 2021). Risk factors can be categorized as hazard factors, pathway factors, and indirect factors (Howard, 2002). Hazard factors include pollution sources, such as sanitation systems or animal feces. Pathway factors allow microbial pollution to enter the groundwater supply, such as poor construction of water systems. Indirect factors enhance the development of pathway factors, but do not directly allow contamination into the supply, nor form a contamination source. Risk factors for fecal contamination of self-supply have been identified in various contexts, including on-site sanitation as hazard factors (Kumpel et al., 2016, 2017; Martínez-Santos et al., 2017; Ngasala et al., 2019) or poor condition of wells and inadequate protection as pathway factors (Ali et al., 2019; Butterworth et al., 2013; MacCarthy et al., 2013; Vaccari et al., 2010). Household wealth as an indirect determinant of self-supply contamination has not been rigorously assessed, either in Indonesia or elsewhere. This is an important evidence gap to address given the poorest may be less able to invest in safer forms of self-supply.

Understanding the extent to which self-supplied water is affected by contamination risk factors is crucial for people's health and wellbeing in urban Indonesia. This study aims to address this evidence gap by examining the extent and predictors of fecal contamination of groundwater self-supply in two Indonesian cities. Specifically, the study seeks to (a) understand the extent to which groundwater self-supply is free from fecal contamination at both source and point-of-use and (b) identify risk factors of fecal contamination in self-supply at the source and point-of-use.

2. Methods

2.1. Study Area

The study was undertaken in the Indonesian cities of Bekasi and Metro. The two study sites were selected based on widespread use of self-supply, the lack of access to piped water, and high population density. Kota Bekasi is one of Indonesia's most populous cities and is located in West Java on the eastern border of Indonesia's capital Jakarta. In 2017, the population density in Kota Bekasi was 13,841 people/km^2 (BPS, 2021). In 2019, the population of Kota Bekasi had reached approximately three million inhabitants (BPS Kota Bekasi, 2021). Kota Bekasi is divided into 12 districts, three of which were the focus of this study. Kota Bekasi's local water utility is only able to serve 26.8% of the total population, with the marginal areas of the city remaining unserved (Bappeda Kota Bekasi, 2018). Previous census data from 2010 suggested more than 40% of households in Kota Bekasi were dependent on groundwater for drinking water (BPS Kota Bekasi, 2010). Kota Bekasi is served by two groundwater systems: a phreatic/semi-confined system associated with volcanic/alluvial-fan deposits and a confined system with recharge (Dirks et al., 1988). The study sites in Kota Bekasi are served by the phreatic/semi-confined system, where the water level is typically at a depth of four to eight m below ground level.

Kota Metro is a city in the Indonesian province of Lampung on Sumatra Island. In 2018, the population of Kota Metro reached 162,976 people, with a population density of 2,371 people/km^2. The city is divided into five districts, namely Metro Barat (West), Pusat (Central), Selatan (South), Timur (East), and Utara (North). According to official statistics, only 2,134 households were connected to the piped municipal water system in 2018 (1.3% of Metro's population), with most customers from the districts of Metro Pusat (1032 customers) and Metro Timur (920 customers), whereas in Metro Utara no communities used water from Indonesian's water supply company (BPS Kota Metro, 2019). Geologically, Kota Metro is dominated by young volcanic deposits (ESDM, 2021).

2.2. Data Collection

The data collection was carried out during wet season in Bekasi (February–March 2020) and during dry season in Metro (October–November 2020). For the months of data collection, 60 and 12 rainy days were recorded with a precipitation of 2553 mm and 163 mm for Bekasi and Metro, respectively (BPS Kota Bekasi, 2021; BPS Kota Metro, 2021). Data were collected from 300 randomly selected households in both Bekasi and Metro. In Bekasi, participating households were randomly selected across three sub-districts (*Kelurahan*) (Jatiluhur, Sumur Batu, and Jatirangga) from three different districts (*Kecamatan*) in Bekasi (Jatiasih, Bantar Gebang, and Jatisampurna). In Metro, the participating households were randomly selected across five sub-districts (Karangrejo, Hadimulyo Barat, Ganjarasri, Iringmulyo, and Rejomulyo) from the five different districts in Metro (Figure 1). In Bekasi and Metro, districts and sub-districts were selected purposively based on the same criteria, such as self-supply prevalence, lack of access to piped water, and poverty status, with information obtained from secondary data and local government. Although the same selection criteria were applied, all five districts were selected in Metro, while only three were selected in Bekasi. The hamlets (*RW Rukun Warga*), which consist of several neighborhoods (*RT Rukun Tetangga*), were selected in consultation with the heads of the selected sub-districts. After further consultations with the respective head of the selected hamlets, the neighborhoods to be surveyed were chosen. All households of the selected neighborhoods were listed and then randomly selected using the randomization formula in Microsoft Office Excel 2016. The target number of households to be surveyed in each neighborhood was determined in proportion to the population size (Table S1 in Supporting Information S1). Based on the randomization output, households were sorted from smallest to largest randomization output number and then divided into a priority list and a reserve list. The households in the reserve list were only interviewed if the households on the priority list could not be visited or were not willing to be interviewed. Data collection included a household questionnaire, sanitary inspection of self-supply sources, and water quality testing. Prior to the data collection, informed consent was obtained in local language from heads of neighborhoods and from all participants. Ethical approval to conduct the research was provided by the Research Ethics Committee of University of Technology Sydney as well as the Universitas Indonesia.

2.3. Water Quality

Water samples were collected in sterile Whirl-Pak® bags (120 mL capacity, Nasco, Fort Atkinson, WI, USA) from 287 to 296 randomly selected households in Bekasi and Metro, respectively. Samples included 240 and 271 self-supply sources and at point-of-use 81 and 92 drinking water samples (including bottled and refill water) in Bekasi and Metro, respectively. Point-of-use samples were collected for every fifth household. At point-of-use, water was collected as household members would typically do when drinking (e.g., pouring water into a glass or cup, or directly from the storage container). Samples were stored at 2–8°C for transport and processed within 6 hours at a field laboratory in close proximity to the study area. Fecal indicator bacteria *Escherichia coli* (*E. coli*) was quantified with IDEXX Colilert-18 using the IDEXX Quanti-Tray®/2000 system with the Quanti-Tray® sealer model 2X according to manufacturer's instructions (IDEXX Laboratories, 2015). Samples were incubated at 35°C for 18–20 hr. *E. coli* cells were enumerated according to the manufacturer's instructions using an ultraviolet source (365 nm) and the Most Probable Number (MPN) table for the Quanti-Tray®/2000 system. The number of *E. coli* was reported as MPN per 100 mL with lower and upper 95% confidence limits. The Quanti-Tray®/2000 system is capable of quantifying the number of *E. coli* in 100 mL water samples over a range of 1–2419.6 MPN per 100 mL. Data falling outside the detection range were set to half the lower limit of detection (LOD) or to the upper LOD according to Cole et al., 2009.

Figure 1. Study sites in Metro (1: Karangrejo, 2: Hadimulyo Barat, 3: Ganjarasri, 4: Iringmulyo, and 5: Rejomulyo) and Bekasi (1: Jatiluhur, 2: Sumur Batu, and 3: Jatirangga) (QGIS, version 3.24.1).

2.4. Household Survey

A structured household survey was conducted in local language by trained enumerators simultaneously with the water sampling. The main household questionnaire covered a range of themes about the household and water sources used. Questions about the household included themes on health and socio-economic status, water management and decision-making. Self-supply water sources were defined as groundwater sources (boreholes, protected dug wells, or unprotected dug wells) that were privately owned by a household (Text S1 in Supporting Information S1).

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2.5. Sanitary Inspection

The household survey questionnaire included a sanitary inspection module with observations on water supply and sanitation infrastructure. Observational questions of the WHO sanitary inspection form were adapted to the local context and included questions on the construction of the well, water lifting device, sanitation facilities, and household water storage and treatment (WHO & UNICEF, 2017). The borehole depth (to bottom of borehole) was determined based on the respondent's information. Further observations were made on borehole infrastructure such as the headworks and the presence of a concrete platform. For dug wells it was recorded whether water was delivered through a pump or a rope and bucket. Potential contamination sources were identified such as the number and proximity of sanitation systems and ownership of animals. Number of on-site sanitation facilities within a radius of 20 m and the lateral distance to the closest sanitation facility were considered and based on surveyed household responses and enumerator estimates. Type and protection of storage container as well as treatment method were recorded for point-of-use water samples (Text S1 in Supporting Information S1).

3. Data Analysis

3.1. Descriptive Analysis

Descriptive analysis was performed using water quality data of self-supply water sources. Due to the focus on self-supply, collected data from public sources were excluded from analysis in Bekasi (Source: $n = 47$, Point-of-use: $n = 3$) and Metro (Source: $n = 25$, Point-of-use: $n = 2$). Refill and bottled (packaged) water were considered for households that only used packaged water at point-of-use and no self-supplied water (Bekasi: $n = 27$, Metro: $n = 26$). Missing data were excluded from the analysis.

3.2. Conceptual Model of Fecal Contamination

To understand risk factors for fecal contamination of self-supply, potential predictors were categorized as hazard factors, pathway factors, and indirect factors (Howard, 2002). The pathway factors were further divided into source and point-of-use (Text S2, Figure S1 in Supporting Information S1, Data Set S1 and Data Set S2).

- Hazard factors: Sanitation systems (number of sanitation systems within 20 m, distance to closest sanitation facility) and animals (ownership)
- Pathway factors:
  - Source: Source type (borehole, unprotected, and protected dug well), infrastructure attributes (borehole depth, borehole concrete platform, and dug well water lifting device)
  - Point-of-use: Infrastructure (piped conveyance vs. manual collection), storage (covered or uncovered storage container)
- Indirect factors: Multidimensional wealth index

3.3. Statistical Analysis

Statistical analysis software R (version 1.2.5001, R Foundation for Statistical Computing, Vienna, Austria) was used for analysis. To determine whether microbial water quality differs between source and point-of-use, *E. coli* concentration at source and point-of-use was comparatively assessed using paired samples Wilcoxon and McNemar's test. Paired samples Wilcoxon assesses *E. coli* as a continuous variable, while McNemar's test assesses it as dichotomous variable. R packages "tidyverse," "rstatix," and "coin" were used for calculation. Effect size (r) for Wilcoxon test was calculated based on Pallant, 2007 by dividing the test statistic (Z) by the square root of the number of observations (n). Further, *E. coli* concentration for each water source type and wealth quintile were classified into WHO health risk classes of "safe or low," "intermediate," "high," or "very high" for water samples with <1, 1–9, 10–99, or ≥ 100 *E. coli* counts per 100 mL, respectively. The association between wealth and water quality was investigated using Spearman's rank correlation. The "aod" package in the statistical analysis software R was used to calculate crude odds ratio (OR) and adjusted odds ratio (aOR) based on univariate and multivariate analysis. To assess whether the use of the water type varied by wealth, ORs were calculated based on univariate analysis. At source, the self-supply source type was considered and at point-of-use the water type used for drinking (including refill and bottled water). The analysis considered if multiple sources for drinking were tested for water quality at the household (Bekasi: $n = 6$, Metro: $n = 0$), and distinguished between the water types used for drinking. To examine the influence of risk factors at source and point-of-use, ORs and aORs were calculated based on univariate and multivariate analysis. At the source, multivariate analyses were performed including all self-supply source types, and separately for boreholes and dug wells only including type-specific variables such as borehole depth or dug well lifting device. The distance to the closest sanitation facility was considered as a dichotomous variable based on the presence/absence of sanitation system within less or more than 10 m from the water source and as a continuous numerical variable for the estimated distance in the supplementary material. The distance of 10 m between the sanitation systems and the water sources was chosen based on the government construction standards (Apendix III of Minister of Public Works Reg. 33/PRT/M/2016). At the point-of-use, multivariate analyses were performed with and without considering refill and bottled water. The variable treatment was excluded from univariate and multivariate analysis since almost all households reported treating their drinking water. For a summary of the explanatory variables used, see the supplementary material (Text S2, Figure S1, Table S13 in Supporting Information S1, Data Set S1, and Data Set S2).

For each multivariate model, a full model that included all independent variables was adopted rather than a stepwise model selection. This was because the intent of the analysis was to identify variables that were significantly associated with the outcome of interest rather than to find the "best" model for predictive purposes. Chi-Square statistic was used to indicate the fit of the multivariate models. Explanatory variables were tested for multi-collinearity by assessing variance inflation factors using the R package "car."

3.4. Wealth Index

To determine wealth status of households, information on 23 indicators such as household asset ownership, dwelling structure, type of cooking fuel, and household composition were collected in the household survey. A wealth index was constructed for Bekasi and Metro using the same approach as the 2017 Indonesian Demographic and Health Survey (DHS) based on the relevant variables and corresponding indicator values generated from principal component analysis (National Population and Family Planning Board (BKKBN) 2018). Wealth quintiles (Q) were calculated based on the wealth index and the number of household members. The wealth index scores in Bekasi ranged from −1.314 to 1.470 and were divided into quintiles Q1 (−1.314-0.019) reflecting poorest households, Q2 (0.026–0.321), Q3 (0.326–0.518), Q4 (0.519–0.702), and Q5 (0.714–1.470) reflecting wealthiest households. For Metro, wealth index scores ranged from −1.478 to 1.611 and were divided into Q1 (−1.478 to −0.224), Q2 (−0.218-0.068), Q3 (0.073–0.330), Q4 (0.351–0.612), and Q5 (0.617–1.611). Spearman's rank correlation was performed considering wealth as a continuous index variable, while wealth quintiles as categorical variables were used for descriptive analysis. Multivariate analyses were performed considering wealth as a continuous index variable and considering wealth as categorical quintile variable. Univariate and multivariate analyses considering wealth as a categorical quintile variable are included in the supplementary material. A histogram was created using the "ggplot 2" package in the statistical analysis software R (version 1.2.5001, R Foundation for Statistical Computing, Vienna, Austria) to compare the calculated wealth index scores from Metro and Bekasi with the wealth index scores from urban Indonesia more broadly (Figure S2 in Supporting Information S1, Data Set S3, and Data Set S4).

3.5. Quality Control

Alongside collected water samples, one field and one laboratory negative control (sterilized water) were processed as quality control on each sampling day. Duplicates were processed for more than 5% of samples in Bekasi ($n = 20$) and Metro ($n = 20$). Precision of water quality testing was assessed first by calculating the relative percent difference $\mathrm{RPD} = \frac{|C_1 - C_2|}{\left(\frac{C_1 + C_2}{2}\right)} \cdot 100$, where C_1 and C_2 represent duplicate pairs, second by the proportion of pairs indicating equal risk, and third by linear regression between log-transformed microbial counts (Text S3, Figure S3, and S4 in Supporting Information S1). Scatter plots were generated using Microsoft Office Excel 2016.

4. Results

4.1. Water Quality of Self-Supply

Self-supply was commonly contaminated with *E. coli* at source, but lower levels of contamination were detected at the point-of-use. Self-supply in Bekasi was dominated by boreholes ($n = 215$), while unprotected dug wells ($n = 187$) were more prevalent in Metro. Protected dug wells were rarely present at both study sites. In Bekasi, *E. coli* was detected in 59% ($n = 142$) of all self-supply sources and in 28% ($n = 23$) of all self-supply samples at point-of-use. Similarly, in Metro, *E. coli* was present in 72% ($n = 195$) of all self-supply sources and 32% ($n = 29$) of all self-supply samples at point-of-use (Table 1 and Table 2). In Bekasi, 23% ($n = 55$) of source samples fell into the high risk class of ≥100MPN per 100 mL (Table 1 and Figure 2). However, only one borehole sample and one bottled water sample were in the high risk category at point-of-use (Table 2). In Metro, 35% ($n = 96$) of source samples and 8% ($n = 7$) of point-of-use samples showed high risk (Tables 1 and 2, and Figure 3). Paired samples Wilcoxon and McNemar tests showed significant improvement of water quality between source and point-of-use for all self-supply sources ($p < 0.001$) (Table 3). Point-of-use samples were mostly treated: no treatment was reported for only one and three point-of-use samples in Bekasi and Metro, respectively. Survey results also showed that households usually treat their self-supplied water at the point-of-use.

4.2. Socio-Economic Status

4.2.1. Water Quality Varies by Wealth

Self-supply of poorer households was more frequently contaminated than that of wealthier households. There was a statistically significant correlation between wealth and water quality in Metro, but not in Bekasi. Spearman's rank test showed no statistical significant correlation between wealth and water quality in Bekasi at source (rho = 0.029, $p = 0.643$) and point-of-use (rho = −0.043, $p = 0.705$). The level of contamination at source was similar across all wealth quintiles in Bekasi (Figure 4). In each wealth category, between 17% and 33% of the source samples showed high *E. coli* contamination greater than ≥100 MPN per 100 mL. In Metro, self-supply sources of poorer households were more likely to be contaminated than of wealthier households. The relationship between wealth and water quality at source was statistically significant (rho = −0.240, $p < 0.001$), but there was not a statistically significant relationship between wealth and water quality at point-of-use (rho = −0.150, $p = 0.150$). In Metro, the level of contamination was highest in samples from self-supply sources of the poorest households, with 50% of samples from households categorized in Q1 ($n = 29$) showing *E. coli* contamination greater than ≥100 MPN/100 mL (Figure 5).

4.2.2. Water Source Type Varies by Wealth

Wealth was a significant predictor of water source type in both Metro and Bekasi. In Metro, wealthier households were more likely to own a borehole and poorer households were more likely to own an unprotected well (Figure 6). In Bekasi, univariate analysis indicated no statistically significant association between wealth and ownership of an unprotected well or borehole. The use of refill and bottled water at the point-of-use was associated with wealth in Bekasi. Wealthier households were more likely to buy bottled water ($p = 0.021$), while poorer households were more likely to buy refill water ($p = 0.075$) (Figure 6). In Metro, no statistically significant association between wealth and drinking water type at the point-of-use was found.

4.3. Risk Factors—Univariate and Multivariate Analysis

4.3.1. Quality at Source

Univariate analysis indicated that unprotected wells were significantly more likely to be contaminated than boreholes with odds of contamination (≥1 MPN per 100 mL) being 11.65 times higher in Bekasi ($p = 0.018$) and 4.08 times higher in Metro ($p < 0.001$) (Table 4). Likewise, the likelihood of a high level of microbial contamination (≥100 MPN per 100 mL) was greater for unprotected dug wells (Bekasi: OR = 2.86, $p = 0.048$, Metro: OR = 5.62, $p < 0.001$). In Metro, households in the wealthier quintiles had significantly lower likelihood of contamination than households in the lowest wealth quintile (Table S2 in Supporting Information S1).

Table 1
Escherichia coli Contamination in Self-Supply Sources From Households in Bekasi and Metro

E. coli presence	Bekasi			Metro		
	Total	≥1 MPN/100 mL	≥100 MPN/100 mL	Total	≥1 MPN/100 mL	≥100 MPN/100 mL
Source	n	n (%)	n (%)	n	n (%)	n (%)
All self-supply sources	240	142 (59.2)	55 (22.9)	271	195 (72.0)	96 (35.4)
Self-supply source types						
Boreholes	215	121 (56.3)	46 (21.4)	71	36 (50.7)	9 (12.7)
Protected wells	9	6 (66.7)	2 (22.2)	13	8 (61.5)	3 (23.1)
Unprotected wells	16	15 (93.6)	7 (43.8)	187	151 (80.7)	84 (44.9)
Wealth						
Q1	47	23 (48.9)	8 (17.0)	58	50 (86.2)	29 (50.0)
Q2	52	34 (65.4)	13 (25.0)	53	39 (73.6)	21 (39.6)
Q3	48	28 (58.3)	9 (18.8)	57	40 (70.2)	19 (33.3)
Q4	43	26 (60.5)	14 (32.6)	52	35 (67.3)	14 (26.9)
Q5	50	31 (62.0)	11 (22.0)	51	31 (60.8)	13 (25.5)
Sanitation systems						
Number: 0	15	4 (26.7)	3 (20.0)	9	5 (55.6)	2 (22.2)
Number: 1–2	156	96 (61.5)	34 (21.8)	168	122 (72.6)	63 (37.5)
Number: 3–4	56	35 (62.5)	15 (26.8)	74	53 (71.6)	23 (31.0)
Number: ≥5	4	1 (25.0)	0 (0.0)	4	2 (50.0)	2 (50.0)
Distance ≤10m[a]	143	90 (62.9)	34 (23.8)	182	130 (71.4)	71 (39.0)
Distance >10m[a]	33	14 (42.4)	7 (21.2)	65	47 (72.3)	17 (26.2)
Animals present						
Animals present	55	30 (54.4)	11 (20.0)	106	80 (75.5)	36 (34.0)
Animals absent	185	112 (60.5)	44 (23.8)	163	113 (69.3)	59 (36.2)
Chicken	53	30 (56.6)	11 (20.8)	101	77 (76.2)	36 (35.6)
Livestock	4	1 (25.0)	0 (0.0)	23	17 (73.9)	5 (21.7)
Infrastructure						
No borehole concrete platform	83	47 (56.6)	18 (21.7)	33	17 (51.5)	6 (18.2)
Borehole concrete platform	119	67 (56.3)	26 (21.8)	29	11 (37.9)	1 (9.1)
Borehole depth <10m	121	75 (62.0)	32 (26.4)	27	17 (63.0)	4 (14.8)
Borehole depth ≥10m	94	46 (48.9)	14 (14.9)	44	19 (43.2)	5 (11.4)
Borehole top open	92	54 (58.7)	18 (19.6)	6	1 (16.7)	0 (0.0)
Borehole top sealed	108	59 (54.6)	26 (24.1)	55	27 (49.1)	7 (12.7)
Motorized pump	220	128 (58.2)	48 (21.8)	101	77 (76.2)	41 (40.6)
No pump	5	3 (60.0)	2 (40.0)	-	-	-
Rope and bucket	0	-	-	41	38 (92.7)	25 (61.0)
Motorized pump and Rope and bucket (~pump)	0	-	-	52	39 (75.0)	18 (34.6)

[a]Minimum distance between shallow wells and pollution source based on construction standards (Apendix III of Minister of Public Works Reg. 33/PRT/M/2016).

Table 2
Escherichia coli Contamination in Self-Supply Samples From Households in Bekasi and Metro at Point-Of-Use

E. coli presence	Bekasi			Metro		
	Total	≥1 MPN/100 mL	≥100 MPN/100 mL	Total	≥1 MPN/100 mL	≥100 MPN/100 mL
Point-of-use	n	n (%)	n (%)	n	n (%)	n (%)
All	81	23 (28.4)	2 (2.5)	92	29 (31.5)	7 (7.60)
Self-supply water						
Boreholes	42	13 (31.0)	1 (2.4)	24	6 (25.0)	2 (8.3)
Protected wells	3	0 (0.0)	0 (0.0)	2	1 (50.0)	1 (50.0)
Unprotected wells	9	4 (44.4)	0 (0.0)	40	17 (42.5)	3 (7.5)
All self-supply	54	17 (31.5)	1 (1.9)	66	24 (36.4)	6 (9.1)
Packaged water						
Refill water	14	2 (14.3)	0 (0.0)	20	3 (15.0)	0 (0.0)
Bottled water	13	4 (30.8)	1 (7.7)	6	2 (33.3)	1 (16.7)
All packaged	27	6 (22.2)	1 (3.7)	26	5 (19.2)	1 (3.8)
Wealth[a]						
Q1	9	0 (0.0)	0 (0.0)	19	10 (52.6)	4 (21.1)
Q2	22	8 (36.4)	0 (0.0)	19	5 (26.3)	2 (10.5)
Q3	17	6 (35.3)	0 (0.0)	18	3 (16.7)	0 (0.0)
Q4	17	6 (35.3)	1 (5.9)	18	6 (33.3)	0 (0.0)
Q5	16	3 (18.8)	1 (6.3)	18	5 (27.8)	1 (5.6)
Treatment self-supply water						
No treatment	1	0 (0.0)	0 (0.0)	3	1 (33.3)	0 (0.0)
Boiling	48	15 (31.3)	1 (2.1)	62	23 (37.1)	6 (9.7)
Bleach/chlorine	1	0 (0.0)	0 (0.0)	0	-	-
Other	1	0 (0.0)	0 (0.0)	0	-	-
Storage type[a]						
Gallon/Dispenser	17	5 (29.4)	1 (5.9)	23	5 (21.7)	1 (4.3)
Bottle	3	1 (33.3)	0 (0.0)	5	2 (40.0)	0 (0.0)
Kettle/teapot	20	4 (20.0)	0 (0.0)	19	6 (60.0)	0 (0.0)
Jug	31	9 (29.0)	1 (3.2)	29	11 (37.9)	3 (10.3)
Bucket	1	0 (0.0)	0 (0.0)	7	3 (42.9)	1 (14.3)
Pot	3	1 (33.3)	0 (0.0)	4	1 (25.0)	1 (25.0)
Kedi/barrel	1	1 (100.0)	0 (0.0)	2	0 (0.0)	0 (0.0)
Storage protection[a]						
Storage container covered	71	20 (28.2)	1 (1.4)	89	28 (31.5)	6 (6.7)
Storage container uncovered	5	0 (0.0)	0 (0.0)	0	-	-

[a]Including all water types.

Similarly, wealth index was a significant predictor of *E. coli* with odds of contamination (≥1 MPN per 100 mL) more than doubling with a unit decrease in wealth index score ($p = 0.003$). In Bekasi, there was no statistically significant association between water quality and wealth. The analysis did, however, find a significant association between presence of *E. coli* and proximity to sanitation systems in Bekasi. Water sources were more frequently contaminated if they were located within 10 m of a sanitation system. There was no association

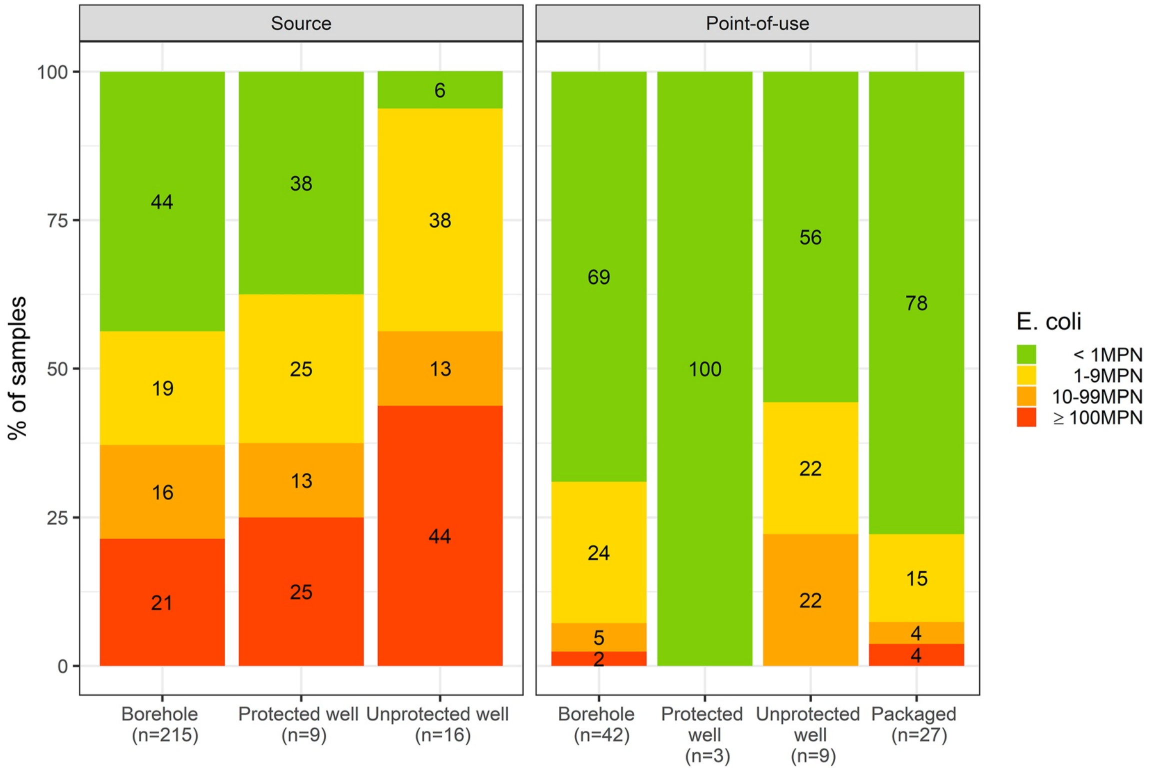

Figure 2. *Escherichia coli* risk classification of water sources in Bekasi City at source and point-of-use.

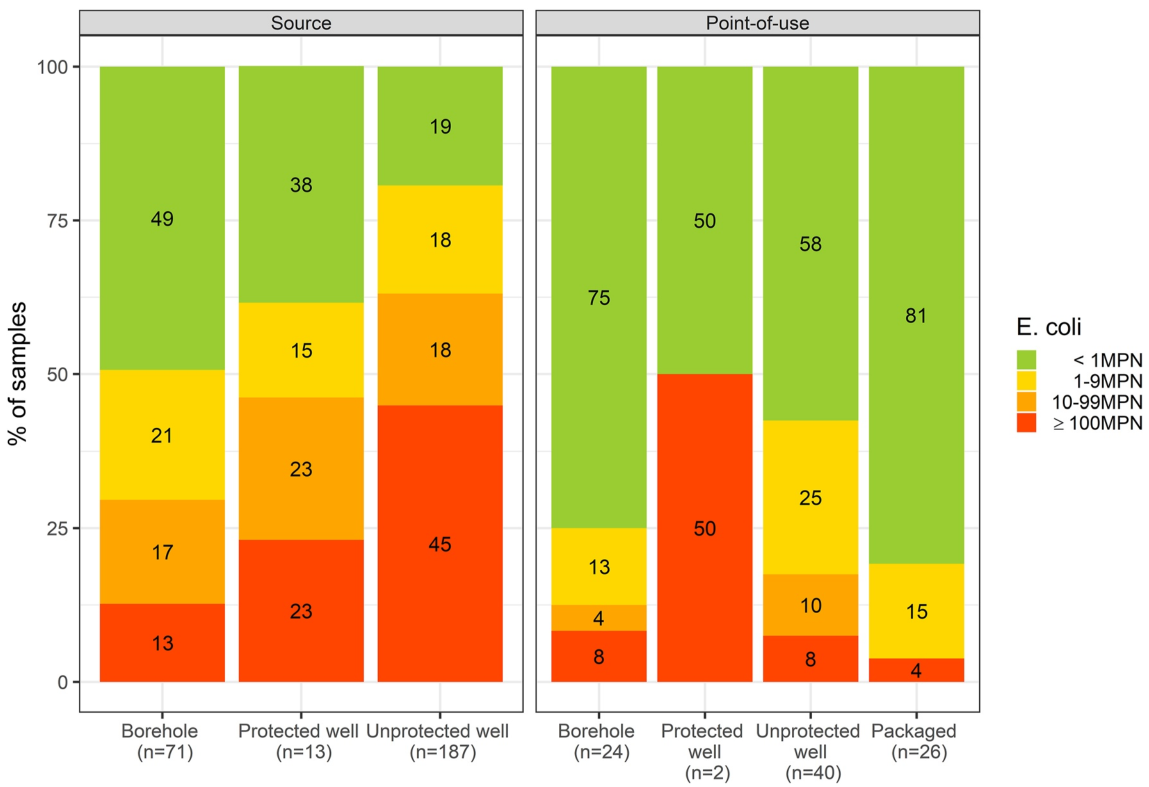

Figure 3. *Escherichia coli* risk classification of water sources in Metro City at source and point-of-use.

10.1029/2021WR031843

Table 3
Paired Samples Wilcoxon and McNemar Tests for Differences in Water Quality Between Source and Point-Of-Use

	Bekasi						Metro					
		Paired samples wilcoxon			McNemar			Paired samples wilcoxon			McNemar	
	n	P-value (greater)	Z	r[a]	Chi-square	P-value	n	P-value (greater)	Z	r[a]	Chi-square	P-value
Borehole	42	**<0.001**	3.5	0.5	5.04	**0.025**	24	0.143	1.2	0.2	2.4	0.121
Protected well	3	0.186	1.4	0.8	-	-	2	0.977	-	-	-	-
Unprotected well	9	**0.007**	2.6	0.9	-	-	40	**<0.001**	3.8	0.6	7.6	**0.001**
All self-supply sources	54	**<0.001**	4.5	0.6	11.1	**<0.001**	66	**<0.001**	3.5	0.4	25.4	**<0.001**

Note. Bold values indicate statistical significance ($p < 0.05$).
[a]Effect size with small effect for $r = 0.1$-<0.3, moderate effect for $r = 0.3$-<0.5, and large effect for $r \geq 0.5$.

between presence of *E. coli* and ownership of chickens or livestock in either study site. In Metro, water from dug wells was more likely to be contaminated and to a higher level when a rope and bucket was used to withdraw water as compared to a pump (≥1 MPN per 100 mL: OR = 3.88, $p = 0.036$, ≥100 MPN per 100 mL: OR = 2.27 $p = 0.032$). In Bekasi, the odds of a high level of contamination (≥100 MPN per 100 mL) decreased with well depth (OR = 0.94, $p = 0.025$).

Multivariate analysis showed that hazard, pathway, and indirect factors are risks for fecal contamination. Consistent with the univariate analysis, multivariate analysis showed that unprotected wells were significantly more likely to be contaminated with *E. coli* and at higher levels than boreholes, with this relationship evident in both study sites (Table 5 and Table S3 in Supporting Information S1). In Bekasi, water sources within 10 m of a sanitation system were more likely to be contaminated than those more than 10 m away (adjusted odds ratio (aOR) = 2.46, $p = 0.035$). In Metro, wealthier households using self-supply had significantly lower odds of *E. coli* concentration exceeding ≥100 MPN per 100 mL (aOR = 0.50, $p = 0.020$) (Table 5 and Table S3

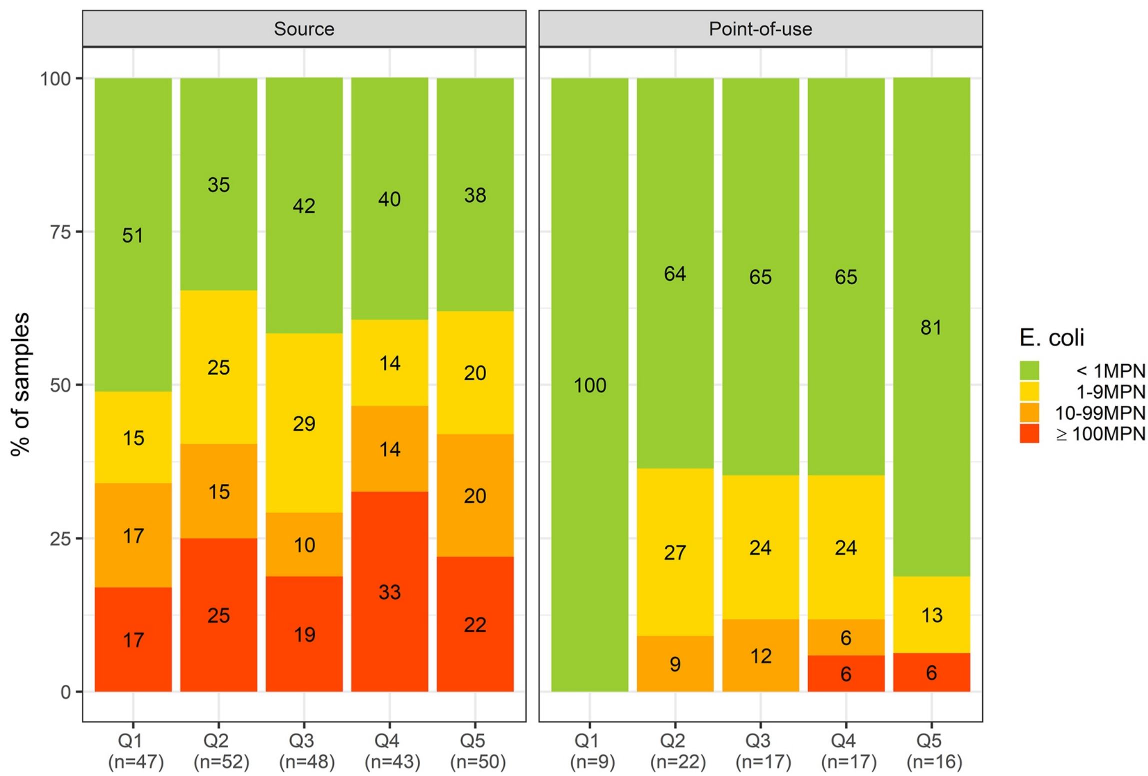

Figure 4. *Escherichia coli* risk classification of self-supply by wealth quintiles in Bekasi, with poorest households categorized in wealth quintile Q1.

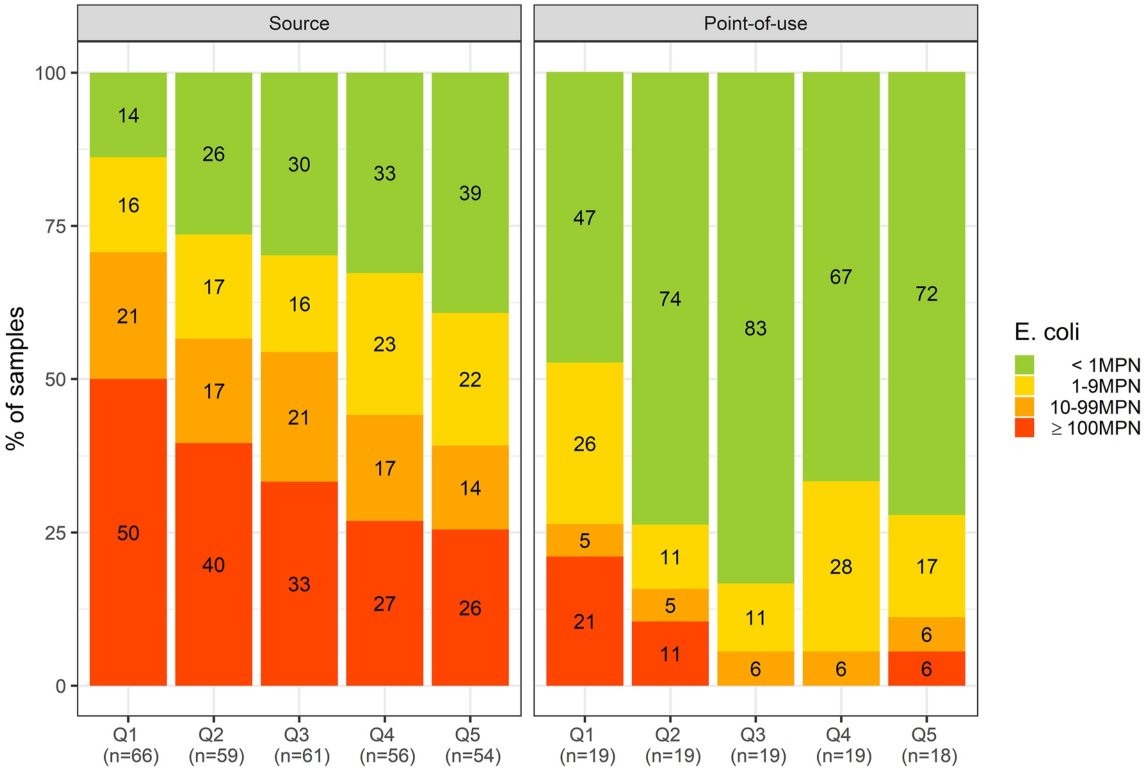

Figure 5. *Escherichia coli* risk classification of self-supply by wealth quintiles in Metro, with poorest households categorized in wealth quintile Q1.

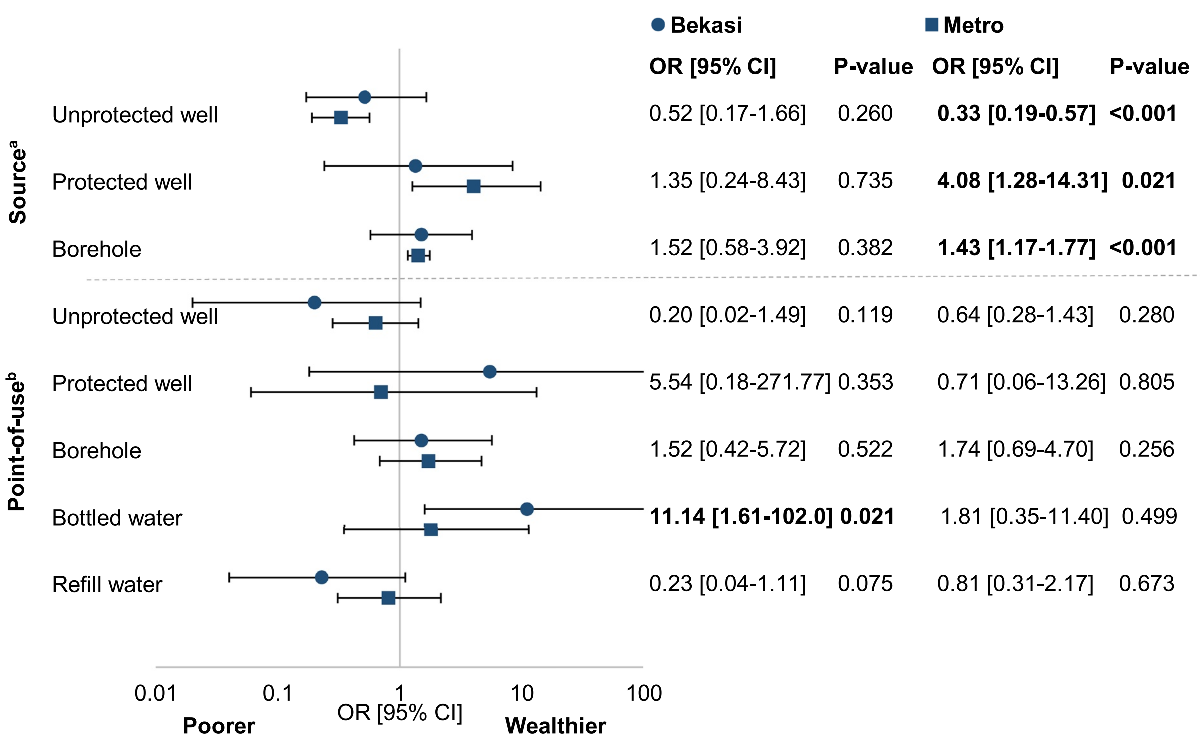

Figure 6. Calculated Odds Ratios show that use of water source types vary by wealth status, with wealthier households in Metro being significantly more likely to have improved self-supply sources and wealthier households in Bekasi being significantly more likely to purchase bottled water. *Note*. (a) For n values refer to Table 1, (b) for n values refer to Table 2, bold values indicate statistical significance ($p < 0.05$).

Table 4
Crude Odds Ratios of Risk Factors for Self-Supply Water Quality at Source in Bekasi and Metro

	Bekasi				Metro			
	≥1 MPN per 100 mL		≥100 MPN per 100 mL		≥1 MPN per 100 mL		≥100 MPN per 100 mL	
Variable[a]	OR [95% CI]	P-value	OR [95% CI]	P-value	OR [95% CI]	P-value	OR [95% CI]	P-value
Wealth[b]								
Wealth index	1.27 [0.70–2.32]	0.436	1.23 [0.61–2.52]	0.566	**0.43 [0.24-0.74]**	**0.003**	**0.44 [0.26-0.72]**	**<0.001**
Source type								
Protected well versus borehole	1.55 [0.40–7.51]	0.541	1.05 [0.15–4.52]	0.953	1.56 [0.47–5.58]	0.474	2.07 [0.41–8.41]	0.332
Unprotected well versus borehole	**11.65 [2.30-212.60]**	**0.018**	**2.86 [0.97-8.08]**	**0.048**	**4.08 [2.27-7.41]**	**<0.001**	**5.62 [2.76-12.72]**	**<0.001**
Protected well versus unprotected well	0.13 [0.01–1.27]	0.107	0.37 [0.04–2.13]	0.290	0.38 [0.12–1.33]	0.108	0.37 [0.08–1.25]	0.138
Sanitation systems								
Number	1.00 [0.80–1.23]	0.971	0.94 [0.73–1.21]	0.626	0.92 [0.76–1.11]	0.383	0.98 [0.82–1.16]	0.787
Closest distance	1.01 [0.97–1.05]	0.577	1.02 [0.98–1.07]	0.315	1.03 [0.99–1.07]	0.170	1.03 [1.00–1.07]	0.074
Sanitation system ≤10m versus >10m	**2.30 [1.07-5.05]**	**0.033**	1.16 [0.48–3.10]	0.754	0.94 [0.49–1.74]	0.841	1.71 [0.93–3.23]	0.090
Animals								
Chicken present versus absent	0.87 [0.47–1.63]	0.667	0.85 [0.39–1.75]	0.672	1.44 [0.83–2.56]	0.206	1.02 [0.61–1.71]	0.931
Livestock present versus absent	0.22 [0.01–1.78]	0.199	-	-	1.13 [0.45–3.23]	0.809	0.48 [0.15–1.25]	0.162
Animals total present versus absent	0.78 [0.43-0.144]	0.428	0.80 [0.37–1.64]	0.558	1.36 [0.79–2.39]	0.275	0.91 [0.54–1.51]	0.708
Infrastructure								
Borehole depth	0.97 [0.93–1.00]	0.076	**0.94 [0.89-0.99]**	**0.025**	0.93 [0.87–1.00]	0.065	1.02 [0.92–1.14]	0.700
Borehole top open versus sealed	1.18 [0.67–2.08]	0.563	0.78 [0.38–1.50]	0.444	0.21 [0.01–1.40]	0.163	-	0.995
Borehole concrete platform present versus absent	0.99 [0.56–1.74]	0.964	1.03 [0.52–2.04]	0.943	0.58 [0.20–1.57]	0.285	0.16 [0.00–1.03]	0.101
Dug well rope and bucket versus pump	-	-	-	-	**3.88 [1.25-17.10]**	**0.036**	**2.27 [1.08-4.85]**	**0.032**
Dug well rope and bucket and pump versus rope and bucket	-	-	-	-	**0.22 [0.05-0.77]**	**0.028**	**0.33 [0.14-0.77]**	**0.011**
Dug well rope and bucket and pump versus pump	-	-	-	-	0.87 [0.40–1.95]	0.734	0.75 [0.36–1.51]	0.421

Note. Bold values indicate statistical significance ($p < 0.05$).
[a]For n values please refer to Table 1. [b]Q1 refers to the poorest quintile of households and Q5 refers to the wealthiest quintile of households.

Table 5
Multivariate Analysis of Water Quality for Self-Supply Sources in Bekasi and Metro

	Bekasi				Metro			
	≥1 MPN per 100 mL		≥100 MPN per 100 mL		≥1 MPN per 100 mL		≥100 MPN per 100 mL	
Variable[a,b]	aOR [95% CI]	P-value	aOR [95% CI]	P-value	aOR [95% CI]	P-value	aOR [95% CI]	P-value
Wealth index	1.75 [0.83–3.75]	0.142	1.26 [0.53–3.06]	0.598	0.62 [0.33–1.16]	0.139	**0.50 [0.28-0.89]**	**0.020**
Protected well versus borehole	2.21 [0.43–16.88]	0.374	1.40 [0.19–7.03]	0.700	2.10 [0.61–7.83]	0.247	2.32 [0.44–10.12]	0.278
Unprotected well versus borehole	**9.03 [1.62-169.60]**	**0.040**	2.23 [0.54–8.14]	0.233	**4.58 [2.34-9.08]**	**<0.001**	**4.73 [2.14-11.70]**	**<0.001**
Sanitation system ≤10m versus >10m	**2.46 [1.08-5.81]**	**0.035**	1.22 [0.47–3.47]	0.692	0.95 [0.46–1.91]	0.886	1.77 [0.92–3.51]	0.093
Number of sanitation systems	0.92 [0.66–1.26]	0.595	0.83 [0.56–1.20]	0.333	1.03 [0.78–1.38]	0.839	0.97 [0.74–1.27]	0.845
Animals present versus absent	0.55 [0.25–1.21]	0.139	0.50 [0.16–1.30]	0.185	1.23 [0.65–2.35]	0.521	0.83 [0.46–1.48]	0.538

Note. Bold values indicate statistical significance ($p < 0.05$).
[a]For n values please refer to Table 1. [b]Chi-Square and p-value: Bekasi ≥1 Most Probable Number (MPN): $X^2 = 16.40$, $p = 0.012$; Bekasi ≥100 MPN: $X^2 = 4.77$, $p = 0.574$; Metro ≥1 MPN: $X^2 = 30.63$, $p < 0.001$; Metro ≥100 MPN: $X^2 = 32.37$, $p < 0.001$.

Table 6
Multivariate Analysis of Water Quality for Private Boreholes in Bekasi and Metro

	Bekasi				Metro			
	≥1 MPN per 100 mL		≥100 MPN per 100 mL		≥1 MPN per 100 mL		≥100 MPN per 100 mL	
Variable[a,b]	aOR [95% CI]	P-value	aOR [95% CI]	P-value	aOR [95% CI]	P-value	aOR [95% CI]	P-value
Wealth index	1.88 [0.81–4.45]	0.145	1.19 [0.44–3.30]	0.737	0.43 [0.09–1.66]	0.238	**0.004 [0.00-0.18]**	**0.025**
Number of sanitation systems	0.96 [0.68–1.34]	0.809	1.02 [0.67–1.53]	0.942	0.95 [0.56–1.57]	0.839	0.31 [0.04–1.42]	0.172
Sanitation system ≤10m versus >10m	**3.18 [1.26-8.52]**	**0.012**	1.51 [0.48–5.89]	0.504	0.59 [0.11–2.90]	0.519	0.37 [0.00–17.44]	0.628
Animals present versus absent	0.65 [0.26–1.58]	0.337	0.55 [0.15–1.65]	0.324	0.52 [0.12–1.94]	0.346	0.14 [0.00–1.67]	0.166
Borehole depth	0.97 [0.93–1.02]	0.279	**0.93 [0.87-0.99]**	**0.020**	0.98 [0.89–1.08]	0.694	1.21 [1.00–1.61]	0.087
Concrete platform present versus absent	0.77 [0.37–1.60]	0.485	1.76 [0.76–4.27]	0.198	**0.29 [0.08-1.00]**	**0.057**	**0.001 [0.00-0.09]**	**0.033**
Borehole top open versus sealed	1.42 [0.69–2.99]	0.342	0.79 [0.34–1.82]	0.583	0.20 [0.01–1.67]	0.184	-	0.996

Note. Bold values indicate statistical significance ($p < 0.05$).
[a]For n values please refer to Table S10 in Supporting Information S1. [b]Chi-Square and p-value: Bekasi ≥1 Most Probable Number (MPN): $X^2 = 13.42$, $p = 0.063$; Bekasi ≥100 MPN: $X^2 = 15.21$, $p = 0.033$; Metro ≥1 MPN: $X^2 = 4.04$, $p = 0.775$; Metro ≥100 MPN: $X^2 = 11.26$, $p = 0.128$.

in Supporting Information S1). Multivariate analysis of private boreholes showed that borehole depth had a significant association with water quality in Bekasi, with deeper boreholes less likely to have high levels (≥100 MPN per 100 mL) of *E. coli* contamination (aOR = 0.93, $p = 0.020$) (Table 6 and Table S4 in Supporting Information S1). In Metro, high levels of *E. coli* contamination (≥100 MPN per 100 mL) in private boreholes were again significantly associated with lower wealth status (aOR = 0.004, $p = 0.025$) and the absence of a concrete platform (aOR = 0.001, $p = 0.033$). Water from dug wells lifted with a rope and bucket was more likely to be contaminated and at higher levels than water lifted with a pump (Table 7, Table S5 and Table S6 in Supporting Information S1).

4.3.2. Quality at Point-Of-Use

Univariate analysis found that source type and wealth were significantly related to water quality at point-of-use in Metro, but not in Bekasi (Table 8 and Table S7 in Supporting Information S1). In Metro, refill water was significantly less likely to be contaminated than water from unprotected wells at the point-of-use with a crude OR of 0.24 ($p = 0.042$) (Table 8). In Metro, water at the point-of-use from household members categorized in the middle wealth quintile (Q3) was significantly less likely to be contaminated with *E. coli* compared with households in the poorest quintile (Q1) (OR = 0.18, $p = 0.028$) (Table S7 in Supporting Information S1). In Bekasi, no statistically significant association between wealth and water quality at the point-of-use was

Table 7
Multivariate Analysis of Water Quality for Dug Wells in Metro

	Metro			
	≥1 MPN per 100 mL		≥100 MPN per 100 mL	
Variable[a,b]	aOR [95% CI]	P-value	aOR [95% CI]	P-value
Wealth index	0.76 [0.32–1.78]	0.528	0.70 [0.36–1.34]	0.118
Unprotected versus protected	1.78 [0.48–6.05]	0.360	2.07 [0.57–9.83]	0.300
Number of sanitation systems	0.99 [0.68–1.49]	0.961	1.03 [0.75–1.39]	0.871
Sanitation system ≤10m versus >10m	1.02 [0.43–2.33]	0.954	1.72 [0.85–3.58]	0.137
Animals present versus absent	1.58 [0.71–3.63]	0.272	0.82 [0.44–0.54]	0.539
No pump versus pump[c]	**5.08 [1.34-33.58]**	**0.038**	1.88 [0.85–4.22]	0.119

Note. Bold values indicate statistical significance ($p < 0.05$).
[a]For n values please refer to Table S11 in Supporting Information S1. [b]Chi-Square and p-value: Metro ≥1 Most Probable Number (MPN): $X^2 = 170.31$, $p = 0.061$ and Metro ≥100 MPN: $X^2 = 12.71$, $p = 0.048$. [c]Households with rope and bucket and pump are considered as households using a pump. No pump refers to households using rope and bucket as water lifting device.

Table 8
Crude Odds Ratios of Risk Factors for Water Quality at the Point-Of-Use in Bekasi and Metro Including Refill and Bottled Water

	Bekasi		Metro	
	≥1 MPN per 100 mL		≥1 MPN per 100 mL	
Variable[a]	OR [95% CI]	P-value	OR [95% CI]	P-value
Wealth				
Wealth index	1.66 [0.40–7.41]	0.490	0.59 [0.24–1.38]	0.224
Water type				
Protected well versus borehole	-	0.991	3.00 [0.11–84.29]	0.461
Unprotected well versus borehole	1.78 [0.39–7.86]	0.440	2.22 [0.75–7.20]	0.162
Refill water versus borehole	0.37 [0.05–1.63]	0.440	0.53 [0.10–2.35]	0.417
Bottled water versus borehole	0.99 [0.23–3.68]	0.990	1.50 [0.18–9.99]	0.681
Protected well versus unprotected well	-	0.991	1.35 [0.05–35.87]	0.835
Refill water versus unprotected well	0.21 [0.02–1.42]	0.123	**0.24 [0.05-0.85]**	**0.042**
Bottled water versus unprotected well	0.55 [0.09–3.29]	0.514	0.68 [0.09–3.89]	0.672
Refill water versus protected well	-	0.991	0.18 [0.01–5.27]	0.262
Bottled water versus protected well	-	0.991	0.50 [0.01–17.47]	0.676

Note. Bold values indicate statistical significance ($p < 0.05$).
[a]For *n* values please refer to Table 2.

found. Whether or not self-supplied water was piped to a tap (as compared to being manually collected from the well/borehole) did not have a significant influence of water quality at the point-of-use (Table 9 and Table S9 in Supporting Information S1). Univariate and multivariate analysis showed that self-supply water quality at the source had a significant influence on water quality at the point-of-use in Bekasi, but not in Metro (Tables 9 and 10).

Table 9
Crude Odds Ratios of Risk Factors for Self-Supply Water Quality at the Point-Of-Use in Bekasi and Metro Excluding Refill and Bottled Water

	Bekasi		Metro	
	≥1 MPN per 100 mL		≥1 MPN per 100 mL	
Variable[a]	OR [95% CI]	P-value	OR [95% CI]	P-value
Wealth				
Wealth index	1.02 [0.17–6.11]	0.982	0.96 [0.22–2.76]	0.939
Infrastructure				
Manual collection versus piped conveyance[b]	-	-	1.10 [0.12–7.36]	0.936
Rope and bucket and pump versus rope and bucket only[b]	-	-	2.29 [0.33–20.42]	0.413
Rope and bucket and pump versus pump only[b]	-	-	2.48 [0.62–10.57]	0.205
Treatment and storage				
E. coli concentration (MPN/100 mL)	**1.00 [1.00-1.00]**[c]	**0.036**	1.00 [0.99–1.01]	0.940
>100 MPN/100 mL	2.82 [0.74–10.92]	0.125	1.03 [0.22–3.08]	0.959
Storage container covered versus uncovered	-	0.994	-	-

Note. Bold values indicate statistical significance ($p < 0.05$).
[a]For *n* values please refer to Table 2 and Table S12 in Supporting Information S1. [b]Households with rope and bucket and pump considered as households using a pump (piped conveyance), boreholes and dug wells included in analysis. [c]For every 100 Most Probable Number increase in source quality, odds of *E. coli* detection at the point-of-use increases by 20%.

Table 10
Multivariate Analysis for Self-Supply Water Quality at Point-Of-Use

	Bekasi		Metro	
	≥1 MPN per 100 mL		≥1 MPN per 100 mL	
Variable[a,b]	aOR [95% CI]	P-value	aOR [95% CI]	P-value
Wealth				
Wealth index	1.55 [0.23–12.17]	0.658	1.23 [0.26–6.17]	0.797
Manual collection versus piped conveyance[c]	-	-	0.79 [0.10–4.99]	0.804
E. coli source concentration (MPN/100 mL)	**1.00 [1.00-1.00]**[d]	**0.031**	1.00 [1.00–1.00]	0.652

Note. Bold values indicate statistical significance ($p < 0.05$).
[a]For n values please refer to Table 2. [b]Chi-Square and p-value: Bekasi ≥1 Most Probable Number (MPN): $X^2 = 10.75$, p = 0.005; Metro ≥1 MPN: $X^2 = 0.39$, p = 0.942. [c]Households with rope and bucket and pump considered as households using a pump (piped conveyance), boreholes and dug wells included in analysis. [d]For every 100 MPN increase (per 100 mL) in source quality, odds of *Escherichia coli* detection at the point-of-use increases by 20%.

4.4. Discussion

This study shows groundwater self-supply in Bekasi and Metro is commonly contaminated with *E. coli*. Fecal contamination was detected in 66% of self-supply sources across the two study sites. Previous studies in other contexts have typically found lower frequency of fecal contamination for self-supply sources (Genter et al., 2021). A pooled estimate from 30 studies in LMICs found fecal indicator bacteria were reported in 36% of self-supply sources, including 28% of samples from boreholes, 81% of samples from unprotected wells, and 77% of samples from protected wells (Genter et al., 2021). Of the 15 urban specific studies included, fecal indicator bacteria were reported in 34% of self-supply sources (Genter et al., 2021). The variation in water quality across studies indicates that fecal contamination of self-supply and corresponding pathways are site-specific and depend on local conditions, such as aquifer type, soil type, and standard of infrastructure.

However, reduced levels of fecal contamination were detected at the point-of-use compared to the source. At the point-of-use, *E. coli* was present in 34% of self-supply water samples. This contrasts with findings from numerous previous studies, which have instead observed a deterioration in water quality after collection, which in turn has been attributed to several factors such as water storage conditions and post handling practices (Clasen & Bastable, 2003; Gundry et al., 2006; Lechevallier et al., 1996; McGuinness et al., 2020; Meierhofer et al., 2018; Shaheed et al., 2014; Shields et al., 2015; Trevett et al., 2005; Wright et al., 2004). In Bekasi and Metro, households reported treating their self-supplied water frequently and almost all households (98%) covered their water storage containers. Boiling to disinfect drinking water has also been shown to effectively reduce fecal contamination despite the high source concentration in rural Vietnam (Clasen et al., 2008). Notwithstanding widespread boiling practices in Bekasi, contaminated source water still had a significant influence on water quality at the point-of-use. This highlights that proper household water treatment and measures to improve source quality are simultaneously important in order to reduce health risks. In contrast, source quality in Metro exhibited no relationship with point-of-use quality, indicating that testing the source water is not necessarily representative of the safety of water at the point-of-use. Monitoring of self-supply source quality might overstate the risk for households in urban Indonesia. This raises questions about the suitability of source quality as an indicator of self-supply water quality and whether the point-of-use water quality should be considered in monitoring programs.

Wealth of households had a significant negative association with fecal contamination of source water, even when adjusting for other sanitary factors. Results from Metro showed that poorer households were at higher risk than wealthier households when considering all self-supply types and boreholes separately, but not when only dug wells were included in the multivariate analysis. In Metro, wealth might reflect unaccounted contamination pathway factors or limitations in the sanitary risk factors assessed. Categorical measures of sanitary conditions may be overly simplistic and well condition might be more of a spectrum, with poorer household relying on unprotected wells that lie at the higher-risk end of the spectrum. Wealth also had an influence on which water sources were used by households. In Bekasi, bottled water was more common in wealthier households, suggesting that poorer household may be unable or unwilling to pay for it. In Metro, poorer households were more likely to own an unprotected well as compared to wealthier households, who instead were more likely to own a borehole.

These outcomes are consistent with the findings of Sugiyono and Dewancker (2020), who reported that private dug wells were the preferred main domestic water source for the poorest households in Metro.

Various sanitary risk factors emerged as significant predictors of water quality in both Bekasi City and Metro City. Well type was a significant determinant of self-supply water quality. The analysis demonstrated that unprotected wells were more likely to be contaminated with *E. coli* than boreholes. These findings are consistent with previous studies from LMICs that compared microbial water quality between improved and unimproved groundwater sources (Bain et al., 2014; Genter et al., 2021). However, high levels of contamination were still detected in boreholes and protected wells across both study sites, reinforcing previous findings that protected sources do not ensure that the water is free of contamination (Bain et al., 2014; Genter et al., 2021).

Water abstraction system for dug wells was related to water quality, with high levels of fecal contamination occurring more frequently when water was abstracted by rope and bucket than when a motorized pump was used. Improving the water abstraction system by replacing a rope and bucket with a pump (manual or motorized) could therefore reduce frequency and magnitude of contamination (Ali et al., 2019; Bazaanah & Dakurah, 2021; Gorter et al., 1995). A shift of private investment toward motorized pumps would also enable self-supplying households to have the convenience of water being piped into the house.

The absence of a borehole concrete platform had a significant association with more frequent high levels of fecal contamination in Metro, highlighting the need for appropriate well protection. In the context of urban Indonesia, the presence of a concrete platform may often indicate that the borehole is present inside the house, meaning contaminated run-off is less likely to enter the boreholes. Other studies on self-supply also found that appropriate well protection is important to improve microbial water quality, such as sealing of the annulus (Knappett et al., 2013) and proper condition of protected borehole casings (Potgieter et al., 2006).

Deeper boreholes were less likely to have high *E. coli* concentration in Bekasi, suggesting deeper groundwater is less liable to contamination from fecal sources. This finding aligns with the results of Kazama and Takizawa (2021) who reported elevated contamination levels in areas with a higher water table in Yogyakarta (Kazama & Takizawa, 2021). Bacterial transfers to aquifers depend on the attenuation potential and the natural travel time to the saturated zone (ARGOSS, 2001; Banerjee, 2011; Voisin et al., 2018), with greater depths resulting in longer travel time and greater attenuation. The study sites in Bekasi are situated in a flat alluvial terrain, suggesting little bacterial transfer through the aquifer.

Fecal contamination of groundwater supplies due to inadequate spacing between sanitation facilities and wells is perceived as a major threat to water quality (Graham & Polizzotto, 2013). A statistically significant relationship between contaminated wells and nearby sanitation systems was found in Bekasi, but not in Metro. In Bekasi, the most prevalent on-site sanitation types were cubluks (a single tank without a concrete base) (47%, $n = 226$), followed by "empangs" (flush to ponds) (19%, $n = 93$), septic tanks (15%, $n = 72$), and pit latrines (6%, $n = 27$). In Metro, household members usually use septic tanks or cubluks (94%, $n = 280$) and to a less extent pit latrines (4%, $n = 13$). Several studies on self-supply in urban areas in low income settings have found significant associations between fecal water contamination and proximity of the well to a sanitation system (Kumpel et al., 2017; Martínez-Santos et al., 2017; Ngasala et al., 2019). The studies reported the use of poorly constructed pit latrines and septic tanks, which leads to the contamination of groundwater wells in close proximity. Ngasala et al., 2019 reported a significant correlation between well depths along with lateral distance to sanitation systems in sand aquifers in Tanzania. In contrast, a study by Ravenscroft et al. (2017) concluded that pit latrines are a minor contributor to fecal contamination of drinking water in alluvial-deltaic terrains and attention should be given to reduce contamination around the well-head. The findings of Ravenscroft et al. (2017) are in line with our results in Metro, but provide a contrast to the results in Bekasi.

Results from Bekasi suggest that lateral separation between sanitation systems and self-supply wells may be insufficient to prevent transport of fecal indicator bacteria through the aquifer pathway. Out of 176 and 247 wells analyzed in Bekasi and Metro, 81% and 74% were located ≤10 m from sanitation systems, respectively. Based on construction standards in Bekasi and Metro, a minimum distance between shallow wells and a pollution source of 10 m is required (Appendix III of Minister of Public Works Reg. 33/PRT/M/2016). The results show that these regulations are not respected in the case of self-supply. Appropriate siting of sanitation systems to ensure low risk of fecal contamination to groundwater sources highly depends on the soil and aquifer properties in the particular

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environment. Studies in other environments reported distances from the well to on-site sanitation systems have to be at least 12 or 15 m (Graham & Polizzotto, 2013).

Further investigation is needed to confirm the risk to groundwater from on-site sanitation in Bekasi and Metro, and urban Indonesia more broadly. Results from this study should be interpreted with caution since some data on sanitation systems such as setback distance and sub-surface design attributes were self-reported by households or estimated by enumerators. Further studies into sanitation-groundwater interactions in urban Indonesia might also consider groundwater flow and transport modeling (Ngasala et al., 2021), monitoring networks with new installed sanitation systems and piezometers (Ravenscroft et al., 2017), and spatial GIS databases (Martínez-Santos et al., 2017).

This study was subject to a number of other limitations related to the measure of self-supply water safety. Water quality was determined by the single measure of *E. coli* contamination during wet season in Bekasi and dry season in Metro, thereby providing only a point-in-time snapshot. Conclusions on the water quality should be also drawn with caution since fecal indicator bacteria do not represent pathogens such as viruses, which might survive for longer travel times in the subsurface. Charles et al., 2020 highlights the need to shift from a focus on direct water quality measurements toward a prospective safety perspective to ensure the sustainability and security of water services. Frequent water testing accompanied by understanding of risks from sanitary inspections, systematic management concepts, and routine monitoring are essential for water safety.

Additional factors not considered in the study may have an impact on water quality. For example, indirect factors such as flooding, lack of fencing, or poor surface drainage are not considered. It was not possible to measure the depth to groundwater on-site. Furthermore, generalizations should be made with caution, as the quality of self-supply may vary greatly by region, due to temporal and spatial heterogeneity of water quality and varying hydrogeological conditions. Moreover, the sampling frame was based on areas with a high prevalence of self-supply, which is not necessarily representative for urban Indonesia as a whole. Finally, household use of multiple water sources might not be fully captured, since water quality was tested on water sources that were available at the time of the visit. However, consideration of the use of multiple water sources to meet daily household needs is beneficial to understand household water management and safety (Elliott et al., 2017).

Questions remain on how policy and practice need to respond to water quality concerns of self-supply in urban Indonesia. The cost-benefit of supporting self-supply improvements needs to be assessed in relation to other strategies such as investing in safe and reliable piped services. Financial and technical support for households is needed where piped networks are not feasible and where households cannot afford to invest in safer forms of self-supply. The improvement of self-supply source protection and water abstraction systems is required to improve groundwater quality of self-supply sources. This is especially true in Metro, where many households rely on unprotected dug wells, and where the poorest households are at higher risk of relying on drinking water with fecal contamination. In Bekasi, despite water treatment, source water quality was still related to water quality at the point-of-use, and poorer households were more likely to rely on refill water for drinking. This highlights the need for household education on water quality and associated safe water treatment and storage. Water quality monitoring and awareness raising could encourage households to choose safer water sources and to properly treat their self-supply water.

5. Conclusions

This study is of importance as it provides new evidence on the microbial quality of self-supplied water and contamination risk factors in urban Indonesia, which have hitherto been a major knowledge gap. The findings have significant implications for government decisions on how to respond to self-supply in urban areas of Indonesia and elsewhere in Asia. This study found that groundwater self-supply in Bekasi and Metro commonly contains *E. coli*, with fecal contamination in 66% of self-supply sources and 30% of samples at the point-of-use. At the source, contamination risks were related to infrastructure, proximity to sanitation systems, and wealth. Unprotected dug wells were at greater risk of contamination than boreholes. Water from dug wells equipped with a pump was less likely to be contaminated than dug wells with a rope and a bucket. The presence of a concrete platform around the borehole and greater borehole depth reduced the risk of contamination. Poorer households were at greater risk of fecal contamination in Metro. The distance of sanitation systems, which were based on households' estimates, were related to the risk of fecal contamination in Bekasi, but not in Metro. Households frequently boiled their water before consumption, and this significantly reduced likelihood of *E. coli* contamination. However, a higher *E. coli* concentration at the source was still associated with a higher risk of contamination at the point-of-use in Bekasi. To increase the safety of self-supply, the following recommendations can be concluded from this study: (a) financial support for households to invest in better self-supply infrastructure, such as improved well protection and replacement of rope and bucket systems with pumps; (b) education provided to households to raise awareness regarding proper water treatment and storage; and (c) source water quality of self-supply does not necessarily provide information about the quality water that households consume, and monitoring should also consider quality at the point-of-use. However, these recommendations must be weighed against other strategies such as expansion of municipal piped systems that deliver reliable and high quality water.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data sets for this research are available in the supporting information files and at https://doi.org/10.26195/72rj-ey57.

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References

Adeniji-Oloukoi, G., Urmilla, B., & Vadi, M. (2013). Households' coping strategies for climate variability related water shortages in Oke-Ogun region, Nigeria. *Environmental Development*, *5*(1), 23–38. https://doi.org/10.1016/j.envdev.2012.11.005

Ali, R., Bünzli, M. A., Colombo, L., Khattak, S. A., Pera, S., Riaz, M., & Valsangiacomo, C. (2019). Water quality before and after a campaign of cleaning and disinfecting shallow wells: A study conducted during and after floods in Khyber Pakhtunkhwa, Pakistan. *Journal of Water, Sanitation and Hygiene for Development*, *9*(1), 28–37. https://doi.org/10.2166/WASHDEV.2018.2722020

Allen, A., Dávila, J. D., & Hofmann, P. (2006). The peri-urban water poor: Citizens or consumers? *Environment and Urbanization*, *18*(2), 333–351. https://doi.org/10.1177/0956247806069608

ARGOSS. (2001). Guidelines for assessing the risk to groundwater from on-site sanitation. *British Geological Survey*, *01*(142), 97.

Bain, R., Cronk, R., Wright, J., Yang, H., Slaymaker, T., & Bartram, J. (2014). Fecal contamination of drinking-water in low- and middle-income countries: A systematic review and meta-analysis. *PLoS Medicine*, *11*(5), e1001644. https://doi.org/10.1371/journal.pmed.1001644

Banerjee, G. (2011). Underground pollution travel from leach pits of on-site sanitation facilities: A case study. *Clean Technologies and Environmental Policy*, *13*(3), 489–497. https://doi.org/10.1007/s10098-010-0331-3

Bappeda Kota Bekasi. (2018). Rencana Pembangunan Jangka Menengah Daerah Kota Bekasi 2018-2023.

Bazaanah, P., & Dakurah, M. (2021). *Comparative analysis of the performance of rope-pumps and standardized handpumps water systems in rural communities of the northern and upper east regions of Ghana* (Vol. 13). Groundwater for Sustainable Development. https://doi.org/10.1016/j.gsd.2021.100563

BPS. (2021). Statistics of Bekasi Regency. Retrieved from https://bekasikab.bps.go.id/statictable/2021/07/17/2801/distribusi-dan-kepadatan-penduduk-menurut-kabupaten-kota-di-provinsi-jawa-barat-2017.html

BPS Kota Bekasi. (2010). *Sensus Penduduk 2010*. BPS-Statistics of Bekasi Municipality. Retrieved from https://sp2010.bps.go.id/index.php/site/tabel?wid=3275000000&tid=303&fi1=588&fi2=

BPS Kota Bekasi. (2021). *Bekasi Municipality in Figures 2021* (Vol. 1907). BPS Kota Bekasi.

BPS Kota Metro. (2019). Metro Municipality in Figures 2019. 1907–4751.262.

BPS Kota Metro. (2021). Metro Municipality in Figures 2021.

Butterworth, J., Sutton, S., & Mekonta, L. (2013). Self-supply as a complementary water services delivery model in Ethiopia. *Water Alternatives*, *6*(3), 405–423.

Charles, K. J., Nowicki, S., & Bartram, J. K. (2020). A framework for monitoring the safety of water services: From measurements to security. *Npj Clean Water*, *3*(1), 1–6. https://doi.org/10.1038/s41545-020-00083-1

Clasen, T. F., & Bastable, A. (2003). Fecal contamination of drinking water during collection and household storage: The need to extend protection to the point of use. *Journal of Water and Health*, *1*(3), 109–115. https://doi.org/10.2166/wh.2003.0013

Clasen, T. F., Do, H. T., Boisson, S., & Shipin, O. (2008). Microbiological effectiveness and cost of boiling to disinfect drinking water in rural Vietnam. *Environmental Science and Technology*, *42*(12), 4255–4260. https://doi.org/10.1021/es7024802

Cole, S. R., Chu, H., Nie, L., & Schisterman, E. F. (2009). Estimating the odds ratio when exposure has a limit of detection. *International Journal of Epidemiology*, *38*(6), 1674–1680. https://doi.org/10.1093/ije/dyp269

Cronin, A. A., Odagiri, M., Arsyad, B., Nuryetty, M. T., Amannullah, G., Santoso, H., et al. (2017). Piloting water quality testing coupled with a national socioeconomic survey in Yogyakarta province, Indonesia, towards tracking of Sustainable Development Goal 6. *International Journal of Hygiene and Environmental Health*, *220*(7), 1141–1151. https://doi.org/10.1016/j.ijheh.2017.07.001

Dirks, F. J. H., Rismianto, D., & De Wit, G. J. (1988). Groundwater in Bekasi district, West Java, Indonesia. *Natuurwetenschappelijk Tijdschrift Natuurwet. Tijdschr*, *70*(6), 47–55. Retrieved from http://www.swim-site.nl/pdf/swim10/swim10_2_1_Dirks-Rismianto-deWit.pdf

Elliott, M., MacDonald, M. C., Chan, T., Kearton, A., Shields, K. F., Bartram, J. K., & Hadwen, W. L. (2017). Multiple household water sources and their use in remote communities with evidence from Pacific Island Countries. *Water Resources Research*, *54*(11), 9106–9117. https://doi.org/10.1002/2017wr021047

ESDM. (2021). Kegeologian. Retrieved from https://geoportal.esdm.go.id/geologi/

Ezbakhe, F., Giné-Garriga, R., & Pérez-Foguet, A. (2019). Leaving no one behind: Evaluating access to water, sanitation and hygiene for vulnerable and marginalized groups. *Science of the Total Environment*, *683*, 537–546. https://doi.org/10.1016/j.scitotenv.2019.05.207

Flores Baquero, O., Jiménez, A., & Pérez Foguet, A. (2016). Measuring disparities in access to water based on the normative content of the human right. *Social Indicators Research*, *127*(2), 741–759. https://doi.org/10.1007/s11205-015-0976-8

Foster, S., Hirata, R., Eichholz, M., & Alam, M. F. (2022). Urban self-supply from groundwater—An analysis of management aspects and policy needs. *Water (Switzerland)*. https://doi.org/10.3390/w14040575

Foster, T., Priadi, C., Kotra, K. K., Odagiri, M., Rand, E. C., & Willetts, J. (2021). Self-supplied drinking water in low- and middle-income countries in the Asia-Pacific. *Npj Clean Water*, *4*(1), 1–10. https://doi.org/10.1038/s41545-021-00121-6

Furlong, K., & Kooy, M. (2017). Worlding water supply: Thinking beyond the network in Jakarta. *International Journal of Urban and Regional Research*, *41*(6), 888–903. https://doi.org/10.1111/1468-2427.12582

Genter, F., Willetts, J., & Foster, T. (2021). Fecal contamination of groundwater self-supply in low- and middle income countries: Systematic review and meta-analysis. *Water Research*, *201*, 117350. https://doi.org/10.1016/j.watres.2021.117350

Gorter, A. C., Alberts, J. H., Gago, J. F., & Sandiford, P. (1995). A randomized trial of the impact of rope-pumps on water quality. *Journal of Tropical Medicine & Hygiene*, *98*, 247–255.

Graham, J. P., & Polizzotto, M. L. (2013). Pit latrines and their impacts on groundwater quality: A systematic review. *Environmental Health Perspectives*, *121*(5), 521–530. https://doi.org/10.1289/ehp.1206028

Grönwall, J. (2016). Self-supply and accountability: To govern or not to govern groundwater for the (peri-) urban poor in Accra, Ghana. *Environmental Earth Sciences*, *75*(16), 1163. https://doi.org/10.1007/s12665-016-5978-6

Grönwall, J., & Danert, K. (2020). Regarding groundwater and drinking water access through a human rights lens: Self-supply as A norm. *Water*, *12*(419), 21. https://doi.org/10.3390/w12020419

Grönwall, J. T., Mulenga, M., & Mcgranahan, G. (2010). Groundwater, self-supply and poor urban dwellers—A review with case studies of Bangalore and Lusaka. *Human Settlements Working Paper Series—Water and Sanitation*, *26*, 87.

Gundry, S. W., Wright, J. A., Conroy, R., Du Preez, M., Genthe, B., Moyo, S., et al. (2006). Contamination of drinking water between source and point-of-use in rural households of South Africa and Zimbabwe: Implications for monitoring the millennium development goal for water. *Water Practice and Technology*, *1*(2). https://doi.org/10.2166/wpt.2006.032

Hadipuro, W. (2010). Indonesia's water supply regulatory framework: Between commercialisation and public service? *Water Alternatives*, *3*(3), 475–491.

Howard, G. (2002). Water quality surveillance—A practical guide. *Environmental Science and Technology*, *5*(2), 114–119.

IDEXX Laboratories. (2015). *Colilert-18 Procedure*. Idexx Laboratories. Retrieved from https://www.lagaay.com/Catalogus/Product%20information/279555/Colilert%20-18%E0-coli%20detection%20Manual.pdf

Kazama, I. S., & Takizawa, S. (2021). Evaluation of microbial contamination of groundwater under different topographic conditions and household water treatment systems in special region of Yogyakarta province, Indonesia. *Water (Switzerland)*, *13*(12), 1673. https://doi.org/10.3390/w13121673

Knappett, P. S. K., McKay, L. D., Layton, A., Williams, D. E., Alam, M. J., Mailloux, B. J., et al. (2013). Unsealed tubewells lead to increased fecal cotamination of drinking water. *Journal of Water and Health*, *10*(4), 565–578. https://doi.org/10.1038/jid.2014.371

Komakech, H. C., & de Bont, C. (2018). Differentiated access: Challenges of equitable and sustainable groundwater exploitation in Tanzania. *Water Alternatives*, *11*(3), 623–637.

Kooy, M., Walter, C. T., & Prabaharyaka, I. (2018). Inclusive development of urban water services in Jakarta: The role of groundwater. *Habitat International*, *73*, 109–118. https://doi.org/10.1016/j.habitatint.2016.10.006

Kulabako, R. N., Nalubega, M., Wozei, E., & Thunvik, R. (2010). Environmental health practices, constraints and possible interventions in peri-urban settlements in developing countries—A review of Kampala, Uganda. *International Journal of Environmental Health Research*, *20*(4), 231–257. https://doi.org/10.1080/09603120903545745

Kumpel, E., Albert, J., Peletz, R., De Waal, D., Hirn, M., Danilenko, A., et al. (2016). Urban water services in Fragile States: An analysis of drinking water sources and quality in port Harcourt, Nigeria, and Monrovia, Liberia. *The American Journal of Tropical Medicine and Hygiene*, *95*(1), 229–238. https://doi.org/10.4269/ajtmh.15-0766

Kumpel, E., Cock Esteb, A., Duret, M., De Waal, O., & Khush, R. (2017). Seasonal variation in drinking and domestic water sources and quality in Port Harcourt, Nigeria. *The American Journal of Tropical Medicine and Hygiene*, *96*(2), 437–445. https://doi.org/10.4269/ajtmh.16-0175

Kurniasih, H. (2008). Water not for all: The concequences of water Privitisation in Jakarta, Indonesia. *The 17th Biennial Conference of the Asian Studies Association of Australia*, *1–19*.

Lechevallier, M. W., Welch, N. J., & Smith, D. B. (1996). Full-scale studies of factors related to coliform regrowth in drinking water. *Applied and Environmental Microbiology*, *62*(7), 2201–2211. https://doi.org/10.1128/aem.62.7.2201-2211.1996

Liddle, E. S., Mager, S. M., & Nel, E. L. (2016). The importance of community-based informal water supply systems in the developing world and the need for formal sector support. *Geographical Journal*, *182*(1), 85–96. https://doi.org/10.1111/geoj.12117

MacCarthy, M. F., Annis, J. E., & Mihelcic, J. R. (2013). Unsubsidised self-supply in eastern Madagascar. *Water Alternatives*, *6*(3), 424–438.

Martínez-Santos, P., Martín-Loeches, M., García-Castro, N., Solera, D., Díaz-Alcaide, S., Montero, E., & García-Rincón, J. (2017). A survey of domestic wells and pit latrines in rural settlements of Mali: Implications of on-site sanitation on the quality of water supplies. *International Journal of Hygiene and Environmental Health*, *220*(7), 1179–1189. https://doi.org/10.1016/j.ijheh.2017.08.001

McGuinness, S. L., O'Toole, J., Barker, S. F., Forbes, A. B., Boving, T. B., Giriyan, A., et al. (2020). Household water storage management, hygiene practices, and associated drinking water quality in rural India. *Environmental Science and Technology*, *54*(8), 4963–4973. https://doi.org/10.1021/acs.est.9b04818

Meierhofer, R., Bänziger, C., Deppeler, S., Kunwar, B. M., & Bhatta, M. (2018). From water source to tap of ceramic filters—Factors that influence water quality between collection and consumption in rural households in Nepal. *International Journal of Environmental Research and Public Health*, *15*(11), 2439. https://doi.org/10.3390/ijerph15112439

National Population and Family Planning Board (BKKBN), Statistics Indonesia (BPS), Ministry of Health (Kemenkes), & ICF. (2018). Indonesia Demographic and health survey 2017. Retrieved from https://dhsprogram.com/pubs/pdf/FR342/FR342.pdf

Ngasala, T. M., Masten, S. J., & Phanikumar, M. S. (2019). Impact of domestic wells and hydrogeologic setting on water quality in peri-urban Dar es Salaam, Tanzania. *Science of the Total Environment*, *686*, 1238–1250. https://doi.org/10.1016/j.scitotenv.2019.05.202

Ngasala, T. M., Phanikumar, M. S., & Masten, S. J. (2021). Improving safe sanitation practices using groundwater transport modelling and water quality monitoring data. *Water Science and Technology*, 1–12. https://doi.org/10.2166/wst.2021.428

Pallant, J. (2007). *A step-by-step guide to data analysis using SPSS for Windows (version 15)* (3rd ed.). Allen and Unwin.

Potgieter, N., Mudau, L. S., & Maluleke, F. R. S. (2006). Microbiological quality of groundwater sources used by rural communities in Limpopo Province, South Africa. *Water Science and Technology*, *54*(11–12), 371–377. https://doi.org/10.2166/wst.2006.890

Ravenscroft, P., Mahmud, Z. H., Islam, M. S., Hossain, A. K. M. Z., Zahid, A., Saha, G. C., et al. (2017). The public health significance of latrines discharging to groundwater used for drinking. *Water Research*, *124*, 192–201. https://doi.org/10.1016/j.watres.2017.07.049

Shaheed, A., Orgill, J., Ratana, C., Montgomery, M. A., Jeuland, M. A., & Brown, J. (2014). Water quality risks of “improved” water sources: Evidence from Cambodia. *Tropical Medicine and International Health*, *19*(2), 186–194. https://doi.org/10.1111/tmi.12229

Shields, K. F., Bain, R. E. S., Cronk, R., Wright, J. A., & Bartram, J. (2015). Association of supply type with fecal contamination of source water and household stored drinking water in developing countries: A bivariate meta-analysis. *Environmental Health Perspectives*, *123*(12), 1222–1231. https://doi.org/10.1289/ehp.1409002

Sugiyono, & Dewancker, B. J. (2020). Study on the Domestic Water Utilization in Kota Metro, Lampung Province, Indonesia: Exploring Opportunities to Apply the Circular Economic Concepts in the Domestic Water Sector. *Sustainability*, *12*(21), 8956. https://doi.org/10.3390/su12218956

Sutton, S. (2009). An introduction to self supply: Putting the user first - Incremental improvements and private investment in rural water supply rural water supply series (pp. 1–7). Retrieved from http://www.rwsn.ch/documentation/skatdocumentation.2009-07-27.8158674790/file

Trevett, A. F., Carter, R. C., & Tyrrel, S. F. (2005). The importance of domestic water quality management in the context of fecal-oral disease transmission. *Journal of Water and Health*, *3*(3), 259–270. https://doi.org/10.2166/wh.2005.037

Vaccari, M., Collivignarelli, C., Tharnpoophasiam, P., & Vitali, F. (2010). Wells sanitary inspection and water quality monitoring in Ban Nam Khem (Thailand) 30 months after 2004 Indian Ocean tsunami. *Environmental Monitoring and Assessment*, *161*(1–4), 123–133. https://doi.org/10.1007/s10661-008-0732-5

Voisin, J., Cournoyer, B., Vienney, A., & Mermillod-Blondin, F. (2018). Aquifer recharge with stormwater runoff in urban areas: Influence of vadose zone thickness on nutrient and bacterial transfers from the surface of infiltration basins to groundwater. *Science of the Total Environment*, *637–638*, 1496–1507. https://doi.org/10.1016/j.scitotenv.2018.05.094

WHO, & UNICEF. (2017). Guidelines for drinking-water quality: Fourth edition incorporating the first addendum (Vol. *53*). https://doi.org/10.1017/CBO9781107415324.004

WHO, & UNICEF. (2019). Progress on household drinking water, sanitation and hygiene 2000–2017. Special focus on inequalities.140.

WHO, & UNICEF. (2021). Five years into the SDGs—Progress on household drinking water, sanitation and hygiene. Retrieved from https://www.oecd.org/dac/

Wright, J., Gundry, S., & Conroy, R. (2004). Household drinking water in developing countries: A systematic review of microbiological contamination between source and point-of-use. *Tropical Medicine and International Health*, *9*(1), 1–117. https://doi.org/10.1046/j.1365-3156.2003.01160.x

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Research Paper

Associations between seasonality and faecal contamination of self-supply sources in urban Indonesia

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ABSTRACT

Water quality monitoring that accounts for seasonal variability is crucial to ensure safe water services at all times, including groundwater self-supply, which provides drinking water for more than 40 million people in urban Indonesia. Seasonal variation of self-supply water quality remains a key evidence gap in Indonesia and elsewhere; therefore, this study investigated the associations between seasonality and faecal contamination of groundwater self-supply in the Indonesian cities of Bekasi and Metro. The study demonstrated mixed results in terms of associations between seasonality and microbial water quality. McNemar's test showed that high concentrations of *Escherichia coli* (*E. coli*) ($\geq$100 MPN per 100 mL) were significantly more likely during the wet season than during the dry season in Bekasi ($p = 0.050$), but not in Metro ($p = 0.694$). There was no statistically significant association between the season and the presence of *E. coli* in self-supply sources for both study sites, nor was there a significant association between the season and the presence of high concentrations of *E. coli* at the point-of-use. At both study sites, presence and high concentrations of *E. coli* during the dry season significantly increased the risk of contamination in the wet season, but the predictive power was weak. Regular water quality testing complemented by sanitary inspection is required to understand the contamination risks of self-supply sources.

Key words: drinking water quality, faecal contamination, groundwater, seasonality, self-supply, urban Indonesia

HIGHLIGHTS

- Insights into the relationship between seasonality and water quality of self-supply.
- Implications for self-supply water quality monitoring in urban Indonesia.
- Highlighting the need for regular water quality testing, complemented with sanitary inspections.

INTRODUCTION

Groundwater self-supply provides drinking water to hundreds of millions of households in low-and middle-income countries (LMICs), including more than 40 million people in urban Indonesia (Foster *et al.* 2021). Household self-supply relying on groundwater refers to on-premises boreholes or dug wells that are typically self-financed and self-managed by individual households (Grönwall & Danert 2020). Being located on a user household's premises, self-supply could have the potential to provide a safely managed water service, which is defined as an improved water source accessible on-premises, available in sufficient quantities when needed and free from faecal and chemical contamination (WHO and UNICEF 2017). However, self-supply services are generally unregulated and unmonitored (Grönwall *et al.* 2010; Grönwall & Danert 2020; Foster *et al.* 2022), resulting in insufficient knowledge of water quality risks such as faecal contamination.

Faecal contamination of unregulated self-supply services remains a prime concern in urban Indonesia, and elsewhere. A systematic review of 30 studies in different LMIC contexts found that faecal indicator bacteria were present in 36% of self-supply sources, including 28% of samples from boreholes, 81% of samples from unprotected wells, and 77% of samples from protected wells (Genter *et al.* 2021). Among the 15 studies conducted in urban areas, faecal indicator bacteria were reported in 34% of self-supply sources (Genter *et al.* 2021). A recent study from urban Indonesia assessed sanitary and socio-economic risk factors of microbial contamination of groundwater self-supply and detected faecal contamination in 66% of household groundwater self-supply sources in two cities, with unprotected dug wells being more prone to contamination than boreholes (Genter *et al.* 2022). Despite widespread boiling practices in the study sites, faecal contamination was detected in 30% of the drinking water samples at point-of-use (Genter *et al.* 2022).

Monitoring of faecal contamination of drinking water is usually based on faecal indicator bacteria. The presence of *Escherichia coli* (*E. coli*) in a 100 mL water sample is the recommended measure of faecal contamination by the World Health Organization (WHO) (WHO 2022). The WHO states as a guideline value that no *E. coli* should be detected in any 100 mL sample (WHO 2022). Water quality monitoring relies often on a single or infrequent test of water for *E. coli* due to limited resources (Kostyla *et al.* 2015; Charles *et al.* 2020). Considering only one season (e.g. wet or dry season) in testing is a particular concern for evaluating water safety (Kostyla *et al.* 2015), as understanding variability (seasonal or otherwise) in occurrence and detection of *E. coli* is necessary to identify and manage threats (Charles *et al.* 2020). Information on the relationship between *E. coli* data from the dry and wet seasons can also provide insight into seasonal bias in sampling at individual time points.

It is known that seasonal effects can impact water quality (Kostyla *et al.* 2015; Bain *et al.* 2021; Nijhawan & Howard 2022), however most studies on water quality are cross-sectional, especially those focusing on self-supply. This may lead to seasonal bias, meaning contamination risks may be under- or overestimated (Bain *et al.* 2014; Genter *et al.* 2021). In a systematic review of faecal contamination of groundwater self-supply in LMICs (Genter *et al.* 2021), only five of the 30 self-supply studies distinguished between water quality in the wet and dry season (Potgieter *et al.* 2006; Pujari *et al.* 2012; Butterworth *et al.* 2013; Knappett *et al.* 2013; Adams *et al.* 2016) and six covered water quality measurements during both seasons but did not differentiate between the seasons (Nogueira *et al.* 2003; Vollaard *et al.* 2005; Van Geen *et al.* 2011; Ravenscroft *et al.* 2017; Davoodi *et al.* 2018; Ebner *et al.* 2018). Other included studies either focused on one season or did not document the season in which data collection took place (Genter *et al.* 2021). Similarly, in the aforementioned study on urban Indonesia, seasonality could not be directly assessed as a risk factor since water quality of self-supply sources was tested during the wet season in one city, and during the dry season in the other city (Genter *et al.* 2022). With climate change leading to more intense rainfall and dry periods (IPCC 2021), there is an urgent need to consider seasonal variability and its influence on faecal contamination and to improve long-term monitoring with more strategically planned water testing to inform drinking water safety (Nijhawan & Howard 2022). Therefore, this study aims to assess the seasonality aspect of microbial water quality in groundwater self-supply sources in urban Indonesia.

METHODS

The study was undertaken in the Indonesian cities of Bekasi and Metro (Supplementary material, Figure S1). Data were collected during the wet season (Bekasi: February–March 2020, Metro: February–March 2022), and during the dry season (Bekasi: October 2021, Metro: October–November 2020).

During the months in which the dry season sampling took place in Metro (October–November 2020), 12 rainy days were recorded with precipitation totalling 163 mm (BPS Kota Metro 2021). In comparison, Metro recorded a total of 22 rainy days with precipitation totalling 604 mm in the wet season months of February and March of the same year (BPS Kota Metro 2021). During the months in which the wet season sampling took place in Bekasi (February–March 2020), 60 rainy days were recorded with precipitation totalling 2,553 mm (BPS Kota Bekasi 2021). In comparison, the preceding dry season months of October and November 2019 yielded 16 rainy days with precipitation totalling 332 mm (BPS Kota Bekasi 2020, 2021).

Concentration of faecal indicator bacteria *E. coli* was quantified for self-supply sources and at point-of-use using IDEXX Colilert-18 and the IDEXX Quanti-Tray®/2000 system based on the most probable number (MPN) approach according to manufacturer's instructions (IDEXX Laboratories, 2015). Matched samples for wet and dry seasons included 204 and 217 self-supply sources, respectively (Supplementary material, S1). These self-supply sources included private boreholes (Bekasi: $n = 186$, Metro: $n = 58$) and dug wells (Bekasi: $n = 18$, Metro: $n = 159$). The majority of dug wells were unprotected (>85%). At point-of-use, 41 and 50 drinking water samples in Bekasi and Metro were from self-supply sources.

See Genter *et al.* (2022) for more information on the study sites, data collection, water quality testing, and quality control procedures.

Water quality samples for wet and dry season were matched considering the household ID and water source type using Microsoft Office Excel 2016. Source types categorized as unprotected and protected dug wells were considered as dug wells. In Bekasi, 39 and 51 samples and in Metro, 61 and 60 samples for wet and dry season, respectively, could not be assigned and were excluded due to the use of different water sources in the wet and dry seasons. *E. coli* concentration for each self-supply source type and season were classified into WHO health risk classes of 'safe or low', 'intermediate', 'high', or 'very high' for water samples with <1, 1–9, 10–99, ≥ 100 *E. coli* counts per 100 mL, respectively. Statistical analysis software R (version 1.2.5001, R Foundation for Statistical Computing, Vienna, Austria) was used for analysis. To determine whether microbial water quality differs between wet and dry seasons, *E. coli* concentration was comparatively assessed using paired samples Wilcoxon test and McNemar's test. Wilcoxon test assesses *E. coli* as a continuous variable, while McNemar's test assesses it as a dichotomous variable. Effect size (r) for Wilcoxon test was calculated by dividing the test statistic (Z) by the square root of the number of observations (n) (Pallant 2007). The proportion of samples with the presence of *E. coli* and high concentrations (≥ 100 MPN per 100 mL) of *E. coli* were calculated.

To investigate whether single time-point water samples are adequate, logistic regression analysis was performed to predict whether *E. coli* contamination present in dry season increases risk in the wet season (Supplementary material, S2). Presence/absence of *E. coli* and high concentration of *E. coli* (cut-off value 100 MPN) during dry season was used to build a logistic regression model (R package: tidyverse) predicting the probability of *E. coli* being present during the wet season. Spearman's rank correlation rho was calculated to assess the correlation between *E. coli* counts from wet and dry season samples (R package: ggpubr)

Information on whether households had recently experienced flooding was obtained from the household survey (Genter *et al.* 2022). Households in Bekasi ($n = 300$) and Metro ($n = 300$) were asked (yes/no) if there has been any flooding in or around the house in the last 12 months in Bekasi and in the last month in Metro. Paired samples Wilcoxon test and McNemar's test were used to assess whether *E. coli* concentration and presence in self-supply sources differs between wet and dry seasons specifically for households that experienced flooding in the past months during rainy season.

RESULTS

E. coli was frequently detected in self-supply sources in Bekasi and Metro during wet and dry seasons. Self-supply sources in Bekasi were dominated by boreholes ($n = 186$), while dug wells ($n = 159$) were common in Metro (Table 1). In Bekasi, *E. coli*

Table 1 | *Escherichia coli* contamination in self-supply sources and drinking water from households in Bekasi and Metro

	Bekasi					Metro				
		Wet season		Dry season			Wet season		Dry season	
	Total n	≥1 MPN/100 mL, n (%)	≥100 MPN/100 mL, n (%)	≥1 MPN/100 mL, n (%)	≥100 MPN/100 mL, n (%)	Total, n	≥1 MPN/100 mL, n (%)	≥100 MPN/100 mL, n (%)	≥1 MPN/100 mL, n (%)	≥100 MPN/100 mL, n (%)
Sources										
Borehole	186	97 (52.2)	35 (18.8)	92 (50.5)	23 (12.4)	58	34 (58.6)	10 (17.2)	30 (51.7)	6 (10.3)
Dug well	18	16 (88.9)	6 (33.3)	12 (66.7)	4 (22.2)	159	128 (80.5)	56 (35.2)	126 (79.2)	64 (40.3)
All self-supply sources	204	113 (55.4)	41 (20.1)	104 (51.0)	27 (13.2)	217	162 (79.4)	66 (30.4)	156 (71.9)	70 (32.3)
All sources (including public sources)	219	124 (56.6)	46 (21.0)	115 (52.5)	30 (13.7)	236	171 (72.5)	67 (28.4)	166 (70.3)	71 (30.1)
Point-of-use										
Borehole	33	11 (33.3)	1 (3.0)	9 (27.3)	1 (3.0)	19	6 (31.6)	0 (0.0)	5 (26.3)	2 (10.5)
Dug well	8	3 (37.5)	0 (0.0)	1 (12.5)	0 (0.0)	31	9 (29.0)	2 (6.5)	15 (48.4)	4 (12.9)
All self-supply sources	41	14 (34.1)	1 (2.4)	10 (24.4)	1 (2.4)	50	15 (30.0)	2 (4.0)	20 (40.0)	6 (12.0)
All sources (including refill and bottled water)	55	17 (30.9)	1 (1.8)	14 (25.5)	1 (1.8)	69	22 (31.9)	4 (5.8)	23 (33.3)	6 (8.7)

was present in 55% ($n = 113$) and 51% ($n = 104$) of all self-supply sources during wet and dry seasons, respectively. In Metro, *E. coli* was detected in 79% ($n = 162$) of self-supply sources during the wet season and 72% ($n = 156$) of self-supply sources during the dry season (Table 1). In Bekasi, the proportion of dug wells with high concentrations of *E. coli* (≥100 MPN) was 33% ($n = 6$) in the wet season and 22% ($n = 4$) in the dry season; while the proportion of boreholes with high concentrations of *E. coli* (≥100 MPN) was 19% ($n = 35$) in the wet season and 12% ($n = 23$) in the dry season (Figure 1). Similarly, in Metro, 35% ($n = 56$) of dug wells and 17% ($n = 10$) of boreholes were in the high risk category during the wet season and 40% ($n = 64$) of dug wells and 10% ($n = 6$) of boreholes during the dry season (Figure 2).

Self-supply sources were more frequently contaminated in the wet season than in the dry season, with a statistically significant difference for high levels of contamination in Bekasi, but not in Metro. Paired samples of Wilcoxon test and McNemar's test (≥1 MPN) showed no significant difference of water quality between wet and dry seasons (Table 2). However, when applying the Wilcoxon test to water sources in Bekasi, *E. coli* concentrations were higher in wet season samples, with p-values less than 0.1 ($p = 0.054$ for all water sources including public sources, 0.078 for all self-supply samples and 0.083 for private boreholes). Applying a high level of contamination of ≥100 MPN as the cut-off, McNemar's test showed a statistically significant difference in water quality of self-supply sources between wet and dry season in Bekasi ($p = 0.050$). No statistically significant difference in water quality was found in Metro. Of the 204 and 217 households relying on self-supply in Bekasi and Metro, respectively, 8 and 12 reported having recently experienced flooding. There was no statistically significant difference in water quality between wet and dry season of self-supply water sources of households experiencing flooding (Supplementary material, S3).

At the point-of-use, *E. coli* was present in drinking water during both seasons, but at lower levels compared to the source. At the point-of-use in Bekasi, *E. coli* was detected in 31% ($n = 17$) of drinking water samples (derived from self-supply, refill and bottled water) during the wet season, and in 26% ($n = 14$) during the dry season (Table 1). Similarly, in Metro, *E. coli* was present in 32% ($n = 22$) and 33% ($n = 23$) of drinking water sources during wet and dry seasons, respectively (Table 1). There was no statistically significant difference between wet and dry seasons for both study sites (Table 2).

Presence and high concentrations of *E. coli* in self-supply sources during the dry season were a significant predictor for risk of contamination during wet season in Bekasi and Metro; however, the power of prediction was weak. The presence of *E. coli* (≥ 1 MPN) during the dry season increased the odds of contamination during the wet season by 2.51 ($p = 0.001$) in Bekasi and 3.63 ($p < 0.001$) in Metro.

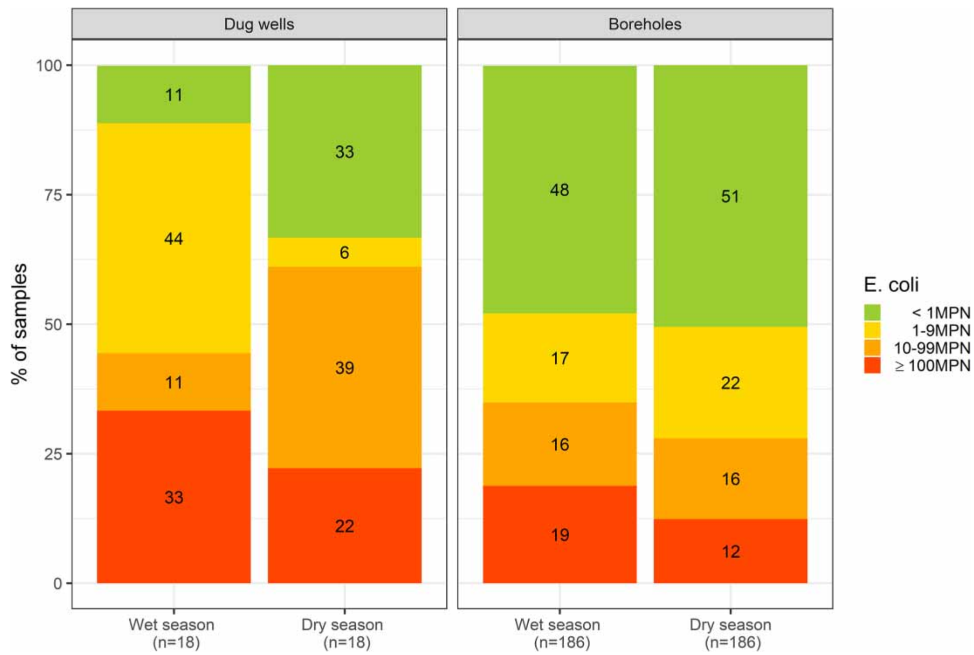

Figure 1 | Risk classification of *Escherichia coli* in self-supply sources in Bekasi City.

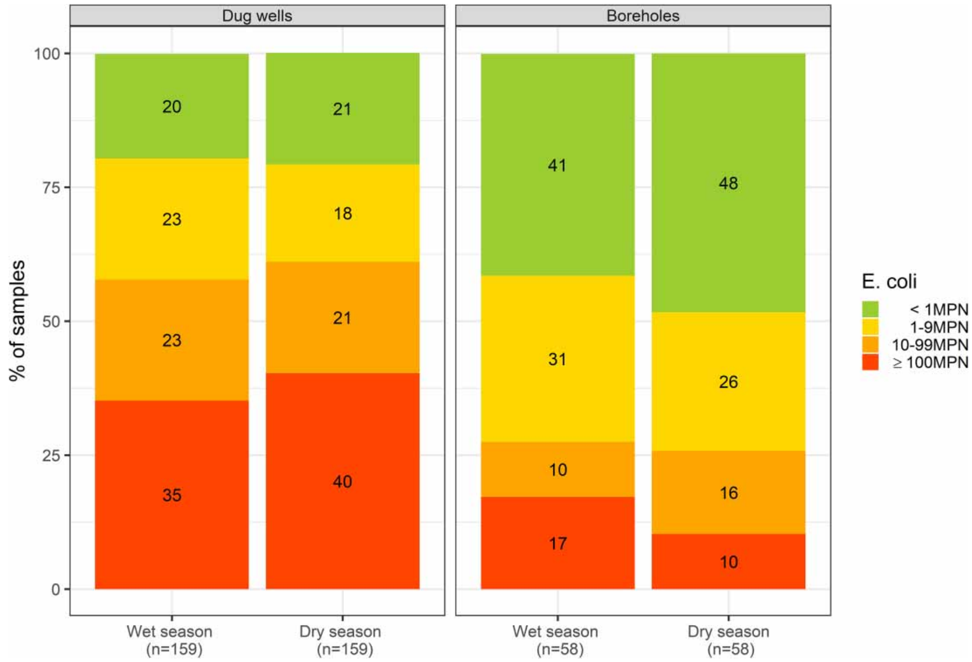

Figure 2 | Risk classification of *Escherichia coli* in self-supply sources in Metro City.

Table 2 | Comparison of *Escherichia coli* concentration using paired samples Wilcoxon and Mc Nemar's test between wet and dry seasons

	Bekasi								Metro							
		Paired samples Wilcoxon			McNemar					Paired samples Wilcoxon			McNemar			
					$\geq$ 1 MPN		$\geq$ 100 MPN						$\geq$ 1 MPN		$\geq$ 100 MPN	
	n	p-value (greater)	z	r^a	X^2	p-value	X^2	p-value	n	p-value (greater for sources, smaller for point-of-use)	z	r^a	X^2	p-value	X^2	p-value
Sources																
Borehole	186	0.083	1.1	0.1	0.2	0.635	3.0	0.082	58	0.399	0.4	0.1	0.4	0.540	0.9	0.343
Dug well	18	0.467	0.8	0.2	1.1	0.289	0.3	0.617	159	0.423	0.2	0.0	0.0	0.871	1.0	0.312
All self-supply sources	204	0.078	1.3	0.1	0.8	0.368	**3.8**	**0.050**	217	0.378	0.3	0.0	0.4	0.525	0.2	0.694
All sources (including public sources)	219	0.054	1.5	0.1	0.7	0.391	**4.5**	**0.034**	236	0.382	0.3	0.0	0.2	0.635	0.2	0.699
Point-of-use																
Borehole	33	0.568	0.1	0.0	0.1	0.773	–	–	19	0.383	0.1	0.0	0.0	1.0	–	–
Dug well	8	0.091	1.7	0.6	0.5	0.480	–	–	31	0.154	−1.2	−0.2	2.1	0.149	0.3	0.617
All self-supply sources	41	0.380	0.8	0.1	0.6	0.423	–	–	50	0.125	−1.0	−7.7	0.8	0.359	1.5	0.221
All sources (including refill and bottled water)	55	0.470	0.5	0.1	0.2	0.628	–	–	69	0.359	−0.1	−0.0	0.0	1.0	0.1	0.724

[a]Effect size with small effect for $r = 0.1 < 0.3$, moderate effect for $r = 0.3– < 0.5$ and large effect for $r \geq 0.5$.
Bold values indicate statistical significance ($p < 0.05$)

High concentrations of *E. coli* ($\geq$100 MPN) during the dry season significantly increased the presence of *E. coli* during the wet season by 5.56 ($p = 0.002$) in Bekasi and by 5.33 ($p < 0.001$) in Metro.

McFadden pseudo-R^2 indicated weak predictive power with pseudo-R^2 values for the presence and high levels of *E. coli* of 0.04 and 0.04 in Bekasi and 0.06 and 0.07 in Metro.

Spearman's rank test indicated a weak positive correlation between *E. coli* counts from wet and dry season samples in Bekasi ($\rho = 0.31$, $p < 0.001$) and Metro ($\rho = 0.55$, $p < 0.001$).

DISCUSSION

This study did not find any significant seasonal differences in the presence of faecal contamination in either Kota Bekasi or Kota Metro. A possible explanation for the lack of a significant association between the *E. coli* presence and the season could be the dominance of contamination sources that are unaffected by rainfall. For instance, several risk factors such as on-site sanitation, a lack of well protection, and manual water lifting devices (e.g. rope and bucket) can lead to faecal contamination of self-supply systems irrespective of rainfall. The findings from this study stand as a contrast to a recent systematic review of 22 studies in LMICs which showed a statistically significant seasonal trend of greater contamination in improved drinking water sources during the wet season (Kostyla *et al.* 2015). Despite the non-significant difference between seasons, our study showed that self-supply sources were frequently contaminated in both the wet and dry seasons, highlighting the need to better understand the complexity of the various risk factors of faecal contamination in self-supply sources.

A significantly increased risk of a high level of *E. coli* contamination during the wet season was observed in Bekasi, but not in Metro. Self-supply in Bekasi consists primarily of boreholes, which are improved water sources and less susceptible to contamination than shallow dug wells, which were more commonly found in Metro and are at higher risk of faecal contamination irrespective of rainfall. The results may suggest that seasonality plays a greater role for certain infrastructure types such as boreholes, while in dug wells, faecal contamination can easily enter the well and therefore the risk of contamination is high irrespective of seasonality. Seasonality might also affect the association between water quality and sanitary risks with some sanitary risks becoming more prominent in the wet season and others in the dry season. Although the same contamination sources and infrastructure failures may be present during the wet and dry seasons, rainfall may accelerate contamination pathways and result in increased pollution and contamination risks (Levy *et al.* 2016; Kelly *et al.* 2020). Rainfall and the resulting saturation of the subsurface can facilitate the transport of pathogens from human and/or animal excreta in the soil, environmental surfaces, or subsurface, causing groundwater contamination (Levy *et al.* 2016). In our previous study, shallow borehole depth was identified as a significant risk factor for faecal contamination in Bekasi during the wet season; while in Metro during the dry season, the lack of a concrete platform for boreholes and the use of a rope and bucket for dug wells were significant risk factors (Genter *et al.* 2022). The differing risk factors support the notion that in sanitary inspections a summative sanitary risk score alone is not sufficient to predict water quality (Kelly *et al.* 2020). However, sanitary inspection as a complementary tool in water quality monitoring, with consideration of seasonality, could facilitate understanding the complexity of the multiple pathways of faecal contamination as well as addressing the vulnerability of a system to contamination.

The weak predictive power of the presence and high concentrations of *E. coli* in self-supply sources during the dry season for the risk of contamination during the wet season suggests that single one-time water quality results are insufficient to represent safety of self-supply sources. The study found that the presence and high concentrations of *E. coli* in self-supply sources during the dry season significantly increased the likelihood of contamination during the wet season at both study sites; however, the predictive power and the correlation were weak. The results suggest that infrequent tests of water for *E. coli* are inadequate to represent the safety of self-supply services, as risk factors for faecal contamination of groundwater self-supply are influenced by a diversity of environmental conditions and possible contamination sources and pathways (Genter *et al.* 2021, 2022). The weak predictive power may indicate varying degrees of pronounced contamination pathways in the wet and dry seasons. This is consistent with other studies that emphasize the need for water quality monitoring to go beyond a single water quality test to make a statement about water safety (Kostyla *et al.* 2015; Charles *et al.* 2020). For example, Kostyla *et al.* (2015) suggest addressing seasonal variation of contamination by both monitoring guidelines for sampling timing and implementation of sanitary inspections and water safety plans to avoid misrepresenting safety of drinking water sources. To overcome the effects of seasonal bias in water quality results, water quality monitoring in self-supply sources should be conducted on a regular basis.

While single, one-time water quality results are inadequate to understand contamination risks, comprehensive spatiotemporal studies could improve the understanding. Future research that incorporates factors such as rainfall data, regular *E. coli* monitoring, and sanitary inspections into spatiotemporal studies has the potential to improve understanding of the complexities of contamination dynamics. A holistic approach encompassing these elements would provide a more robust basis for predictive models, and furthermore inform the development of appropriate water quality monitoring approaches. Additionally, while we considered flood-affected households in our analysis, our study was constrained by a lack of data concerning the interaction between surface water and groundwater. To address this limitation, future research could encompass hydrogeological analyses.

CONCLUSIONS

This work is significant as it provides insights into the relationship between seasonality and groundwater quality of self-supply services and has implications for self-supply water quality monitoring in urban Indonesia. This study demonstrated mixed results regarding the association between water quality and seasonality. There was a statistically significant difference of high levels of faecal contamination between wet and dry season in Bekasi, but not in Metro. The presence of faecal contamination did not show any significant seasonal difference at both study sites. Presence and high concentrations of *E. coli* in self-supply sources during the dry season were significant but are weak predictors for the risk of contamination during the wet season at both study sites. The complexity of faecal contamination risk factors and the influence of seasonal changes highlight the need for regular water quality testing complemented by sanitary inspections to ensure sustainable water safety for self-supply systems.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Adams, G. O., Ogedegbe, P. E. & Tawari-Fufeyin, P. 2016 Assessment of presence of heavy metals and other pollution burden parameters and their effect on water quality in Benin City, Edo State. *Environ. Qual. Manage.* **26**, 65–87. https://doi.org/10.1002/tqem.21485.

Bain, R., Cronk, R., Wright, J., Yang, H., Slaymaker, T. & Bartram, J. 2014 Fecal contamination of drinking-Water in Low- and middle-Income countries: a systematic review and meta-analysis. *PLoS Med.* **11**. https://doi.org/10.1371/journal.pmed.1001644

Bain, R., Johnston, R., Khan, S., Hancioglu, A. & Slaymaker, T. 2021 Monitoring drinking water quality in nationally representative household surveys in low-and middle-income countries: cross-sectional analysis of 27 multiple indicator cluster surveys 2014–2020. *Environ. Health Perspect.* **129**. https://doi.org/10.1289/EHP8459.

BPS Kota Bekasi 2020 *Bekasi Municipality in Figures 2020*.

BPS Kota Bekasi 2021 *Bekasi Municipality in Figures 2021. BPS Kota Bekasi*.

BPS Kota Metro 2021 *Metro Municipality in Figures 2021*.

Butterworth, J., Sutton, S. & Mekonta, L. 2013 Self-supply as a complementary water services delivery model in Ethiopia. *Water Altern.* **6**, 405–423.

Charles, K. J., Nowicki, S. & Bartram, J. K. 2020 A framework for monitoring the safety of water services: from measurements to security. *NPJ Clean Water* **3**, 1–6. https://doi.org/10.1038/s41545-020-00083-1.

Davoodi, R., Pirsaheb, M., Karimyan, K., Gupta, V. K., Takhtshahi, A. R., Sharafi, H. & Moradi, M. 2018 Data for distribution of various species of fecal coliforms in urban, rural and private drinking water sources in ten years period – A case study: Kermanshah, Iran. *Data Brief* **18**, 1544–1550. https://doi.org/10.1016/j.dib.2018.04.053.

Ebner, P. D., Deering, A., Mojadady, M., Rahimi, Z., Amini, R., Popal, M., Eshaqzai, N., Barak, S., Amini, S., Azizi, E., Morshid, E., Mohammadi, N., Rahimi, M., McNamara, K. & Oliver, H. F. 2018 Capacity building through water quality and safety analyses in Herat, Afghanistan. *J. Food Prot.* **81**, 1467–1471. https://doi.org/10.4315/0362-028X.JFP-18-051.

Foster, T., Priadi, C., Kotra, K. K., Odagiri, M., Rand, E. C. & Willetts, J. 2021 Self-supplied drinking water in low- and middle-income countries in the Asia-Pacific. *NPJ Clean Water* **4**, 1–10. https://doi.org/10.1038/s41545-021-00121-6.

Foster, S., Hirata, R., Eichholz, M. & Alam, M. F. 2022 Urban self-Supply from groundwater – an analysis of management aspects and policy needs. *Water (Switzerland)*. https://doi.org/10.3390/w14040575.

Genter, F., Willetts, J. & Foster, T. 2021 Faecal contamination of groundwater self-supply in low- and middle income countries: systematic review and meta-analysis. *Water Res.* https://doi.org/10.1016/j.watres.2021.117350.

Genter, F., Putri, G. L., Pratama, M. A., Priadi, C., Willetts, J. & Foster, T. 2022 Microbial contamination of groundwater self-Supply in urban Indonesia: assessment of sanitary and socio-economic risk factors. *Water Resour. Res.* **58**. https://doi.org/10.1029/2021wr031843.

Grönwall, J. & Danert, K. 2020 Regarding groundwater and drinking water access through A human rights lens: self-supply as A norm. *Water (Basel)* **12**, 21.

Grönwall, J. T., Mulenga, M. & Mcgranahan, G. 2010 Groundwater, self-supply and poor urban dwellers – A review with case studies of Bangalore and Lusaka. *Human Settlements Working Paper Series – Water and Sanitation* **26**, 87.

IPCC 2021 *Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Vol. 2 (Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S. & Zhou, B., eds). Cambridge University Press, Cambridge, UK and New York, NY, USA.

Kelly, E., Cronk, R., Kumpel, E., Howard, G. & Bartram, J. 2020 How we assess water safety: a critical review of sanitary inspection and water quality analysis. *Sci. Total Environ.*. https://doi.org/10.1016/j.scitotenv.2020.137237.

Knappett, P. S. K., McKay, L. D., Layton, A., Williams, D. E., Alam Md, J., ., Mailloux, B. J., Ferguson, A. S., Culligan, P. J., Serre, M. L., Emch, M., Ahmed, K. M., Sayler, G. S. & Van Geen, A. 2013 Unsealed tubewells lead to increased fecal cotamination of drinking water. *J. Water Health* **10**, 565–578. https://doi.org/10.1038/jid.2014.371.

Kostyla, C., Bain, R., Cronk, R. & Bartram, J. 2015 Seasonal variation of fecal contamination in drinking water sources in developing countries: a systematic review. *Sci. Total Environ.*. https://doi.org/10.1016/j.scitotenv.2015.01.018.

Levy, K., Woster, A. P., Goldstein, R. S. & Carlton, E. J. 2016 Untangling the impacts of climate change on waterborne diseases: a systematic review of relationships between diarrheal diseases and temperature, rainfall, flooding, and drought. *Environ. Sci. Technol.*. https://doi.org/10.1021/acs.est.5b06186.

Nijhawan, A. & Howard, G. 2022 Associations between climate variables and water quality in low- and middle-income countries: a scoping review. *Water Res.* https://doi.org/10.1016/j.watres.2021.117996.

Nogueira, G., Nakamura, C. V., Tognim, M. C. B., Abreu Filho, B. A. & Dias Filho, B. P. 2003 Microbiological quality of drinking water of urban and rural communities, Brazil. *Rev Saude Publica* **37**, 232–236. https://doi.org/10.1590/S0034-89102003000200011.

Pallant, J. 2007 *A Step-by-Step Guide to Data Analysis Using SPSS for Windows (Version 15)*, 3rd edn. Allen and Unwin, Crows Nest, Australia.

Potgieter, N., Mudau, L. S. & Maluleke, F. R. S. 2006 Microbiological quality of groundwater sources used by rural communities in Limpopo Province, South Africa. *Water Sci. Technol.* **54**, 371–377. https://doi.org/10.2166/wst.2006.890.

Pujari, P. R., Padmakar, C., Labhasetwar, P. K., Mahore, P. & Ganguly, A. K. 2012 Assessment of the impact of on-site sanitation systems on groundwater pollution in two diverse geological settings-a case study from India. *Environ. Monit. Assess.* **184**, 251–263. https://doi.org/10.1007/s10661-011-1965-2.

Ravenscroft, P., Mahmud, Z. H., Islam, M. S., Hossain, A. K. M. Z., Zahid, A., Saha, G. C., Zulfiquar Ali, A. H. M., Islam, K., Cairncross, S., Clemens, J. D. & Islam, M. S. 2017 The public health significance of latrines discharging to groundwater used for drinking. *Water Res.* **124**, 192–201. https://doi.org/10.1016/j.watres.2017.07.049.

Van Geen, A., Ahmed, K. M., Akita, Y., Alam, M. J., Culligan, P. J., Emch, M., Escamilla, V., Feighery, J., Ferguson, A. S., Knappett, P., Layton, A. C., Mailloux, B. J., McKay, L. D., Mey, J. L., Serre, M. L., Streatfield, P. K., Wu, J. & Yunus, M. 2011 Fecal contamination of shallow tubewells in Bangladesh inversely related to arsenic. *Environ. Sci. Technol.* **45**, 1199–1205. https://doi.org/10.1021/es103192b.

Vollaard, A. M., Ali, S., Smet, J., Van Asten, H., Widjaja, S., Visser, L. G., Surjadi, C. & Van Dissel, J. T. 2005 A survey of the supply and bacteriologic quality of drinking water and sanitation in Jakarta, Indonesia. *Southeast Asian J. Trop. Med. Public Health* **36**, 1552–1561.

WHO 2022 *Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First and Second Addenda*. Geneva.

WHO, UNICEF 2017 *Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First Addendum*. https://doi.org/10.1017/CBO9781107415324.004.

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4.3 Summary

Chapter IV contributes to answering RQ1 of the PhD research by demonstrating that groundwater self-supply in urban Indonesia is at risk of faecal contamination at source and point-of-use and by identifying potential risk factors for faecal contamination. The studies conducted suggest that groundwater self-supply systems are vulnerable to faecal contamination. Results show that self-supply was commonly contaminated with *E. coli* at source, but significant less contamination was detected at the point-of-use. The proximity to on-site sanitation was identified as contributing to an increased risk of contamination. Seasonality was found to have an impact on water quality, but the results were mixed. The absence of a concrete platform, shallower borehole depth and the use of a rope and bucket were identified as significant factors contributing to the risk of contamination. Furthermore, unimproved sources and poorer households were found to be at higher risk of contamination. This highlights the need for improved infrastructure and safe household water treatment.

By considering the different components and interactions of the social-ecological system in the assessment, the findings provided a holistic understanding of the microbial water quality of self-supply systems and potential risk factors. However, to better understand the influence of seasonal changes on the complexity of risk factors for faecal contamination of self-supply, regular water quality testing complemented by sanitary inspections are required. These measures are critical to overcoming the challenges faced by groundwater self-supply systems towards a safely managed water supply.

5. Understanding household self-supply use and management

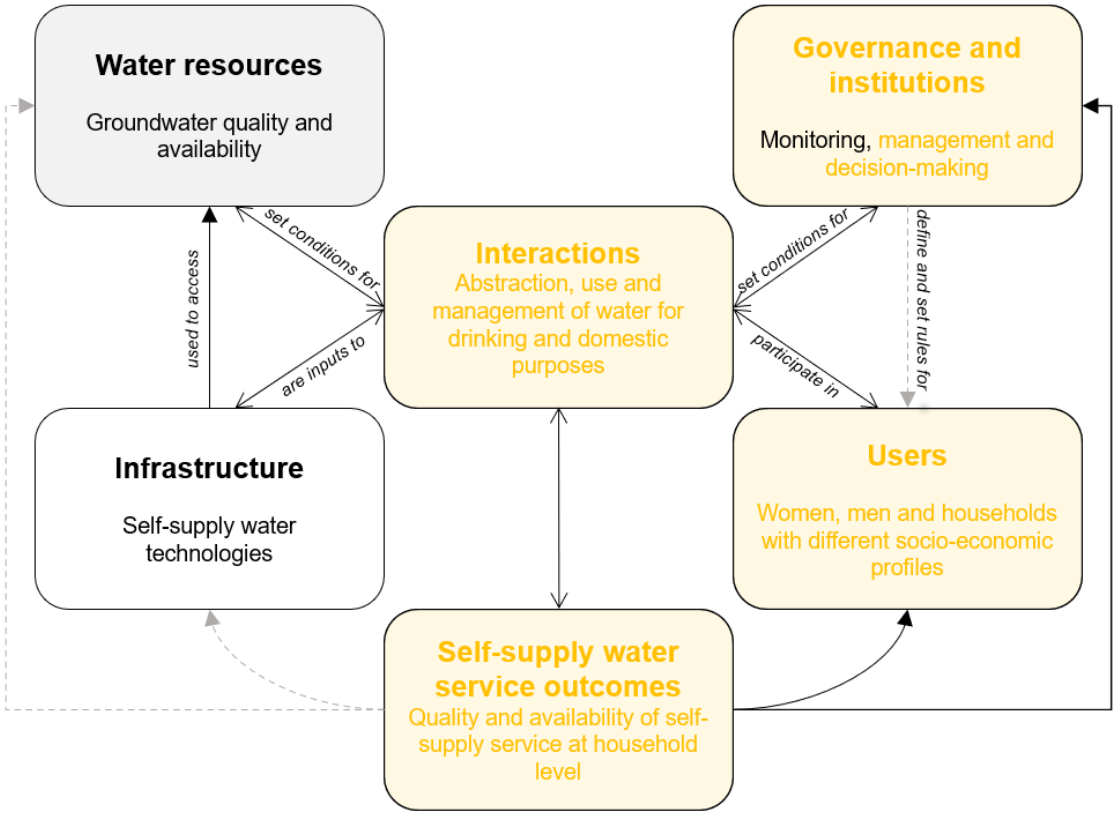

Figure 8: Chapter V focuses on self-supply at the household level in urban Indonesia and addresses RQ2 by providing understanding on the use and management of self-supply water services considering intra-household gender dynamics. The assessment and findings are primarily situated within the components of 'Users', 'Interactions', 'Self-supply water service outcomes' and 'Governance and institutions'.

5.1 Overview

Chapter V addresses RQ2, which seeks to understand how self-supply is used and managed by individual households including intra-household gender dynamics. The chapter consists of one publication, which was published in *PLOS Water* in 2023 (Publication IV). The findings are situated within the 'Water resources', 'Self-supply water service outcomes', 'Interactions', 'Users' and 'Governance and institutions' components of the social-ecological system framework with a strong focus on the components 'Users' and 'Interactions' (Figure 8).

The evaluation (Publication IV) offers valuable understanding into the use and management of self-supply services at the household level considering intra-household gender dynamics. Additionally, it sheds light on the perceptions of water quality and availability among water users, an area that has not been explored extensively before in the self-supply context.

5.2 Publication IV

Publication IV and its supplementary materials are available open access at https://doi.org/10.1371/journal.pwat.0000070 (Genter, Putri, Suleeman, et al., 2023).

PLOS WATER

RESEARCH ARTICLE

Understanding household self-supply use and management using a mixed-methods approach in urban Indonesia

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Abstract

In urban Indonesia, 40 million people rely on groundwater self-supply, however the role of self-supply in securing household water provision remains unexplored. This study used a mixed-methods approach to understand the use and management of household self-supply in the Indonesian cities of Bekasi and Metro, where a high proportion of households rely on private wells for water supply. Self-supply was the preferred drinking water source because of its perceived safety, taste and appearance at both study sites. The most important attributes influencing choice of domestic water source were appearance, reliability and safety in Bekasi, and safety followed by convenience and reliability in Metro. Coping strategies to overcome quality and availability problems of self-supply included water treatment, switching from dug wells to deeper boreholes and the use of multiple water sources. All households reported boiling self-supplied water, however, the labor involved was tiring for some households, leading them to resort to alternative water sources. Reasons for non-use of alternative water sources such as refill water and public piped systems included a lack of trust in water quality and perceived poor taste. Regarding self-supply management, responsibilities and decision-making varied across households, but cooperation between men and women concerning workload was common. Women were mostly responsible for household water management, and men were mostly responsible for maintenance and repairs, cleanliness of the water source and financing. To support and regulate self-supply towards a safely managed water service, strategies for improvements should be considered not only at the source, but also at point-of-use, including promotion of safe household water treatment and management. Although self-supply was the main water source at these study sites, alternative sources such as refill water and public piped systems played an important role in supplementing inadequate supplies, and hence their safety and reliability should be considered when establishing support strategies.

decision to publish, or preparation of the manuscript.

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Introduction

The role of self-supply in securing household water provision in many low- and middle-income countries (LMICs) is gaining recognition in the water sector. Household self-supply refers to an on-premises water supply relying on groundwater or rainwater, that is privately owned, financed and managed by individual households [1]. Self-supply has become essential for people who are beyond the reach of utility- or community managed water supplies, and for those who need to complement an inadequate public supply [2]. Self-supply has emerged in LMICs in a range of different contexts, including densely populated urban as well as remote rural settings [3, 4]. It can be found alongside municipal piped water services as well as in areas unserved by piped systems [5–9]. Despite it being heavily relied upon by households in many LMICs, self-supply is often overlooked by policy and practice.

Self-supply provides an essential contribution to meeting household water needs in many LMICs and has implications for progress towards Sustainable Development Goal (SDG) target 6.1 [4]. At current trends, the world will fall well short of SDG target 6.1, which calls for universal and equitable access to safe and affordable drinking water for all by 2030 [10]. The criteria of a safely-managed drinking water service is met when households use an improved water source that is accessible on-premises, available in sufficient quantities when needed, and free of faecal and chemical contamination [11]. Improved water supply systems are designed to protect against outside contamination, such as boreholes, protected dug wells or rainwater harvesting [11]. Self-supply has the potential to fulfil the criteria of a safely-managed water service as it is located on the premises of a user household, however self-supply services are generally unregulated and unmonitored [1, 2].

In urban Indonesia, approximately 40 million people self-supply their drinking water from groundwater sources in the form of dug wells or boreholes [4], however, poor water quality remains a prime concern. A recent study from two cities in Indonesia detected faecal contamination in 66% (n = 337) of groundwater self-supply sources, with unprotected dug wells being more frequently contaminated than boreholes [12]. Despite widespread boiling practices, *Escherichia coli* (*E.coli)* was present in 30% (n = 52) of point-of-use samples [12]. These findings highlight the importance of understanding more about how self-supply is used and managed by households.

Self-supply can be used alone, in addition to, or alternating with various other water sources. To secure drinking water provision, households often use multiple water sources to meet daily household needs [13, 14]. Global surveys often focus on the main source of drinking water in the household, therefore the reasons for household water choices are not well understood. Water source choice is influenced by seasonality [15–17]; user perceptions of water quality such as taste, odor and color [15, 18, 19]; lack of access to, intermittency of, and insufficient quantity of a primary supply [20]; and distance to and cost of higher quality water [21, 22]. The practice of supplementing improved primary source water with unimproved source water has also been reported globally [3, 14]. It is important to recognize how households choose their water supply to inform measures to improve drinking water quality and public health in contexts where self-supply is used with or without alternative water sources.

Shortcomings in public water supply often mean the responsibility for obtaining an adequate supply falls on households, highlighting the need to consider intra-household gender dynamics and distribution of workload. As a response to inadequate water supply, strategies employed by households include water treatment, storage practices and buying water form small-scale enterprises [23]. In many LMICs, the workload related to water provision falls on women due to traditional roles with women being responsible for household chores [24, 25]. Most research to date on gender dynamics and water supply has focused on community dynamics and in particular water supply governance [26–28]. In the context of self-supply, where water sources are privately owned and located on the premises, water-related responsibilities and decision-making between household members remain unexplored.

Understanding the reliance of households on self-supply and its associated management is crucial to developing appropriate strategies to ensure safe and reliable drinking water services for households in urban Indonesia. This study aims to address this evidence gap by using qualitative research to explain quantitative data. The study seeks to understand (i) the use and non-use of self-supply water services and alternative water choices and (ii) how self-supply is managed by individual households, including intra-household gender dynamics.

Methods

Study area

The study was undertaken in Bekasi and Metro, two densely populated cities in Indonesia (Fig 1). The cities of Bekasi and Metro were selected as study sites because of the lack of access to piped water, the widespread use of self-supply and the high population density. The metropolitan city Bekasi has approximately three million inhabitants and a population density of 13,841 people/km^2 (2017), making it one of the most populous cities in Indonesia [29, 30]. It is located in West Java on the eastern border Indonesia's capital Jakarta. Bekasi city is organized into 12 districts, three of which were covered in this study. The local water supply utility of Bekasi City only serves 26.8% of the city's total population with no service to the marginal areas [31]. In 2010, 40% of the households in Bekasi City were dependent on groundwater as their main drinking water source [32]. The minimum municipal income (Upah Minimum Kabupaten/Kota) of Kota Bekasi was 4,782,935 Rp. (approximately 310 USD) in 2021 [33]. Metro city is located in the Indonesian province of Lampung on Sumatra Island with a population of 162,976 people and a population density of 2,371 people/km^2 (2018). Metro is an urban settlement and is organized into five districts, namely Metro Barat (West), Pusat (Central), Selatan (South), Timur (East) and Utara (North). In 2018, only 1.3% of Metro's population (2,134 households) were connected to the piped municipal water system, with most customers from the district of Metro Pusat (1032 customers) and Metro Timur (920 customers). No communities used water from Indonesian's water supply company in the district of Metro Utara [34]. The minimum municipal income (Upah Minimum Kabupaten/Kota) of Kota Metro was 2,433,381 Rp. (approximately 158 USD) in 2021 [35].

Study design

An explanatory sequential mixed methods approach comprising a quantitative component followed by qualitative component [36] was used to understand the use and management of self-supply in relation to alternative water sources. The quantitative approach focused on a descriptive assessment of a cross-sectional household survey providing generalizable insights into the use and management of self-supply. The qualitative approach included in-depth interviews, providing detailed and contextualized explanatory insights.

Data collection

The data collection was carried out during wet season in Bekasi (February-March 2020) and during dry season in Metro (October-November 2020). Data for the quantitative approach were collected from 300 randomly selected households in both Bekasi and Metro. Participating households were randomly selected across three sub-districts *(Keluraham)* (Jatiluhur, Sumur Batu and Jatirangga) from three different districts (*Kecamatan*) in Bekasi (Jatiasih, Bantar

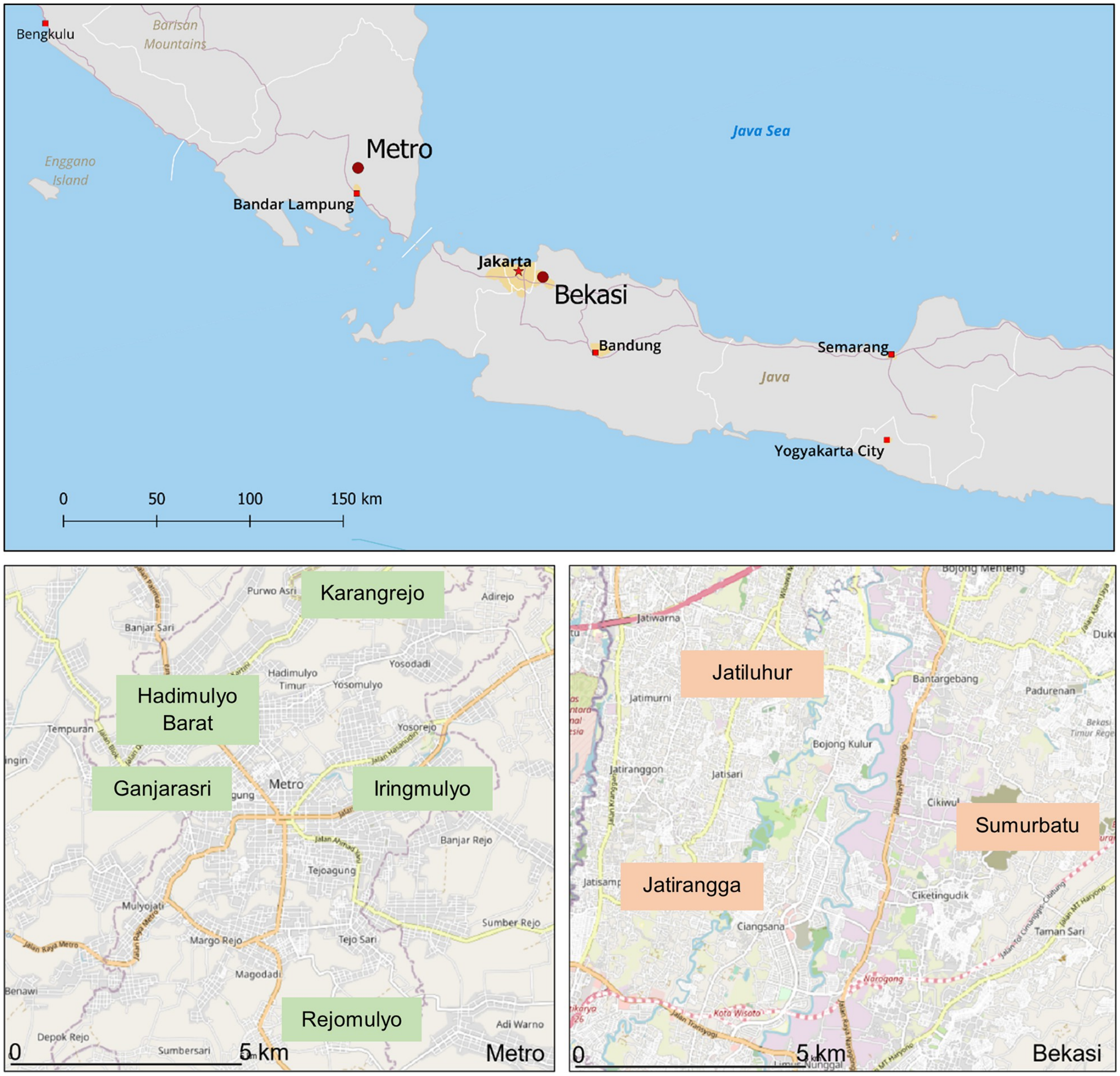

Fig 1. Study sites in Metro (Karangrejo, Hadimulyo Barat, Ganjarasri, Iringmulyo, Rejomulyo) and Bekasi (Jatiluhur, Sumur Batu, Jatirangga) (QGIS, version 3.28.1).

https://doi.org/10.1371/journal.pwat.0000070.g001

Gebang, Jatisampurna), and across five sub-districts (Karangrejo, Hadimulyo Barat, Ganjarasri, Iringmulyo and Rejomulyo) from the five different districts in Metro. Districts and sub-districts were selected purposively based on self-supply prevalence, population density, lack of access to piped water and poverty status, with information obtained from secondary data and local government. In consultation with the heads of the selected sub-districts, the selection of the hamlets (*RW Rukun Warga*) consisting of several neighbourhoods (*RT Rukun Tetangga*) was made. The neighbourhoods to be surveyed were chosen after further consultations with the respective head of the selected hamlets. Households of the selected neighbourhoods were randomly selected using Microsoft Office Excel 2016. Each neighbourhood's target number of households to be surveyed was determined in proportion to its population size.

Data collection included a household survey, sanitary inspection of self-supply sources and water quality testing. For this study, data from the household survey were used. Data on sanitary inspection and water quality are reported elsewhere [12]. Following the household survey, 24 in-depth interviews were carried out by phone (due to covid-19) from 12 purposively selected households in Bekasi (December 2020) and Metro (August 2021 and November 2021-January 2022), respectively. Prior to the data collection, informed consent was obtained in local language from heads of neighbourhoods and from all participants. Ethical approval to conduct the research was provided by the Research Ethics Committee of University of Technology Sydney as well as the Universitas Indonesia. Additional information regarding the ethical, cultural, and scientific considerations specific to inclusivity in global research is included in S2 Text. The data collection in Metro was affected by Covid-19 delays. The timing of data collection in Metro was based on the Covid-19 risk status determined by the national government. The survey was not conducted if the risk status was greater than level two of four. The decision to conduct the survey was made in consultation with all stakeholders in each district, including stakeholders from sub-districts, hamlets and neighbourhoods. During the survey, safety procedures were followed and the health of the research team and participants was paramount.

Quantitative approach. A structured household survey was conducted in local language by trained enumerators using Survey Solutions software (version 20.01, The World Bank, Washington DC, USA) in Bekasi and Qualtrics software (Qualtrics, Provo, UT, USA) in Metro (Tables K and L in S1 Text). The household survey covered a range of themes about the household, water sources used and perceptions of water service attributes. Questions about the household included themes on health and socio-economic status, water management and decision-making. Self-supply water sources were defined as groundwater sources (boreholes, protected dug wells or unprotected dug wells) that were privately owned by a household. Questions on water source usage considered alternative water sources such as public water services, neighbor's water supplies and packaged water (bottled water, refill water) and differentiated between wet and dry season. Questions on water perception included a ranking of attributes that influence households' water choices and reasons for the use and non-use of different water services. Descriptive analysis was performed in Microsoft Office Excel 2016 and statistical analysis software R (version 1.2.5001, R Foundation for Statistical Computing, Vienna, Austria). R package "DescTools" was used to calculate proportions and corresponding confidence intervals (CI). CIs for binominal proportions were calculated using the "BinomCI" function based on the Clopper-Pearson method, while CIs for multinominal proportions were calculated using the "MultinomCI" function based on the Sisonglaz method. Explanations of the various water sources used can be found in the supplementary material (Table A in S1 Text).

Qualitative approach. Following descriptive analysis of the household survey, a question guide for in-depth interviews was prepared covering themes on water choice, perception, management and decision-making. Household selection for the 24 in-depth interviews was carried out on a purposive basis to cover a range of household characteristics. The households were selected based on a sampling strategy to maximize the diversity relevant to the research question. Considered characteristics for household selection included gender of the head of household, gender of responsible person/s for water related tasks, gender of responsible person/s for decision-making processes, shared or single responsibility and decision-making, household wealth, marital status, and disability. Use of a self-supply source and ownership of a mobile phone were pre-requisites for selection. Information on household characteristics was obtained from analysis of the questions from the household survey. For the characteristics of the purposive selected households for the in-depth interviews, see the supplementary material

(Tables B and C in S1 Text). Households were listed and categorized based on the gender of the head of household (female/male) and the wealth of household (poor/middle/non-poor). The categorization of the household wealth was conducted based on the tertiles of the calculated wealth index of households. The wealth index was constructed for households in Bekasi and Metro using the same approach as the 2017 Indonesian Demographic and Health Survey (DHS) based on the relevant indicators and corresponding values [37]. Information on 23 relevant indicators such as household asset ownership, dwelling structure, type of cooking fuel and household composition were collected in the structured household survey. For each study site, a priority list including 12 households was created, taking into account shared or sole (female/male) responsibility for water related tasks and decision-making processes in a way that increases diversity. We also determined the responsibility for water related tasks was shared or assumed by a sole female or male household member from the results of the four household survey questions on water related tasks (Table K in S1 Text, questions 59–62 for Bekasi, Table L in S1 Text, questions 38–42 for Metro). Households where the respondent was the head of household were prioritized. If a mobile phone number was not available, households were exchanged with households from the backup list with similar characteristics. In-depth interviews were conducted by phone in local language and responses were recorded, transcribed and translated into English. The transcribed information was coded manually in Microsoft Office Word and Excel 2016 using a deductive approach to capture the relevant themes on self-supply water quality (risks, mitigation strategies, perceptions), water availability, water choices (reasons for non-use, perception of alternative water sources), workload (roles, responsibilities, decision-making) and conflicts.

Results

The result section draws on both quantitative and qualitative data organized in the following way. The first sub-section on water choice and perceptions includes only quantitative findings and provides an overview of the use of multiple water sources. Subsequent sub-sections are organized by water source types (private dug wells, private boreholes, public water services and packaged water) and cover information on use, water quality, water availability and reason for non-use. These sections begin with quantitative data from the household survey, if available, and are complemented by qualitative findings from the in-depth interview. The last two sub-sections in the result sections include quantitative and qualitative findings on attributes of water perception and self-supply management with regard to responsibilities, workload and decision-making.

Water choice and perceptions

Based on the household survey, households predominantly used self-supply as their main water source for drinking and domestic uses at both study sites. Regarding the main drinking water source, 48% of households (n = 144) were relying on private boreholes in Bekasi, and 47% households on private dug wells (n = 138) in Metro (Table 1). Another common drinking water source was refill water, with 21% of households reported to use refill water as their main drinking water source in Bekasi (n = 63) and Metro (n = 61). Public water service, including water from public boreholes, dug wells, piped systems and taps, was used by 12% (n = 35) and 8% (n = 22) of households as a main drinking water source in Bekasi and Metro, respectively. At the study sites, water for domestic purposes was obtained from private boreholes by 72% of households (n = 217) in Bekasi and from private dug wells by 65% of households (n = 191) in Metro mainly (Table 1). Besides self-supply, public water services, including water from public boreholes, dug wells, piped systems and taps, were used as a main source of water for domestic

Table 1. Proportion of main sources for drinking and domestic uses in Bekasi and Metro.

	Main drinking water source						Main domestic water source					
	Bekasi			Metro			Bekasi			Metro		
	n	[%]	95% CI [%]	n	[%]	95% CI [%]	n	[%]	95% CI [%]	n	[%]	95% CI [%]
Private borehole	144	48.0	42.3–53.8	39	13.3	7.8–19.4	217	72.3	67.7–77.6	61	20.7	15.6–26.4
Private dug well	18	6.0	0.3–11.8	138	46.9	41.5–53.0	17	5.7	1.0–10.9	191	65.0	59.9–70.6
Neighbor's borehole	2	0.7	0.0–6.5	8	2.7	0.0–8.8	2	0.7	0.0–5.9	8	2.7	0.0–8.4
Neighbor's dug well	0	0.0	0.0–5.8	8	2.7	0.0–8.8	0	0.0	0.0–5.2	8	2.7	0.0–8.4
Refill water	63	21.0	15.3–26.8	61	20.7	15.3–26.8	3	1.0	0.0–6.2	0	0.0	0.0–5.7
Bottled water	38	12.7	7.0–18.5	18	6.1	0.7–12.2	1	0.3	0.0–5.6	0	0.0	0.0–5.7
Public water service	35	11.7	6.0–17.5	22	7.5	2.0–13.6	60	20.0	15.3–25.2	26	8.8	3.7–14.5
Total	300	100.0		294	100.0		300	100.0		294	100.0	

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purposes by 20% of households (n = 60) in Bekasi and 9% (n = 26) in Metro. Disaggregating the different domestic uses, self-supply was the most common source of water for all domestic uses such as cooking, making tea, washing and watering garden and animals, with private boreholes predominantly used in Bekasi and private dug wells in Metro (Figs A and B in S1 Text). Water uses were comparable in the rainy and dry seasons at both study sites (Figs C and D in S1 Text).

Private dug well. *Use*. Private dug wells were primarily used as a water source for drinking and domestic purposes in Metro, but were also used by a few households in Bekasi. Descriptive analysis from the household survey showed that water from private dug wells was used as a main source for drinking (Bekasi: 6%, n = 18, Metro: 47%, n = 138) and domestic purposes (Bekasi: 6%, n = 17, Metro: 65%, n = 191) at both study sites, but particularly in Metro (Table 1). Of the 24 in-depth interviewed households in Bekasi and Metro, 21 owned or had owned in the past a private dug well. Of those, 12 households still used the water from dug wells for drinking and/or domestic purposes. Among these 12 households, the water from the dug wells was used by ten in-depth interview informants for drinking and by ten for domestic uses such as washing clothes, showering and cooking. Ten households had subsequently replaced the dug well with a borehole (Table D in S1 Text).

Water quality. Water quality perceptions for dug wells were mixed and water treatment was common. Half of the in-depth interview informants perceived the water quality of dug wells as good, as one informant said "*The water from the dug well is safe to drink, [it is] clear and tastes good and fresh*". However, the other half reported water quality concerns such as cloudy or turbid water. One informant constructed a borehole because the water quality of his dug well had decreased "*In the past we used a dug well but now it leaks, the water cannot be used, the water is black like sewage water*." If the self-supplied water was used for drinking, informants reported boiling it before consumption to avoid health issues. "*My child said, if the water is not boiled, the stomach bloats. When the water is boiled, [it is] sweet*." One informant in Metro observed turbid water during the rainy season and let the mud settle before boiling, "*If it rains, the well water for cooking and drinking is deposited in a container overnight. In the morning, we take water with a scoop, then we boil it*".

Water availability. The perception of water availability was mixed, with poor availability reported during the dry season, resulting in dug wells being replaced or deepened. Descriptive analysis from the household survey showed that in Metro, 32% (n = 18) of the surveyed dug well owners had to deepen the dug well at least once. Also in Bekasi, where boreholes were prevalent, the well/borehole and/or pump setting was deepened by 13% (n = 33) and 10% (n = 25) of the surveyed households, respectively (Table E in S1 Text). The well/borehole had gone dry in the past 12 months for 30.4% (n = 7) of the 23 responding households in Bekasi, and in 18.6% (n = 11) of the 59 responding households in Metro (Table J in S1 Text). Half the in-depth interview informants were not satisfied with the water availability of dug wells and explained that dug wells were often deepened or replaced with a borehole, since dug wells dry out during dry season. For example, one informant in Metro described it as follows "*In the dry season, water from the well is like a kid peeing*". Another informant in Metro had to deepen the dug well several times, as he said: *"[The] first [deepening] was 4m due to drought, [after another] deepening, the water came out [and] it was clear. Again drought [came], [so the dug well was] deepened again to 6m [depth], again drought, again deepened 2m, it [the water] was clear. Now the water is in a constant high flow, but the color has changed [no longer clear].*"

Reasons for non-use. Reasons for the non-use of dug wells were connected to the amount of work involved, the large space required, unsatisfactory water quality and availability and lack of protection for children. Dug wells were often used with a bucket and rope or hand pump, which was associated with a higher workload than using a borehole with a motorized pump. One informant explained *"The dug well was often dry. Draw water was tiring, [so we] replaced the dug well with a borehole and a Sanyo pump [Sanyo: Brand of a motorized water pump]. The Sanyo pump is more practical, [since it] doesn't need human power.*" Compared to bottled or refill water, water from dug wells needed to be boiled before consumption, which was also associated with a higher workload. Eight informants elected not to use their dug wells because of the workload, as one widow explained: *"[In the past], when [I was] still strong, [I] looked for wood to boil [the water]. The wood was abundant. Now [I am] no longer strong enough to boil water, so [I] buy water in gallons.*" Descriptive results from the household survey on the fuel used for boiling water showed that liquified petroleum gas (LPG) was the most common fuel for water boiling in Bekasi (96%, n = 288) and Metro (96%, n = 287), however wood was still used by 28.1% (n = 84) in Metro (Table F in S1 Text). Another informant who owned a dug well instead used refill water for drinking, since well water used for drinking needed to be boiled and it was turbid during rainy season: *"[Usually] I'm too lazy to boil the water. [But] when I boil [the water], [I] usually let it [the water] stand first to let the dirt settle to the bottom of the container."* Dug wells were also perceived by two informants as being unsafe for children: "*Dug wells can be worrying because there are many children who could fall into the well.*" A further reason for the replacement included that dug wells required larger land area than boreholes: "*Dug wells are no longer used because they require more open land and are not safe for small children.*"

Private borehole. *Use*. Private boreholes were mostly used as a water source for drinking and domestic purposes in Bekasi, but were also frequently used in Metro. Descriptive analysis from the household survey showed that water from private boreholes was used for drinking (Bekasi: 48%, n = 144, Metro: 13%, n = 39) and domestic purposes (Bekasi: 72%, n = 217, Metro: 21%, n = 61) at both study sites, but particularly in Bekasi (Table 1). Of the 24 households participating in the in-depth interviews in Bekasi and Metro, 12 households owned a private borehole. Of those, 11 households used it for drinking and 10 for domestic purposes. Informants also reported that borehole water was an important source of water not only for drinking, but also for daily needs: *"Borehole water is used quite a lot for washing clothes [and] watering plants. For daily needs [it is] collected in a large tub."* In the past, households often used dug wells, which have been replaced by a borehole with a motorized pump, as one respondent explained: *"It is more practical, [I] don't need to draw water, the water flows out directly from the tap."*

Water quality. The quality of water from private boreholes was mostly perceived as good though water was still commonly boiled. A deterioration of water quality was, however, perceived during rainy season. Two-thirds of the interviewed households perceived water quality from boreholes as clear and good, as for example one respondent said "*The dug well is not closed, but the well that is being used is a borehole. The borehole is equipped with a Sanyo pump. The water from the borehole is good, the water is clear.*" One respondent mentioned the importance of using clean water for the religious purification ritual and linked this use with safety for drinking, *"The important thing is that the water has no odor. If the pure water can be used for wudhu [ritual purity for Muslim], it is drinkable."*

All interviewed households reported boiling the water from boreholes before drinking and a few respondents linked the boiling of water to potential health concerns. *"[When] the water is boiled, [it] does not make you feel sick to the stomach."* A difference between boiled and non-boiled borehole water was also perceived by another informant, as he mentioned *"the children said that the non-boiled water spoils the stomach."*

However, three interviewed households perceived an increased risk of water contamination compared to the past, as one informant noted: "*The water is good, [it is] safe to drink, but when [it is] raining there is white colored dirt. Back then, when [we were] using [a] dug well with a bucket, there was no white [colored dirt], the water remained clear*." Another informant linked the contamination directly to a potential source: *"After the landfill exists, the water from the drilled well is getting oily."*

Some potential risks for water quality deterioration were mentioned during the interviews. If asked whether the motorized Sanyo pump is submerged in runoff during rainfall, one respondent replied: *"Yes the Sanyo is soaked. There is a roof as cover for the pump."* Further, a few respondents indirectly indicated a potential issue of bacteria growth in pipes from boreholes, as one respondent explained, *"The tube is cleaned once a week. It becomes slimy after a while. There is moss inside the tube. I saw it myself, when I saw the water from Sanyo, it was slimy on the inside of the tube, sometimes it is cleaned. [I am] afraid that the moss will get thicker the longer it goes. [I am] afraid that the tube will get clogged. Then it becomes more work."*

Water availability. Results from the household survey suggested self-supply provides a relatively reliable service, but the in-depth interviews revealed water scarcity problems during the dry season, and therefore households often shifted from shallow dug wells to deeper boreholes. In the household survey, 97.2% (n = 176) and 97.0% (n = 258) households reported to have water available the past two weeks in Bekasi and Metro, respectively (Table I in S1 Text). However, ten in-depth interviewed households had replaced the dug wells with boreholes, partly for the reason to improve the water availability. An informant from Bekasi explained, that people in Bekasi use boreholes, because the water is better and more reliable. In Metro, availability of water was noted to improve when a dug well was replaced with a deeper borehole: *"Initially, [I] used a dug well [with a rope and bucket]. But when it is dry, there is often no water. So I started using a borehole (35 m) three to four years ago. The dug well is about 10m deep, and if the well is dug again, it will collapse, so I don't dare [to deepen the dug well]."* Three in-depth informants reported that even with boreholes, water shortages were still experienced during dry season, *"[Water from the] borehole is decreasing during the dry season for at least one month. It [the location of the borehole] has been moved three times. [Previously, when it was] next to the house bedroom, it was equipped with a hand pump. Now the borehole is located at the house yard*." or "*Last dry season, the water from the well decreased and one had to wait a while for water to come out after turning on the Sanyo pump. The Sanyo pump was lowered once*".

To counteract availability issues and to save time, some households stored the collected water from boreholes. One respondent with a 100 liter storage container explained: "*So, it won't take long. After it is used for washing, showering, there is still some left. If the lights go out [no electricity], the remaining water can still be used*." Another household reported to store the water after boiling, as he said "*Drinking water after being boiled is collected in a bucket with a volume of 30 liters for about 5 days*."

Reasons for non-use. Private boreholes were a preferred source of drinking water for most households in Bekasi, however boiling water can be tiring and households typically used multiple water sources for different purposes. One main reason for the switch to refill water for drinking was linked to the hassle of boiling the borehole water, as for private dug wells. "*For drinking, the process is long. [The water] must be boiled first. Sometimes turning on the stove first. So that is quite something*." One informant even reported a deterioration in water quality due to boiling using firewood, as he said, "*Every week I boil two gallons of water and store the boiled water in the clean gallon. [I] put it first in the pan and then pour it into the gallon. The special characteristic of the boiled water is smoky, because it is boiled using firewood."* Households used multiple water sources for different purposes, as one informant said, "*For drinking, it is refill water. But when it comes to making tea, it is borehole water. And that is not much, one teapot at most*." Even if informants used borehole water, alternative sources provided a useful back-up option, as one informant proposed: *"Maybe we can use both, the water from the artesian well and [the water] from the borehole. For backup, one could say. If the water from my borehole fails, that means the water from the artesian well is available, right."* One respondent mentioned the possibility to get access to clean borehole water from mosques, *"If they don't have a well, it will be difficult. Sometimes, they also go to the mosque. There is government aid [subsidies] for [drilling] boreholes [in mosques]. Take the water from there. If it is in the mosque, it is free. And mosques can get a discount from PLN [State Electricity Company]."*

Another reason for the non-use of private boreholes was the high cost of construction. In the household survey, 24.0% (n = 12) of respondents in Bekasi and 39.4% (n = 13) of respondents in Metro reported high construction costs as a reason for not using private boreholes (Table G in S1 Text). In the in-depth interviews, one dug well owner in Metro stated the cost of seven million rupiah (approximately 460 USD) as a reason for not using a private borehole. Another respondent in Metro, when asked why he did not use a borehole, replied, *"Yes, later. I am waiting for the [money] transfer"*.

One informant expressed his concern regarding the increasing use of boreholes: *"If everyone uses boreholes, it would be a pity for the one without. So it can be dry, left and right. I think there needs to be a regulation. Except, if the neighbor doesn't have any water, he gives it, it is okay maybe, there is a solution. Now if they are using boreholes, maybe it is just for them, right? Left and right neighbors can't get water, it is a pity thing."*

Public water services. *Use*. A few households used public piped systems as a water source to supplement self-supply for domestic purposes, but most households did not have access to public piped systems. Descriptive analysis from the household survey showed that public water services, including public boreholes, dug wells, piped systems and taps, were commonly used as a main source of water for domestic purposes (Bekasi: 20%, n = 60, Metro: 9%, n = 26). However, 75% (n = 224) and 36% (n = 101) households reported that public piped service does not supply water to this area in Bekasi and Metro, respectively (Table G in S1 Text). Of the interviewed households, 13 did not have access to public piped services fed either from surface water or groundwater from artesian aquifers. Eight households used water from public piped water supplies. The water was not used for cooking or drinking, but as an additional source of water to supplement and backup self-supply for daily needs only, such as washing or watering plants. "*Given piped water is okay for flushing, for washing motorbikes, for washing bicycles.*"

One informant in Metro who was offered access to the piped network in front of his house did not use it and described the situation as follows: "*Why should I use piped water? Well water is enough, there is no shortage. If you use public piped water, you will spend more money. The water from public piped water should be boiled, which means more work. Neighbors who use the public piped service may experience shortage during the dry season. [. . .] Then the water quality is also bad. It can be black, and sometimes it smells. So people don't use it for cooking. Usually they use it for watering flowers. That is all people say. I don't use piped water anyway.*

Water quality. Water quality of public piped water supplies was perceived negatively by households that had access and households that did not have access. *"That is public piped water. The water is likely black-colored. If it is clear, it is clear, sometimes it is really black. In the rainy season, it is cloudy, it is black."* Another informant who did not have access said *"The informants are not interested in public water services from artesian wells because the quality is not good. Public water service, it is lacking, the water is bad. Lots of sand."* Therefore, the water was generally not used for drinking or cooking, as one informant said: *"Water is just for washing. For cooking or drinking, it is not quite suitable."* Also the smell of chlorine was unfavourable for consumers, as a respondent explained: *"Everyone here has public pipes installed, but the water is bad. The water is a little cloudy. Second, the smell of chlorine. So not all of us use public water services. So, in the end it stopped. In 1995–1996 there was no public water service."*

One informant who used the public supply which was connected to his sibling's house was happy with the quality, as he said *"Same taste, same clearness, but not every day [the water flow] is smooth"*. He did not have to pay and saw the connection as beneficial. *"There are many benefits, saving a lot of electricity. Sometimes [I] wash [e.g. laundry, not showering] using water from public water services."*, he said.

Water availability. Problems were identified with public piped water supply in terms of access, reliability and availability of water. Many households still did not have access to a piped water service, and some were not even aware of this as a water supply option, with an informant replying: "*There isn't one. It is in the village, not in the city*." Public piped water did not reach all households equally; therefore, not all households could get access to pipe connections, as for example one informant said *"My house is far from the road, so I can't get a pipe from the government or urban village. My house is inside, so the connections are far away"*. Another respondent from the same district mentioned the same issue "*The pipe network is unevenly distributed. Here too. There is no pipe. The artesian pipes are mainly located only next to the main road. It is said that it will be installed gradually, per community association (RT–rukun tetangga). It is said that the pipe network installation for my community association will be done later. But after some time, it is not installed yet. But it is alright."*

A decrease in the water availability was also perceived from public piped services based on groundwater, "*In the dry season, water from artesian wells also decreases, so the distribution must be in shifts."* Public water service is also not always reliable, as one informant said "*Water from public water services does not always flow, the benefit is saving electricity usage*." Another informant mentioned that the public piped supply was broken since a long time. *"Previously there was piped water from the landfill artesian well [artesian well was constructed as the compensation of the new landfill], but it had been damaged for a long time by a neighbor's children. Water from the artesian well was used only for washing, not for drinking."*

Reasons for non-use. Most households did not have the possibility to connect to public piped services because they were not available in these regions (Table G in S1 Text). However, if available, public piped services were generally not used due to several reasons such as lack of trust, lack of reliability, perceived bad smell of chlorine, costs, and the preference for self-supply water. Descriptive results from the household survey showed that most households would not connect if public services were to expand infrastructure to their area (Bekasi: Definitely not n = 108, 38%; Metro: Unlikely n = 132, 52%) (Table H in S1 Text).

A major reason for not using piped water was the general preference of groundwater self-supply. Three respondents associated the preference for private supply over public supply with the taste of chlorine, *"Well water is better because if water is from public piped service, there is a taste of chlorine, maybe we are not used to chlorine. The well water has no [chlorine taste]. It is pure."* Respondents connect the taste of chlorine with medicine, *"It tastes different, smells like medicine. What smell, I don't know. It does not smell good."* One respondent mentioned a preference for groundwater supplied from public boreholes owned by mosques compared to the chlorinated public piped water because of the chlorine taste *"Once, I opened it [public piped service], the water was not good. Maybe too much chlorine. Medicine [refers to chlorine] is added to the public piped water, right? This morning, I took the water at the mosque because I avoided the chlorine. We are not used to the smell of chlorine. Water from the mosque is good, [it is] from boreholes, a support from the mosque. The borehole is a government aid. I only take two gallons to boil drinking water. However for washing clothes and showering, we use water from the dug well."*

Public services were also not perceived as reliable sources of water for some households, as one informant said *"People who get artesian piped water also have [private] wells, because artesian water doesn't always flow every day, it just flows at midnight. What is the point if the water only flows at night."*

Respondents did not want to pay for bad public services, if they already had access from self-supply. *"If I had to pay, I would change my mind. Roughly speaking, only for daily needs we made the effort [and] dug [the well]. For Sanyo water [from private borehole], we do not need to pay for as much as we use."* However, if water from public supply were reliable, people would also be willing to connect, as one informant said "*I also want to pay as long as the water is good and abundant, proportional to the usage. It is natural if we use it [public piped water]. The [use of the] public piped water is the recommendation of the government."*

Packaged water. *Use*. Packaged water was frequently used as a drinking water supplement for self-supply. Refill water and branded bottled water were commonly used as a main drinking water source by households in Bekasi (21%, n = 63) and Metro (21%, n = 61). Of the 24 interviewed households, six households mentioned drinking refill water and seven bottled branded water. Many households used refill water as a backup for self-supply, as one informant explained *"[I] buy gallon water—refill water—when there is no more water."*

Packaged water was considered as practical and hassle-free, since it did not need to be boiled. *"The refill water [is practical] if you want to have an event, any gathering, just buy refilled water. Let it be easy, let it be practical, that's it. The drinking water for families is still boiled water."* Thus, informants also drank bottled water if they got invited *"when I go to a wedding invitation, I drink bottled water. Therefore, I know that bottled water is tasteless."* It was also consumed if household members did not wish to go to the effort of boiling water. *"[I am] already not strong enough to boil water, so [I] buy gallon water, [it costs] 5000 rupiah."*

Water quality. Water quality of bottled branded water was perceived as good, while some respondents believed refill water led to health issues. Water quality of bottled branded water was perceived as good by seven of eight in-depth informants. However, 11 of 14 informants perceived the water quality of refill water as poor. Refill water consumers needed to get used to the taste, as one informant elaborated *"According to my tongue, the taste is different. I'm more confident with boiled water, out of habit, maybe. Habit from childhood.*" However, other respondents might already be used to the taste. *"The taste of gallon water and well water is the same."* Many refill water consumers reported health issues and feeling bloated after drinking it, as one informant said: *"Before, I wasn't used to it, I had a bloated stomach. Now I'm used to it [and my stomach is] no longer bloated."*

Reasons for non-use. Generally, the self-supply water source was preferred, which was often because of the taste. *"I have never bought it... it tastes better when I boil it myself..."* or *"My water source is already good and clear. I don't want to use refill water. I tried refill water, it is the same. But I and my children feel that refill water is tasteless. It is better to use my own source."*

Other informants had no trust in refill water and experience health issues, as one informant elaborated, *"[There are] many fake branded bottled water, [I] had a stomachache. [I] experienced it myself when I went to Cirebon by bus [and] bought [a water bottle] from a street vendor,* *many were fake. The water was a bit cloudy and the taste was different. The branded bottled water has a hint of sweetness"*. Also in the household survey, 29% (n = 57) and 38% (n = 81) of households reported as a main reason for the non-use that refill water is unsafe to drink.

Reasons for non-use were also the costs, with packaged branded water having higher costs than refill water. "*Refill water is 7 thousand rupiah. Branded bottled water is more expensive, 17 thousand rupiah. People say branded bottled water is good. My child also likes boiled water."* Even if refill water was seen as more practical, it could not always be used because of the cost, as one informant explained, *"Refill water is more practical. After eating, [I] don't have to bother boiling water or looking for a water container. There is refill water available, then it is okay. But if there is no money at all, then [I] have to boil water, just one teapot"*.

Attributes of water perception

Descriptive analysis from the household survey indicated that safety was the most important attribute for drinking water choice, followed by taste and appearance at both study sites (Table 2). The most important attribute for domestic water choice was appearance, followed by reliability and safety in Bekasi, and safety followed by convenience and reliability in Metro (Table 2).

Descriptive results from the household survey were in agreement with the qualitative results from the in-depth interviews. Households perceived water as safe, if the consumption was not related to disease or pain, as one informant said, *"The currently used water is safe, in the sense that it does not cause pain."* Another informant mentioned taste and appearance as important attributes of safe water, *"Safe water is like gallon water, clear, tasty, cool, fresh."* That taste is considered more important than appearance when choosing drinking water was also noted by a statement of a dug well owner in Metro, who said "*I'm just afraid, the color isn't very clear, that is how it is. But [the water from the dug well is] still used for drinking because it doesn't smell.*"

Self-supply management

Responsibility, workload and decision-making. Water management tasks of self-supply services were usually distributed between female and male household members. Based on the descriptive results of the household survey, female household members were mostly responsible for managing water in home, while male household members were mostly responsible for maintenance and repairs, cleanliness of source and finance at both study sites (Fig 2). Approximately two-thirds of the surveyed households shared the responsibility of self-supply tasks

Table 2. Most important attributes for drinking and domestic water choice in Bekasi and Metro.

	Most important attribute for drinking water choice						Most important attribute for domestic water choice					
	Bekasi			Metro			Bekasi			Metro		
	n	[%]	95% CI [%]	n	[%]	95% CI [%]	n	[%]	95% CI [%]	n	[%]	95% CI [%]
Safety	125	41.7	36.0–47.6	116	38.8	33.1–44.8	61	20.4	14.7–26.4	84	28.2	19.0–29.4
Taste	68	22.7	17.0–28.6	85	28.4	22.7–34.4	11	3.7	0.0–9.7	85	28.5	19.3–29.7
Appearance	48	16.0	10.3–21.9	31	10.4	4.7–16.3	89	29.8	24.1–35.8	32	10.7	4.0–14.5
Reliability	24	8.0	2.3–13.9	16	5.4	0.0–11.3	84	28.1	22.4–34.1	46	15.4	8.0–18.5
Affordability	9	3.0	0.0–8.9	12	4.0	0.0–10.0	9	3.0	0.0–9.0	16	5.4	0.0–9.9
Convenience	15	5.0	0.0–10.9	15	5.0	0.0–11.0	30	10.0	4.3–16.0	65	21.8	13.5–24.0
Smell	11	3.7	0.0–9.6	24	8.0	2.3–14.0	15	5.0	0.0–11.0	20	6.7	0.6–11.0
Total	300	100.0		299	100.0		299	100.0		298	100.0	

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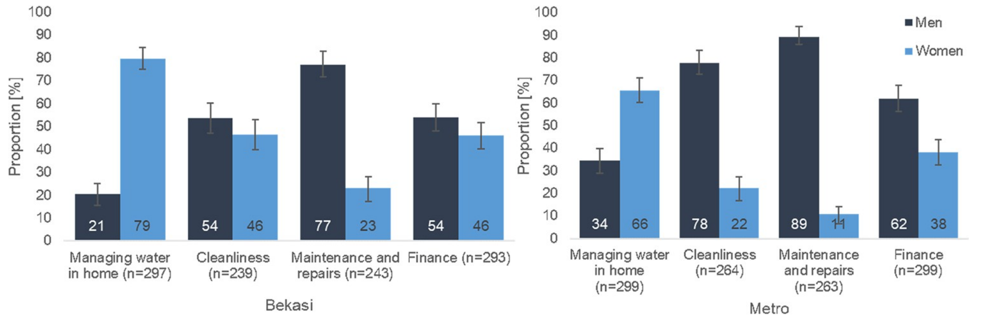

Fig 2. Responsibilities of self-supply tasks based on gender in Bekasi and Metro.

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between household members at both study sites (Fig 3). In one-third of the surveyed households in Bekasi, either only one male household member or one female household member was responsible for all the tasks. In Metro, it was more common for male household members to be solely responsible for all the tasks than female household members. Decisions related to self-supply were usually made jointly or were solely the responsibility of a man. In nearly half of the surveyed households in Bekasi, solely a man decided to invest in the construction of a dug well or borehole (Fig 3). In approximately 12% of the surveyed households, a woman solely decided to invest and in 24%, the decision was shared between different household members. In Metro, the decision-making was mostly joint by 67% of the households surveyed. In 25% of households, a man was the sole decision-maker, while in 8% of households a woman was the sole decision-maker.

Household members usually cooperated on responsibilities and workload of self-supply services. One male informant explained, *"I handle all the tools [tools to repair the well]. I'm the one who bought the Sanyo, installed it and turned it on. The boiling is the part of the wife. If there is any damage [of the well], it is my part [to repair it]. Yes, [it is] team work."* Responsibilities were typically distributed such that the wife was responsible for managing the water in the home, while the husband took the lead in maintenance and repairs, cleanliness of the source, and

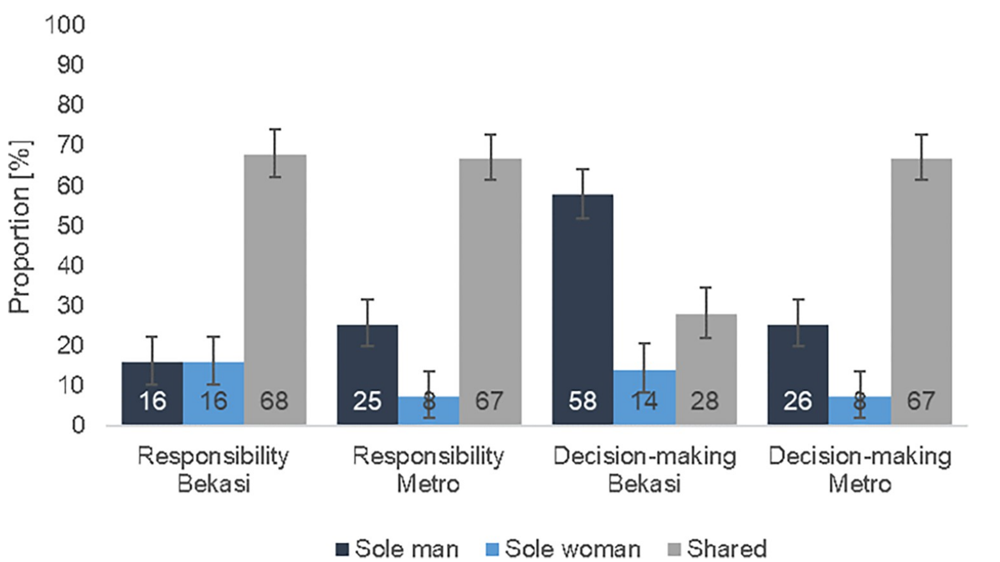

Fig 3. Distribution of self-supply responsibilities and decision-making by gender.

https://doi.org/10.1371/journal.pwat.0000070.g003 finance. One woman in Metro reported that when her husband was still alive, he never boiled water to drink and that mostly women take care of the housework. "*It is all me. My husband was just making money. My husband only helped sweeping the floor and not cooking. Cooking is women's thing. Housework is women's thing. The husband only helped cleaning the house, when he was not working. If there were no activities, [the husband] helped in the house, cleaning up. However, I think a lot of women take care of the house."* Also specific tasks were shared amongst household members, as for example one wife told that she and her husband shared the responsibility to clean the bathtub. "*If I see a dirty bathtub then I clean it. We always take turns to do it."* Broken pumps were usually repaired by external mechanics, as one woman told, "*Since I have lived [here], the pump has broken once. [I] called someone to fix it* ". Also a male informant from Metro told: "*Boiling water is done together with the wife, washing is also done together. This morning, my wife was washing dishes, I was washing clothes."*

However, some respondents had specific gender norms and expectations regarding the roles of women and men. One woman said, "*Water is my responsibility, wife's job is at the kitchen then husband just eat."* When a women in Metro was asked why the man would not boil water, she replied: *"Seriously, the man who boils water? Have you ever imagined a man boiling water?"* The informant laughed and said, "*No need. It is simple. Just turn the stove button, that is all. Take water, it is not difficult.*"

Widows, people who were living alone and families with members with special needs faced increased challenges regarding workload. One widow said, "*[if] there is no male, it is difficult, there is no head of the family."* Children were often helping with household chores, even with special needs. "*My last child has special needs. She is just helping what she can. She can turn off the stove. Sweeping floor after waking up and after eating [she] does the dishes by herself. That is all she can do. She has only been able to walk for three months, previously she used a wheelchair."*

Decision-making related to self-supply was typically the responsibility of the head of the household. However, a few households reported a joint decision between household members related to self-supply. One woman explained that her husband determined the location of the well, but she made decisions related to household matters. She further explained, "*That is my husband's responsibility when the gas runs out. He is the one who is making money. I said we were running out of gas, so he told me to just buy it, then I bought it."*

Households usually share the water with the neighbors if they ask for it, when their well is dry or has bad quality. One informant in Metro elaborated "*In fact, sometimes the neighbor's well is dry. So they asked [for water] here."* When the dug well is dry, an informant in Metro explained "*Usually I take water from my neighbors for two or three days, only for drinking. For showering or other things, I usually go to Ayuk [older sister's] place."* Another informant in Metro answered when asking what if a neighbor asks for water and how many have asked for: "*It is okay. Poor them. The water is turbid. A lot [have asked for water]. Ten houses. They draw it [the water] up themselves and use a jerry can to bring it home by motorbike."* However, one informant who relied on polluted water from a dug well decided to drill a borehole since he no longer felt comfortable to ask neighbors for water.

Discussion

Self-supply provides a valuable informal on-premises water service for households in Bekasi and Metro. The question then arises, to what extent self-supply could support achieving and sustaining the SDG 6.1 target of safely managed drinking water for all. The study identified the overall preference for self-supply over alternative water sources, as well as a common perception that water from private boreholes is of good quality. The water quality perception partially aligns with the water quality results, which indicated on the one hand that boreholes provided higher quality water than unprotected dug wells, but on the other hand showed *E. coli* contamination in 55% of boreholes [12]. This study showed that households used coping strategies for water quality and availability problems, such as treatment and storage practices, as well as the replacement of shallow dug wells with deeper boreholes. Boiling water before drinking was shown to be widespread in Bekasi and Metro and was found to improve the water quality between source and point-of-use [12]. The water treatment step, including costs and resource use must be considered in the discussion of whether self-supply provides a safely managed water service. In terms of water availability, household survey results showed that water from dug wells were available the past two weeks during wet season in Bekasi, and dry season in Metro. However, qualitative results of this study showed that half the interview respondents were not satisfied with the water availability of dug wells and explained that dug wells were often deepened or replaced with a borehole, since dug wells dry out during dry season. Supporting households to invest in reliable as well as safe forms of self-supply such as boreholes, could reduce availability and quality issues and contribute towards reaching SDG 6.1.

Water treatment is essential for self-supply to be considered a safely managed drinking water service. The study showed that boiling of self-supplied water before consumption was widely practiced. Boiling is the most prevalent household water treatment and effectively removes waterborne pathogens, but also has limitations such as the associated workload, fuel costs and household air pollution caused by the fuels to boil water [38]. In Bekasi and Metro, LPG was the most frequently used fuel for water boiling, however wood was still used by 28% (n = 84) of households in Metro. Among the primary global health risks, household air pollution is ranked eighth, ahead of unsafe water, which ranks 14th [39]. This highlights the need to promote the use of safer fuels or electricity for water boiling, or better still, promote other household water treatment technologies such as filters. Results from the household survey of this study indicated that all households use boiling for self-supply water treatment. However, a study in peri-urban Cambodia suggested that actual use of boiling for drinking water treatment may be lower than self-reported use [40]. Qualitative results of this study showed that the labor involved in boiling water could not always be managed, so households must resort to alternative water sources. The study showed that refill water from refill water depots was frequently used as an alternative water source, since many households believe it does not require boiling and is therefore more convenient. However, some respondents perceived health issues from drinking refill water. Convenience has also been suggested as a reason for using unsafe bottled water by a study of Cohen et al. 2017 in China, which examined the predictors of drinking water boiling and bottled water consumption. To safely manage self-supply, low-cost, efficient and convenient treatment strategies are necessary. The promotion to switch from boiling with pots towards electric kettles could have a positive impact [38]. However, one-time investment cost and associated electricity costs could be barriers to adaption. To support self-supply for better health impact there is also an opportunity to enhance the adoption of other household water treatment technologies, such as chemical, filtration or ultraviolet, taking into account user preferences [41].

Household management of self-supply showed high levels of cooperation between women and men, which is an important consideration in enhancing and sustaining safely managed drinking water services. Although traditional gender roles were still prevalent, the results from the in-depth interviews showed that the division of labor in managing self-supply was mostly shared between different household members of different genders. However, socially constructed norms mean women and girls disproportionately shoulder the burden of unpaid care and domestic work associated with sub-standard water services [42]. A meta-analysis across 45 developing countries found that in 72% of households, collecting drinking water was the task of women and girls [43]. Since women are often the main users and beneficiaries of water service delivery in the household and generally bear the burden of labour [24, 44–46], it is often assumed that they have a vested interest in its success and their involvement in decision-making will lead to better performance [47]. Several studies in different countries confirm the positive correlation between the participation of women in water committees and improved functionality of community-based water systems [47–49]. However, these studies on women's participation and water service functionality have tended to focus on the community sphere, while self-supply management takes place within the household sphere. In this study, in the household sphere, certain gendered norms and roles were also visible, with women generally responsible for household water treatment, and men more often responsible for maintenance and financial matters. Household decision-making was predominantly shared in one study site, and predominantly by men in the other study site. Nevertheless, the cooperation between household members in terms of management and the shared strong interest in its success was such that operational sustainability was high.

To sustain self-supply services in the long-term, regulations are needed to protect groundwater availability and quality. It is challenging to retrospectively regulate already existing private self-supply infrastructure with individualized responsibility for risk management. Households participating in the in-depth interviews expressed concerns about declining water quality and availability. The depletion of groundwater and its increasingly negative impact on quality and availability, as well as worsening inequalities in access to safe water, are already known in greater Jakarta region [50–52]. The qualitative in-depth interviews of this study revealed that households that could afford to replace dug wells with deeper boreholes with a motorized pump as a response to groundwater problems. The shift towards higher-quality and more convenient services has also been observed in rural Bangladesh [53]. Fischer et al. (2020) viewed the shift towards on-premises piped systems and electric pumps as an opportunity to align user demand and payments with regulated services, since it is more politically palatable to provide new infrastructure over regulating the use of existing infrastructure. Licensing and standardization of drillers as well as education and demonstration on drilling and well installation could provide other approaches for regulation [54].

The feasibility of supporting and regulating self-supply towards a safely managed service should be weighed against other strategies, such as the investment in public piped services. Alternative water sources still provide an important source of water for households relying on self-supply, which should be considered in establishing sustainable supporting strategies for households [13]. This study showed that households often preferred water from self-supply over alternative water sources. Therefore, investment in public piped services comes with the risk of non-use. Households often viewed taste as the most important attribute for drinking water. This raises the prospect of households rejecting chlorinated water in favor of the unsafe option, as the chlorine taste from public water services was generally perceived as unpleasant. Other studies have also shown that taste plays a crucial role in drinking water choice and should therefore be considered in chlorination dosing guidelines for piped services [55]. Further, reliability was identified in the household survey as an important attribute for using water to meet daily needs, and in-depth interviews indicated that reliability was a reason for not using public piped systems. Safety was also rated as an important attribute for water choice, but compared to other attributes such as taste, reliability or appearance, the safety of a water supply is more difficult for households to judge. Accordingly, for households to connect to public water systems, trust must be created through provision of reliable and functioning services. The willingness of households to pay for connection fees and on-going tariffs will ultimately be determined by whether or not piped services meet the expectations of households, particularly in relation to the service attributes that they value most.

This study's explanatory mixed-methods approach provided a deeper insight into the overlooked aspects of purely quantitative or purely qualitative research on understanding of the use and non-use of self-supply. For example, qualitative findings provided further understanding on water availability problems and corresponding coping strategies of households. Half of the participants in the in-depth interviews expressed dissatisfaction with the availability of water from dug wells, particularly in the dry season, and explained that dug wells often had to be deepened or replaced with a borehole. Also, quantitative and qualitative results revealed contradictory findings, as quantitative results suggested that all households boil their self-supply water, while qualitative results indicated that the workload involved in boiling could not always been managed. This highlights the value of using mixed-methods to address limitations of solely quantitative and qualitative methods. Due to some study limitations, further investigations would be beneficial to inform strategies to support and regulate self-supply and weigh them up against other strategies to improve safety and reliability of public water services in urban Indonesia. While data on water quality of self-supply sources was collected [12], data on water quality of alternative water sources would be beneficial for determining the potential health implications of multiple source use. Furthermore, generalizations should be made with caution, as the use and choice of water sources may vary greatly by region and the study sites were selected based on the high prevalence of self-supply.

Conclusion

This study provides important insights into the use and management of self-supply in urban Indonesia. An improved understanding of how and why urban households self-supply their water is crucial for accelerating progress towards SDG target 6.1 in Indonesia. A mixed-methods approach was used, which allowed for more comprehensive findings and provided both broader and deeper insights into the use and management of self-supply than a purely quantitative or qualitative approach. This study found that households in Bekasi and Metro generally preferred groundwater self-supply water, but still used alternative water sources to supplement inadequate supply. Some considerations to support and regulate self-supply towards a safely managed water service can be concluded from this study: (i) self-supply use was connected with water boiling, which increased water quality at the point-of-use but came with an additional workload for household members and the potential use of fuel which is harmful to health; (ii) in response to groundwater availability issues, households that could afford it often switched from shallow dug wells to deeper wells with a motorized pump; (iii) there was little trust in quality of alternative water sources such as refill water and public piped systems; (iv) gendered intra-household dynamics varied across households, but showed cooperation between women and men and certain clearly defined roles in terms of responsibilities and decision-making. Strategies to improve the safety and reliability of self-supply should not only include the improvement of self-supply source infrastructure, but also consider the point-of-use including safe household water treatment and its management. Furthermore, the safety and reliability of alternative water supplies such as refill water and public piped system should be considered, as these supplies serve as a supplement to address groundwater quality and availability issues that will increase in the future.

Supporting information

S1 Text. Supplemental tables and figs.
(DOCX)

S2 Text. Inclusivity in global research.
(DOCX)

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References

1. Grönwall J, Danert K. Regarding Groundwater and Drinking Water Access through A Human Rights Lens: Self-Supply as A Norm. Water. 2020; 12(419):21. https://doi.org/10.3390/w12020419
2. Grönwall JT, Mulenga M, Mcgranahan G. Groundwater, self-supply and poor urban dwellers—A review with case studies of Bangalore and Lusaka. Hum Settlements Work Pap Ser—Water Sanit. 2010; 26:87.
3. Genter F, Willetts J, Foster T. Faecal contamination of groundwater self-supply in low- and middle income countries: Systematic review and meta-analysis. Water Research. 2021. https://doi.org/10.1016/j.watres.2021.117350 PMID: 34198198
4. Foster T, Priadi C, Kotra KK, Odagiri M, Rand EC, Willetts J. Self-supplied drinking water in low- and middle-income countries in the Asia-Pacific. npj Clean Water. 2021; 4(1):1–10. https://doi.org/10.1038/s41545-021-00121-6
5. Foster T, Shantz A, Lala S, Willetts J. Factors associated with operational sustainability of rural water supplies in Cambodia. Environ Sci Water Res Technol. 2018; 4(10):1577–88. https://doi.org/10.1039/C8EW00087E
6. Healy A, Upton K, Capstick S, Bristow G, Tijani M, Macdonald A, et al. Domestic groundwater abstraction in Lagos, Nigeria: A disjuncture in the science-policy-practice interface? Environ Res Lett. 2020; 15(4). https://doi.org/10.1088/1748-9326/ab7463

7. Butterworth J, Sutton S, Mekonta L. Self-supply as a complementary water services delivery model in Ethiopia. Water Altern. 2013; 6(3):405–23.
8. Sutton S, Butterworth J. Self-Supply: Filling the gaps in public water supply provision. Rugby: Practical Action Publishing; 2021. 356 p. https://doi.org/10.1088/1748-9326/ab7463
9. Foster S, Bousquet A, Furey S. Urban groundwater use in Tropical Africa—A key factor in enhancing water security? Water Policy. 2018; 20(5):982–94. https://doi.org/10.2166/wp.2018.056
10. WHO, UNICEF. Five years into the SDGs—Progress on household drinking water, sanitation and hygiene [Internet]. Geneva; 2021. Available from: https://www.oecd.org/dac/
11. WHO, UNICEF. Guidelines for drinking-water quality: fourth edition incorporating the first addendum. Vol. 53. 2017. 1689–1699 p.
12. Genter F, Putri G, Pratama M, Priadi C, Willetts J, Foster T. Microbial Contamination of Groundwater Self-supply in urban Indonesia: Assessment of Sanitary and Socio-economic Risk factors. Water Resour Res. 2022; 58. https://doi.org/10.1029/2021WR031843
13. Elliott M, MacDonald MC, Chan T, Kearton A, Shields KF, Bartram JK, et al. Multiple household water sources and their use in remote communities with evidence from Pacific Island Countries. Water Resour Res. 2017; 54:9106–17. https://doi.org/10.1002/2017WR021047
14. Daly SW, Lowe J, Hornsby GM, Harris AR. Multiple water source use in low- and middle-income countries: A systematic review. J Water Health. 2021; 19(3):370–92. https://doi.org/10.2166/wh.2021.205 PMID: 34152293
15. Kumpel E, Cock-Esteb A, Duret M, Waal O De, Khush R. Seasonal variation in drinking and domestic water sources and quality in port harcourt, Nigeria. Am J Trop Med Hyg. 2017; 96(2):437–45. https://doi.org/10.4269/ajtmh.16-0175 PMID: 27821689
16. Benneyworth L, Gilligan J, Ayers JC, Goodbred S, George G, Carrico A, et al. Drinking water insecurity: water quality and access in coastal south-western Bangladesh. Int J Environ Health Res. 2016; https://doi.org/10.1080/09603123.2016.1194383 PMID: 27277537
17. Kelly E, Shields KF, Cronk R, Lee K, Behnke N, Klug T, et al. Seasonality, water use and community management of water systems in rural settings: Qualitative evidence from Ghana, Kenya, and Zambia. Sci Total Environ. 2018; https://doi.org/10.1016/j.scitotenv.2018.02.045 PMID: 29454211
18. Özdemir S, Elliott M, Brown J, Nam PK, Hien VT, Sobsey MD. Rainwater harvesting practices and attitudes in the mekong delta of Vietnam. J Water Sanit Hyg Dev. 2011; 1(3):171–7. https://doi.org/10.2166/washdev.2011.024
19. Shaheed A, Orgill J, Ratana C, Montgomery MA, Jeuland MA, Brown J. Water quality risks of "improved" water sources: Evidence from Cambodia. Trop Med Int Heal. 2014; 19(2):186–94. https://doi.org/10.1111/tmi.12229 PMID: 24252094
20. Hoko Z. An assessment of the water quality of drinking water in rural districts in Zimbabwe. The case of Gokwe South, Nkayi, Lupane, and Mwenezi districts. Phys Chem Earth. 2005; https://doi.org/10.1016/j.pce.2005.08.031
21. Adeniji-Oloukoi G, Urmilla B, Vadi M. Households' coping strategies for climate variability related water shortages in Oke-Ogun region, Nigeria. Environ Dev. 2013; 5(1):23–38. https://doi.org/10.1016/j.envdev.2012.11.005
22. Kosinski KC, Kulinkina A V., Abrah AFA, Adjei MN, Breen KM, Chaudhry HM, et al. A mixed-methods approach to understanding water use and water infrastructure in a schistosomiasis-endemic community: Case study of Asamama, Ghana. BMC Public Health. 2016; https://doi.org/10.1186/s12889-016-2976-2
23. Nastiti A, Muntalif BS, Roosmini D, Sudradjat A, Meijerink S V., Smits AJM. Coping with poor water supply in peri-urban Bandung, Indonesia: towards a framework for understanding risks and aversion behaviours. Environ Urban. 2017; 29(1):69–88. https://doi.org/10.1177/0956247816686485
24. Acey C. Gender and community mobilisation for urban water infrastructure investment in southern Gender and community mobilisation for urban water infrastructure investment in southern Nigeria. Gend Dev. 2010; 18(1).
25. Carrard N, Crawford J, Halcrow G, Rowland C. A framework for exploring gender equality outcomes from WASH programmes. Waterlines. 2013; 32(4).
26. Caruso BA, Conrad A, Patrick M, Owens A, Kviten K, Zarella O, et al. Water, sanitation, and women's empowerment: A systematic review and qualitative metasynthesis. Vol. 1, PLOS Water. 2022. e0000026 p. https://doi.org/10.1371/journal.pwat.0000026
27. Cleaver F, Hamada K. "Good" water governance and gender equity: A troubled relationship. Gend Dev. 2010;
28. Mandara CG, Niehof A, van der Horst H. Women and rural water management: Token representatives or paving the way to power? Water Altern. 2017;

29. BPS. Statistics of Bekasi Regency [Internet]. 2021 [cited 2021 Sep 1]. Available from: https://bekasikab.bps.go.id/statictable/2021/07/17/2801/distribusi-dan-kepadatan-penduduk-menurut-kabupaten-kota-di-provinsi-jawa-barat-2017.html

30. BPS Kota Bekasi. Bekasi Municipality in Figures 2021. BPS Kota Bekasi. 2021;(1907.3763).

31. Bappeda Kota Bekasi. Rencana Pembangunan Jangka Menengah Daerah Kota Bekasi 2018–2023. 2018;

32. BPS Kota Bekasi. Bekasi Municipality in Figures 2019. BPS-STatistics of Bekasi Municipality; 2019. 352 p.

33. WageIndicator. UMP/UMK Jawa Barat [Internet]. 2022. Available from: https://gajimu.com/garmen/gaji-pekerja-garmen/gaji-minimum/ump-umk-jawa-barat

34. BPS Kota Metro. Metro Municipality in Figures 2019. 2019;(1907–4751):262.

35. WageIndicator. UMP/UMK Lampung [Internet]. 2022. Available from: https://gajimu.com/garmen/gaji-pekerja-garmen/gaji-minimum/ump-umk-lampung

36. Creswell JW, Chu P, Chang Y. Research Design: Qualitative, Quantitative, and Mixed Methods Approaches. J Soc Adm Sci. 2017;

37. National Population and Family Planning Board (BKKBN), Statistics Indonesia (BPS), Ministry of Health (Kemenkes), ICF. Indonesia Demographic and Health Survey 2017 [Internet]. Jakarta; 2018. Available from: https://dhsprogram.com/pubs/pdf/FR342/FR342.pdf

38. Cohen A, Zhang Q, Luo Q, Tao Y, Colford JM, Ray I. Predictors of Drinking Water Boiling and Bottled Water Consumption in Rural China: A Hierarchical Modeling Approach. Environ Sci Technol. 2017; 51 (12):6945–56. https://doi.org/10.1021/acs.est.7b01006 PMID: 28528546

39. Lim SS, Allen K, Dandona L, Forouzanfar MH, Fullman N, Goldberg EM, et al. Measuring the health-related Sustainable Development Goals in 188 countries: a baseline analysis from the Global Burden of Disease Study 2015. Lancet. 2016; https://doi.org/10.1016/S0140-6736(16)31467-2 PMID: 27665228

40. Brown J, Sobsey MD. Boiling as household water treatment in Cambodia: A longitudinal study of boiling practice and microbiological effectiveness. Am J Trop Med Hyg. 2012; https://doi.org/10.4269/ajtmh.2012.11-0715 PMID: 22826487

41. WHO. Results of Round II of the WHO International Scheme to Evaluate Household Water Treatment Technologies. World Heal Organ. 2019;

42. Grant M, Huggett C, Willetts J, Wilbur J. Gender Equality & Goal 6: The Critical Connection. Australian Water Partnership; 2017.

43. WHO, UNICEF. Progress on sanitation and drinking water—2010 update. 2010; Available from: http://whqlibdoc.who.int/publications/2010/9789241563956_eng_full_text.pdf

44. Brocklehurst C, Bartram J. Swimming upstream: Why sanitation, hygiene and water are so important to mothers and their daughters. Bull World Health Organ. 2010; 88(7):482. https://doi.org/10.2471/BLT.10.080077 PMID: 20616962

45. Fisher J. For Her It's The Big Issue: Putting women at the centre of water supply, sanitation and hygiene. Water Sanit Hyg Evid Rep. 2006; 36.

46. Fisher J. Women in water supply, sanitation and hygiene programmes. Munic Eng. 2008; 161 (ME4):223–9.

47. Mommen B, Humphries-Waa K, Gwavuya S. Does women's participation in water committees affect management and water system performance in rural Vanuatu? Waterlines. 2017; 36(3):216–32.

48. Van Wijk-Sijbesma C. The Best of Two Worlds? Methodology for Participatory Assessment of Community Water Services. IRC International Water and Sanitation Centre; 2001.

49. Foster T. Predictors of sustainability for community-managed handpumps in sub-saharan Africa: Evidence from Liberia, Sierra Leone, and Uganda. Environ Sci Technol. 2013; 47(21):12037–46. https://doi.org/10.1021/es402086n PMID: 24111486

50. Delinom RM. Groundwater management issues in the Greater Jakarta area, Indonesia. Groundw Subsurf Environ Hum Impacts Asian Coast Cities. 2008;(8). https://doi.org/10.15068/00147302

51. Kooy M, Walter CT, Prabaharyaka I. Inclusive development of urban water services in Jakarta: The role of groundwater. Habitat Int. 2018; 73:109–18. https://doi.org/10.1016/j.habitatint.2016.10.006

52. Furlong K, Kooy M. Worlding Water Supply: Thinking Beyond the Network in Jakarta. Int J Urban Reg Res. 2017; 41(6):888–903. https://doi.org/10.1111/1468-2427.12582

53. Fischer A, Hope R, Manandhar A, Hoque S, Foster T, Hakim A, et al. Risky responsibilities for rural drinking water institutions: The case of unregulated self-supply in Bangladesh. Glob Environ Chang]. 2020; 65:102152. https://doi.org/10.1016/j.gloenvcha.2020.102152

54. Jamil NB, Feng H, Ahmed KM, Choudhury I, Barnwal P, Van Geen A. Effectiveness of Different Approaches to Arsenic Mitigation over 18 Years in Araihazar, Bangladesh: Implications for National Policy. Environ Sci Technol. 2019; 53(10):5596–604. https://doi.org/10.1021/acs.est.9b01375 PMID: 31033281

55. Smith DW, Islam M, Furst KE, Mustaree S, Crider YS, Akter N, et al. Chlorine taste can increase simulated exposure to both fecal contamination and disinfection byproducts in water supplies. Water Res. 2021; https://doi.org/10.1016/j.watres.2021.117806 PMID: 34768105

5.3 Summary

Chapter V addresses RQ2 by offering insights into the use and management of groundwater self-supply systems in the urban areas of Bekasi and Metro in Indonesia. The findings indicate that households in these cities generally preferred groundwater self-supply over other available water sources, and there was a sense of cooperation among users in managing the water supply. However, self-supply users perceived poor water availability during the dry season. In addition, the study revealed that the workload of users involved in water treatment could not always be managed, leading to the subsequent use of unsafe and more expensive alternative water sources. These findings underscore the need for increased awareness and support for the sustainable management of groundwater self-supply systems in urban areas, with particular attention to the household level.

In contrast to the other chapters, this chapter has a strong focus on the 'Users' and 'Interactions' component, which is crucial as self-supply is privately owned and in the household's own responsibility. Considering not only the 'Water resources' and 'Infrastructure' components, but also the household level including the components of 'Users', 'Interactions' and 'Self-supply water service outcomes' is essential when establishing support strategies to move self-supply towards a safely managed water service.

6. Monitoring of self-supply services

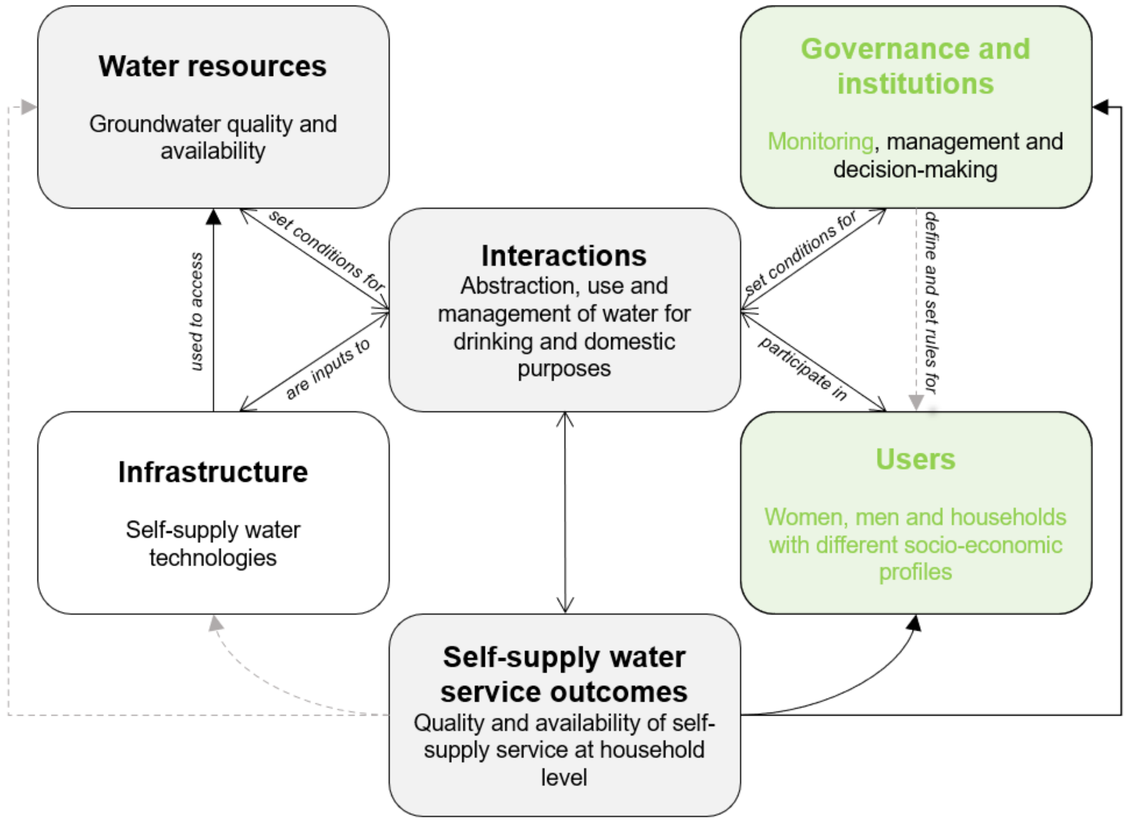

Figure 9: Chapter VI focuses on the water quality monitoring of self-supply services in urban Indonesia and addresses RQ3 by evaluating a participatory monitoring approach and presenting its benefits and limitations. The evaluation and findings are primarily situated within the components of 'Governance and institutions' and 'Users', but also focus on the 'Water resources' and 'Self-supply water service outcomes' components, with an emphasis on monitoring.

6.1 Overview

Chapter VI addresses RQ3, which seeks to understand to what extent participatory citizen monitoring is an appropriate approach to monitor self-supply services in terms of microbial water quality. The chapter consists of one publication, which was published in the *Urban Water Journal* in 2023 (Publication V). The evaluation and findings are situated within the 'Governance and institutions', 'Users', 'Self-supply water service outcomes' and 'Water resources' components with a strong focus on monitoring (Figure 9).

Publication V has important implications for informing government decisions regarding self-supply in urban Indonesia by presenting a household-led monitoring approach in self-supply contexts and its potential benefits and limitations.

6.2 Publication V

Publication V and its supplementary materials are available open access at https://doi.org/10.1080/1573062X.2023.2285438 (Genter, Putri, Handayani, et al., 2023).

Urban Water Journal

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Evaluation of a participatory citizen approach to monitor microbial water quality of self-supply in urban Indonesia

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ABSTRACT
A participatory citizen approach was established to monitor microbial water quality in household self-supply in Bekasi, Indonesia, and evaluated using a conceptual framework for context analysis, process evaluation and impact assessment (CPI). Households tested their self-supplied water for *Escherichia coli* presence every two weeks for six months, accompanied by pre- and post-monitoring surveys. The approach provided reliable water quality results, and increased awareness of water quality; however, nearly half of the households dropped out of the monitoring and increased awareness did not translate into actions that improved water quality within the study period. Contamination rates ranged from 11% to 70% at source and from 15% to 44% at point-of-use. Household-led testing could fulfil an important monitoring role in self-supply contexts, however it may have little impact on the drinking water safety unless accompanied by support to improve source protection and strengthen household water treatment and storage practices.

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Self-supply; water quality monitoring; microbial water quality; participatory monitoring; citizen science

Introduction

More than 1 billion people worldwide secure their household water supply through self-supply (Chávez García Silva et al. 2020; Foster et al. 2022, 2021). Self-supply refers to an on-premises water source, usually groundwater or rainwater, that is privately owned, financed and managed by an individual household (Grönwall, Mulenga, and McGranahan 2010). Self-supply has developed in low- and middle-income countries (LMICs) in a variety of different contexts such as densely populated urban areas as well as remote rural settings (Foster et al. 2021; Genter, Willetts, and Foster 2021). It has become essential for people who need to supplement inadequate public water supplies, and for those outside the reach of water utilities or community-managed water supplies (Grönwall, Mulenga, and McGranahan 2010). Although heavily relied upon by households in many LMICs, self-supply is generally unregulated, unmonitored and overlooked by policy and practice.

Monitoring water service delivery is essential for government's regulation and to track progress towards the Sustainable Development Goal of universal access to safe drinking water by 2030 (SDG 6). The relevant indicator is the proportion of the population using safely managed drinking water services, where safely managed refers to drinking water from an improved water source that is located on-premises, available when needed, and free from faecal and priority chemical contamination (WHO, & UNICEF 2017). Self-supply is often not explicitly recognised as a formal service delivery model and, by default, water safety is the responsibility of households (Genter et al. 2023). Although poor water quality is a major problem (Genter et al. 2022; Genter, Willetts, and Foster 2021), self-supply has the potential to fulfil the criteria of a safely managed water service as it is located on the premises of a user household. Self-supply is not adequately captured in SDG monitoring, as water quality is currently monitored using routine water quality data from utilities or regulators or Multiple Indicator Cluster Surveys (MICS) conducted only in certain countries every few years (Foster et al. 2021) To achieve SDG 6 on safely managed drinking water for all, it is crucial to understand service delivery outcomes of self-supply and water quality monitoring options.

Studies have shown drinking water from groundwater self-supply sources is commonly contaminated, pointing to the need for regular monitoring of water quality (Genter et al. 2022). Monitoring of faecal contamination of drinking water is usually based on faecal indicator bacteria *Escherichia coli (E. coli)* in a 100 mL water sample, which is the recommended measure by the (WHO 2022). The guideline value is that no *E. coli* should be detected in any 100 mL sample (WHO 2022). SDG Target 6.1 calls for regular reporting on the bacteriological quality of drinking water at the national level, conducted at the local or regional level (WHO 2017). Methods for the quantification of *E. coli* include direct quantification of colony forming units via membrane filtration techniques and estimates of the Most Probable Number (MPN) of bacteria via broth-culture-based assays (Bain et al. 2012). Presence/absence tests have shown to offer a cost-effective alternative to quantitative methods, as they are quicker to perform and require less laboratory equipment (MacLeod et al. 2019). Nevertheless, methods for the detection and monitoring of microbial contamination in LMICs may be hampered by limited resources, and inadequate

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or inaccessible laboratory infrastructure (Genter et al. 2019; Khatibi and Yamakanamardi 2010; Schertenleib et al. 2019). To our knowledge, the literature currently lacks documentation on the methods of monitoring and reporting microbial quality in self-supply services. To support the provision of safe drinking water for self-supply, monitoring is necessary to inform self-supply water quality management.

There is little guidance and evidence on best monitoring practices for self-supply services in low resource settings. The WHO guidelines for drinking water quality and the water safety plan manual recommend that operational monitoring and independent surveillance should occur for common drinking water quality monitoring programs (Bartram et al. 2009; WHO 2022). Operational monitoring serves to inform decision-making and corrective actions on control measures such as source protection and water treatment, while surveillance of drinking water quality engages an independent third party in oversight of the water supply, with the specific mandate for protection of public health (Crocker and Bartram 2014). Operational monitoring of piped water supplies using dedicated or shared laboratories and surveillance is a common monitoring scenario, however, operational monitoring of non-piped, or point-source water supplies, such as boreholes, is rare (Crocker and Bartram 2014).

Participatory citizen monitoring has become increasingly popular in natural science research but is still scarce in the field of drinking water monitoring. Citizen science is the participation of the general public in the generation of scientific knowledge (Buytaert et al. 2014). In the water sector, citizen science is most prominent in the field of surface water quality monitoring programs measuring chemical parameters and biological indicators (Brouwer et al. 2018; Conrad and Hilchey 2011). Citizen science water projects are predominantly in the Global North, however, there is growth in citizen science water projects in the Global South (Walker, Smigaj, and Tani 2021). While participatory monitoring projects in the Global North have been dominated by water quality assessments and focused largely on education and raising awareness, Global South projects have focused more on improving livelihoods (Walker, Smigaj, and Tani 2021). Citizen science in the field of drinking water monitoring is scarce, and is often limited to the data collection of physical-chemical parameters in water samples and excludes microbial parameters (Brouwer et al. 2018; Buytaert et al. 2014; Peckenham, Thornton, and Peckenham 2012). The first citizen science project on drinking water that was documented in the academic literature was conducted by (Brouwer et al. 2018) in the Netherlands. In that study, citizens of Amsterdam participated in taking samples from their own kitchen tap and tested the microbiological stability of drinking water using test strips resulting in raised participant's awareness about microbial water quality. In other fields, citizen science has shown positive impacts on participants, including public engagement, raising awareness, social learning, knowledge gain or democratization of science (Walker, Smigaj, and Tani 2021). However, there may also be negative impacts of citizen science such as over-burdening the public (Walker, Smigaj, and Tani 2021).

Since self-supply is managed by households themselves, involving households to self-monitor their water quality could offer a promising approach. Therefore, this study sought to understand the extent to which participatory citizen monitoring using Aquagenx® presence/absence field test is an appropriate approach to monitor self-supply services in terms of microbial water quality. The study focused on the feasibility of the participatory monitoring approach, including motivation of participation, awareness and understanding of participants, as well as the water quality results.

Methods

Study area

The participatory monitoring was undertaken in the Indonesian city of Bekasi. Kota Bekasi was selected based on widespread use of self-supply and the lack of access to piped water. The city is located in West Java on the eastern border of Jakarta and is divided into 12 districts *(Kecamatan)*. With a population density of 12,085 people/km^2 (2020) and approximately three million inhabitants, it is one of the most populous cities in Indonesia (BPS Kota Bekasi 2021). More than 88% of households relied on groundwater as their water source in 2020 (BPS Kota Bekasi 2021). In Kota Bekasi, self-supply is not monitored or regulated and, by default, monitoring and management of water quality sits with households themselves. Based on the regulation of the Ministry of Health (MoH) no. 492/2010, drinking water operators are mandated to ensure water quality standards with support and monitoring from local government and public health agencies (Priadi et al. 2023). Central and local governments must conduct twice-yearly sanitary inspections of non-piped drinking water supplies, including dug wells and boreholes, while those at high and very high risk of contamination are requested to improve water and sanitation facilities (MoH regulation no. 736/2010). Those at low and medium risk should have their water tested at least monthly for microbial and physical parameters and biannually for compulsory and optional chemical parameters (Priadi et al. 2023). However, these regulations are unrealistic for the large number of privately owned self-supply systems in Indonesia and are largely disregarded (Priadi et al. 2023).

The study took part in three purposively selected sub-districts *(Kelurahan)*, namely Jatliluhur, Sumur Batu and Jatirangga, from three different districts (Jatiasih, Bantar Gebang and Jatisampurna). The hamlets *(RW Rukun Warga)* were selected in consultation with the heads of the selected sub-districts, and the neighborhoods *(RT Rukun Tetangga)* in consultation with the respective head of the selected hamlets. Prior to the data collection, informed consent was obtained in local language from heads of neighbourhoods and from all participants. Ethical approval to conduct the research was provided by the Human Research Ethics Committee of the University of Technology Sydney as well as the Community Engagement Ethical Committee of the Universitas Indonesia.

Household selection

All households of the selected neighbourhoods were listed and 300 households were randomly selected for the purposes of the previous studies (Genter et al. 2022, 2023).

Of these 300 randomly selected households, a target number of 30 households was chosen for budget reasons for this study. The selection criteria included a willingness to participate, using self-supply as a water source for drinking and domestic purposes, and the availability of WhatsApp on at least one family member's mobile phone for reporting water quality test results. After three rounds of phone calls, a total of 30 households were selected, ten in Jatiluhur, five in Jatirangga and 15 in Sumur Batu.

Conceptual framework

The context analysis, process evaluation and impact assessment (CPI) framework proposed by Gharesifard et al., (2019) was used to frame and analyse the participatory monitoring approach for self-supply water services and to evaluate its feasibility. The CPI framework, as described by Gharesifard et al., (2019), was introduced to analyse the dynamics underlying the establishment and functioning of community-based monitoring initiatives. The CPI framework emphasizes the importance of community involvement in monitoring, which is also a core principle of participatory monitoring. The CPI framework provides a useful basis for thinking about how to design and implement participatory monitoring approaches that involve community members in monitoring as its principles and components can be adapted to a range of monitoring and evaluation approaches with different scopes, scales, and levels of participation. The framework encompasses five distinct dimensions, which are categorized into context-related and initiative-related aspects, and are suitable for conducting context analysis, process evaluation and impact assessment of the monitoring approach. The five dimensions and corresponding 22 internal and context-related factors considered in the CPI framework are as follows (Figure 1):

- Goals and objectives: What are overarching objectives and actor-specific goals of the initiative and to what extent does the design of the initiative help achieve those goals/objectives?
- Power dynamics: Who controls and influences the initiative and how?
- Participation: Who participates in the initiative and how?
- Technology: How effective and appropriate are the choices and delivery of the selected technologies?
- Results: What are the outputs, outcomes and impacts of the initiative?

This study applies the framework in a novel context, specifically utilizing a household-based rather than a community-based approach. This approach has enabled the identification of new insights and potential areas for improvement within the framework. The 'results' dimension, positioned at the top of the diagram, is influenced by the dimensions of 'power dynamics', 'participation', and 'technology'. In this study, the CPI framework was adapted to place the dimension of 'participation' at the centre of the framework, reflecting the use of a household-based approach where participants play a central role in conducting the water quality testing. Additionally, flows between the dimensions were introduced in the diagram. The 'goals and objectives' dimension located at the bottom of the framework is influenced by the dimensions of 'power dynamics', 'participation', and 'technology'.

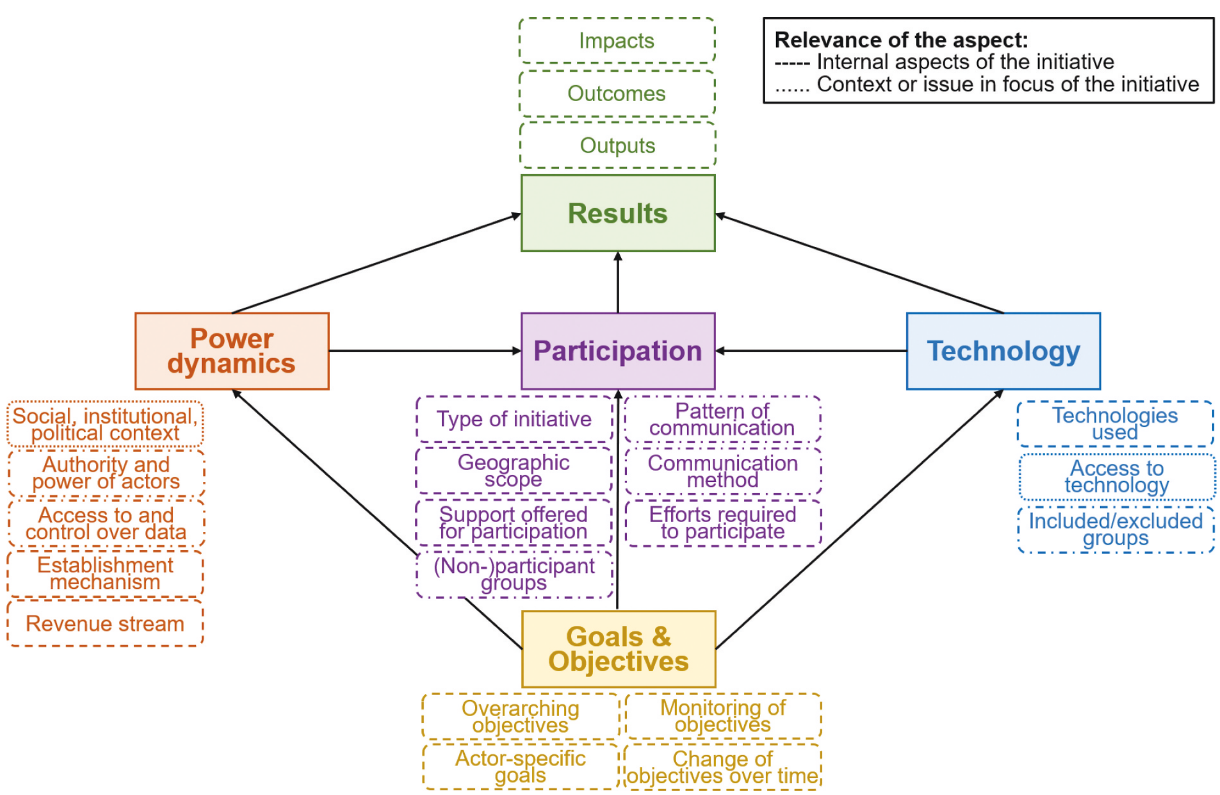

Figure 1. Adapted CPI framework of Gharesifard et al., (2019) including the five dimensions and 22 context and/or internal aspects of the initiative.

The analysis of this study primarily focuses on the 'results' of the framework, including outputs and outcomes, and how these are affected by the 'participation' and 'technology' dimensions. However, the study also sheds light on the other aspects of the framework, as it applies the framework in a novel household-based context. In the participatory monitoring approach, 18 of the 22 proposed internal and context-related aspects of the framework are considered (Supplementary S4 Table A1). It is important to note that the scope of this study was limited to the short term. As such, certain aspects, such as actor-specific goals, change of objectives over time, and monitoring of objectives and impacts, were not taken into account. However, these aspects are covered in the context of long-term implementation in the discussion section.

Participatory citizen approach

Prior to the start of the project, a contextual baseline analysis was conducted as part of the study design, which analysed and defined the contextual factors such as the social, institutional, and political context as well as the authority and power of different actors, access to and control over data and access to the technology. Furthermore, overarching objectives were defined, and the technologies used to achieve the goals. The process evaluation is used to help enhance the understanding of the process that led to the outcomes and outputs by considering the dimensions 'participation' and 'power dynamics'. The internal aspects of the 'participation' dimension, such as efforts required to participate and support offered were defined and evaluated, as well as who controls and influences the initiative and how. The impact assessment focused on the short-term outcomes (i.e. short-term changes) and outputs (i.e. direct outputs), and how these were influenced by the 'participation' and 'technology' dimension. The outputs included the motivation of participation, as well as water quality results. These outputs were obtained through a participatory water quality testing using field test kits, along with pre- and post-monitoring surveys. Short-term outcomes included participants awareness and understanding on water quality. The pre-monitoring survey was used to assess participants' initial awareness and understanding of water quality, while the post-monitoring survey was used to evaluate any changes in these factors following participation in the project. For a comprehensive application of the CPI framework used in this study, see Table A1 in Supplementary S4.

After establishing the study design, including defining relevant contextual and internal aspects, households were advised to test their self-supply water for the presence of *E. coli* every two weeks at both the source and point of use. Households were provided Aquagenx® test kits covering a six-month period between April and November 2022 (total of 12 sampling rounds). Access to this technology was made possible by the import of the test kits to Indonesia. The messaging app WhatsApp was defined as the communication method between the research team and the participants, as such, households without a mobile phone with functioning WhatsApp were not selected for participation. Water quality outputs obtained by participants were shared with the research team by mobile phone using WhatsApp. Support was offered to participate, with a reward of 15,000 Rupiah (approximately US$ 1.00) of mobile phone balance provided to each participant after each sampling round. Furthermore, participants were trained by two local enumerators at the start of the campaign. Participating households were able to discontinue their participation in the monitoring at any time. After one month and at the end of the campaign, a pre- and post-monitoring survey was conducted by the enumerators during field visit to evaluate the outcomes. Three quality control samples were collected by the enumerators during the field visit at the start of the campaign (sampling round 1, $n = 30$), after one month (sampling round 3, $n = 26$) and at the end of the campaign (sampling round 12, $n = 17$) at the same time as household members. Analysed water quality results were shared with participants using WhatsApp.

Microbial water quality testing

Water quality was tested for the presence of *E. coli* using Aquagenx® presence/absence test kits according to the manufacturer's instructions (Aquagenx 2013). The Aquagenx® test kit uses a powdered growth medium containing a glucose substrate known as X-Gluc. When *E. coli* bacteria metabolize this substrate, the water changes colour to blue, serving as an indicator of *E. coli* presence. The Aquagenx® test kit has been evaluated by UNICEF and WHO as part of the Rapid Water Quality Testing Project, aiming to catalyse the continuous improvement of existing and new portable water quality testing products to allow more efficient, accurate, or low-cost testing of drinking water quality in the field (WHO, & UNICEF 2022). The test kit correctly identified the presence or absence of *E. coli* in more than 90% of cases when incubated at a temperature of 25°C for 48 hours, or at a temperature of 35°C for 20 hours (WHO, & UNICEF 2022). This test was chosen as the preferred method for the participatory monitoring approach due to its simplicity and design for on-site field testing in low resource areas. While alternatives such as hydrogen sulphide detecting tests are suitable for low resource settings due to their low-cost nature and ease of local manufacture, these tests are not approved by the U.S. EPA or recommended by the WHO guidelines for drinking water (Bain et al. 2012; Matwewe, Hyland, and Thomas 2018; Wright et al. 2012). Approved methods such as IDEXX Colilert were not considered appropriate for participatory on-site testing in low resource areas due to the extensive equipment and cost (Bain et al. 2012). The primary aim of the participatory monitoring approach was not to evaluate testing methods per se, but rather to assess how households respond to the opportunity to test their own water quality.

Microbial water quality was tested by participants from the main self-supply source and main drinking water source at the point-of-use. The 100 mL Whirl-Pak Thio-bags were labelled using a permanent marker with the participants' initials, the source or point-of-use type code and the date. Hands were disinfected with hand sanitizer immediately before collecting the 100 mL water samples from the groundwater self-supply source or point-of-use source using the Whirl-Pak Thio-Bag. The water samples from self-supply sources were collected in a way participants usually would obtain water. Point-of-use samples were collected in a way participants usually would when drinking from a storage container, as for example pouring water into a glass or cup, or directly from a storage container. Water samples were filled to the upper black fill mark line and the Aquagenx® growth medium was added to the water sample in the Whirl-Pak Thio-Bag. Whirl-Pak Thio-Bags were closed and growth medium in the sample was dissolved by swirling the bag gently. The sample was incubated for 48 hours at ambient temperature, ideally more than 30°C. Instructions of Aquagenx® recommend an incubation period of 40–48 hours at an ambient temperature of 25–30°C, 24–30 hours at 31–34°C and 20 hours at 35–37°C. Ambient temperature was recorded during the study period using temperature loggers (Elitech RC-5 USB temperature data logger) in a total of three households, one in each district. The temperature was also recorded by the enumerators during the quality control field visits. Incubation time was recorded by participants. After 48 hours, a picture of the labelled water sample was taken and shared with the research team using WhatsApp. If the water sample was blue/blue green it was positive for *E. coli*, if it was yellow/yellow brown it was negative for *E. coli*. The microbial water quality testing is part of the CPI framework 'technology' dimension and was used to obtain the outputs on water quality.

Pre- and post-monitoring survey

A structured pre-monitoring survey and a structured post-monitoring survey was conducted in local language by the enumerators using Qualtrics software (Qualtrics, Provo, UT, USA). The pre-monitoring survey was conducted one month after the start of the campaign (May 21st – 25th, 2022, sampling round 3) while the post-monitoring survey was conducted at the end of the campaign (October 29th - November 8th, 2022, sampling round 12). The surveys covered themes on participants' socio-economic and demographic characteristics, feasibility, and motivation to use the test, awareness and understanding as well as perception of water quality. The pre- and post-monitoring survey was used to evaluate how different aspects of the 'participation' and 'technology' dimensions lead to the outputs and outcomes in terms of motivation of participation, as well as awareness and understanding of participants.

Rainfall and groundwater measurements

Rainfall and groundwater levels were measured to provide insight into the temporal variability and as potential factors influencing water quality. Rainfall was measured using a Davis® (0.2 mm) Rain Gauge Smart Sensor at a household in Jatirangga during five months from June 2nd to November 4th, 2022, according to the manufacturer's instructions. Groundwater levels were measured using HOBO® MX Bluetooth Water Level Loggers (MX2001) in two private protected dug wells in Jatirangga during five months from June 2nd to November 4th, 2022, and in one private protected dug well in Jatiluhur from June 3rd to November 6th, 2022, according to the manufacturer's instruction (Supplementary S2 Database). Rainfall and groundwater output data over time were plotted using Microsoft Office Excel 2016.

Data analysis

Statistical analysis software R (version 1.2.5001, R Foundation for Statistical Computing, Vienna, Austria) and Microsoft Office Excel 2016 were used for analysis. R package 'DescTools' was used to calculate proportions and corresponding confidence intervals (CI), as well as statistical significant tests. CIs for binominal proportions were calculated using the 'BinomCI' function based on the Clopper-Pearson method, while CIs for multinominal proportions were calculated using the 'MultinomCI' function based on the Sisonglaz method. Fisher's exact test was calculated to examine the relationship between the socio-economic and demographic characteristics of participants who dropped out and those who completed the full testing. Stuart-Maxwell test was used to compare marginal homogeneity for pre- and post-survey responses of single-select questions for participants who completed monitoring and did not drop out.

For the purposes of previous studies, the wealth index was constructed for households in Bekasi using the same approach as the 2017 Indonesian Demographic and Health Survey (DHS) based on the relevant indicators and corresponding values (National Population and Family Planning Board BKKBN et al. 2018). See (Genter et al. 2022) for more information on the wealth index and wealth quintiles calculations.

To examine whether self-testing water quality resulted in improved water quality over time, a generalized estimating equations (GEE) analysis was conducted that accounted for rainfall variability. Cumulative rainfall was calculated for periods of three days, one week and two weeks prior to each microbial water quality sampling date using Microsoft Office Excel 2016. Microbial water quality data measured before the first rainwater measurement until sampling round four were excluded for this analysis. GEE (R package 'gee') were used to model the longitudinal repeated measures to specify the correlation between cumulative rainfall (three days, one week and two weeks) and the presence of *E. coli* at source and point-of-use over time. The specific households were considered as a grouping factor (id variable). Households that only participated in one sampling round were excluded from analysis, resulting in a cluster size of $n = 22$ households for the analysis of three days cumulative rainfall prior to water sampling, and $n = 21$ households for the analysis of one- and two-weeks cumulative rainfall prior to water sampling (Supplementary S3 Database). An autoregressive correlation structure was used to adjust for the correlation between measurements within each household. Odds ratios, 95% CIs and *p*-values were calculated for the sampling round and rainfall predictors in the GEE model fit. Robust standard errors were used to calculate the 95% CIs. The *p*-values were calculated based on the z-values obtained from the coefficient estimates and standard errors of the model, using the 'pnorm' function in R. The resulting *p*-values were used to determine whether each predictor variable was statistically significant at the 0.05 significance level. Quasi-Likelihood Information Criterion (QIC) was used as a measure of goodness-of-fit for the GEE models. The QIC is a measure of model fit that adjusts the traditional Akaike Information Criterion to account for the quasi-likelihood estimation used in GEEs

(Pan 2001). A lower QIC value indicates a better fit to the data.

Results

Context – participants' socio-economic, demographic and water supply characteristics

Participants' socio-economic and demographic characteristics are presented in Table 1. Of the 30 final selected participants, ten were from Jatiluhur, five from Jatirangga and 15 from Sumur Batu. Households were evenly distributed amongst the wealth quintiles. The selected participants were mostly female with about three quarters ($n = 23$) of the respondents being female and about one quarter being male ($n = 7$). The socio-economic and demographic characteristics were comparable to the full sample of households included in the previous studies (Supplementary S1 Table A1, Genter et al. 2022, 2023). Of the 30 selected households that agreed to participate in participatory monitoring, about half ($n = 16$) fully completed all tasks, including fortnightly water quality testing for six months and responding to the pre- and post-monitoring survey; the other half ($n = 14$) dropped out from testing during the six months period. The pre- and post-monitoring survey were conducted by 87% ($n = 26$) and 57% ($n = 17$) of the selected participants. Sixteen participants completed the pre- and post-monitoring survey, ten participants completed only the pre-monitoring, one participant completed only the post-monitoring survey, and three participants did not participate in either the pre- or post-monitoring survey.

Self-supply sources were used for drinking, cooking, showering, washing cars and watering plants (Supplementary S1 Table A2). Pre-survey results indicate that private boreholes were the most frequently used source of drinking water (n = 24, 92%), followed by refill water (n = 10, 39%). If used for drinking, water from self-supply sources was boiled every time before consumption by most participants (Supplementary S1 Table A2). Refill water and bottled water were never or only sometimes boiled before consumption. Diarrhoea was experienced within 15% of households in the past month prior to the start of the monitoring. Five participants experienced problems with accessing the self-supply water sources due to drought (n = 4), flood (n = 2) and pump failure (n = 2), in the past month prior to the start of the monitoring. Water from self-supply sources was available 24 hours per day for most participants (n = 21, 81%), however, five participants reported an availability of less than 24 hours per day (19%).

Outputs – motivation of participation and dropout from testing

The study found a high dropout rate among participants, with nearly half of the selected households dropping out by the end of the monitoring period. The dropout rate was 53%, with 14 participants dropping out from testing. Out of those participants, five dropped out by the end of the fourth round and eleven by the end of the eighth round (Figure 2). One participant who dropped out after the first sampling round took a sample at the final twelfth sampling round and participated in the post-monitoring survey. When asking participants about the reason for the dropout, five were too busy, one got sick, one was bothered by the smell of the test and one didn't trust that the reward would be transferred. The reasons were unknown for six participants who dropped out. Fisher's exact test showed a significant relationship between participants' place of living and the dropout from monitoring (Table 1). Participants were significantly more likely to complete the monitoring in Jatirangga ($p = 0.045$) as compared with other sub-districts (Sumur Batu and Jatiluhur). No significant associations were observed for wealth status, participant gender, reason for participation, preferred frequency of testing, difficulties of testing, and understanding of the training and usage of the test (Tables 1 and 2). Sampling interruption was observed from three participants. One sample was excluded because of the result was falsified, with a household -resubmitting a photograph of an older sample. In sampling round five, nine results were taken by the participants, but the results could not be recorded due to an enumerator error.

The participants who completed the monitoring were motivated and willing to continue monitoring, with their primary

Table 1. Socio-economic and demographic characteristics of (i) participants from all selected households; (ii) those who participated in the full duration of the water quality testing and completed pre- and post-monitoring survey; (iii) those who dropped out from water quality testing; (iv) those who conducted the pre-monitoring survey; and (v) those who conducted the post-monitoring survey. Percentages refer to the total number of selected participants (n = 30).

Participants	Final selection			Full participation			Dropout			Pre-survey			Post-survey		
Variables	n	[%]	95% CI [%]	n	[%]	95% CI [%]	n	[%]	95% CI [%]	n	[%]	95% CI [%]	n	[%]	95% CI [%]
Total	30	100	-	16	53.3	34.3–71.7	14	46.7	28.3–65.7	26	86.7	69.3–96.2	17	56.7	37.4–74.5
Village															
Jatiluhur (p = 0.709)	10	33.3	16.6–52.2	6	37.5	18.8–67.0	4	28.6	14.5–55.6	9	34.6	19.2–57.2	7	41.2	23.5–69.9
Jatirangga (p = 0.045)*	5	16.7	0.0–35.6	5	31.3	12.5–60.8	0	0.0	0.0–27.0	5	19.2	3.8–41.9	5	29.4	11.8–58.1
Sumur Batu (p = 0.066)	15	50.0	0.3–68.9	5	31.3	12.5–60.8	10	71.4	57.1–98.5	12	46.2	30.8–68.8	5	29.4	11.8–58.1
Wealth[a]															
Q1 (poorest)	5	16.7	0.0–33.9	1	6.3	0.0–33.9	4	28.6	7.1–56.9	4	15.4	0.0–36.8	1	5.9	0.0–33.3
Q2	5	16.7	0.0–33.9	2	12.5	0.0–40.1	3	21.4	0.0–49.8	4	15.4	0.0–36.8	2	11.8	0.0–39.2
Q3	8	26.7	10.0–43.9	7	43.8	25.0–71.4	1	7.1	0.0–35.5	8	30.8	15.4–52.2	7	41.2	23.5–68.6
Q4	5	16.7	0.0–33.9	3	18.8	0.0–46.4	2	14.3	0.0–42.6	5	19.2	3.8–40.6	3	17.6	0.0–45.1
Q5 (wealthiest)	7	23.3	6.7–40.6	3	18.8	0.0–46.6	4	28.6	7.1–56.9	5	19.2	3.8–40.6	4	23.5	5.9–51.0
Sex															
Female (p = 1.000)	23	76.7	57.7–90.1	12	75.0	47.6–92.7	11	78.6	49.2–95.3	21	80.8	60.6–93.4	12	70.6	44.0–89.7
Male (p = 1.000)	7	23.3	9.9–42.3	4	25.0	7.3–52.4	3	21.4	4.7–50.8	5	19.2	6.6–39.4	5	29.4	10.3–56.0

*Significant category $p < 0.05$, full participation versus dropout.

[a]Fisher's exact p-value $p = 0.568$ for poorer households (Q1 and Q2) versus wealthier households (Q3, Q4 and Q5).

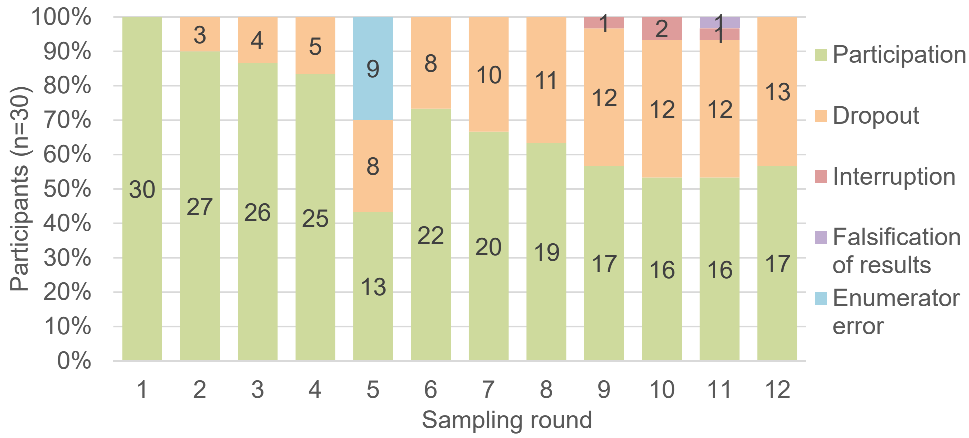

Figure 2. Participation of the selected households in fortnightly water quality testing (12 rounds) during the six months period.

Table 2. Understanding motivation for participation and drop-out from testing based on pre-survey results of participants who completed the monitoring and those who dropped out.

	Pre-survey Full Participation			Pre-survey Dropout		
Variables	n	[%]	95% CI [%]	n	[%]	95% CI [%]
Total	16	100	-	10	100	-
Who in the household has the main responsibility for doing the testing?						
Woman (*p* = 0.617)	12	75.0	62.5–99.2	9	90.0	80.0–100.0
Man (*p* = 0.617)	4	25.0	12.5–49.2	1	10.0	0.0–26.5
Child	0	0.0	0.0–24.2	0	0.0	0.0–16.5
More than one person	0	0.0	0.0–24.2	0	0.0	0.0–16.5
Why are you interested to participate in the water quality testing?						
Learning about drinking water quality (*p* = 1.000)	16	100.0	79.4–100.0	9	90.0	55.5–99.7
Caring about personal and family's health (*p* = 1.000)	16	100.0	79.4–100.0	9	90.0	55.5–99.7
Recognition or respect from others (*p* = 1.000)	3	18.8	4.0–45.6	1	10.0	0.3–44.5
Felt compelled to participate	0	0.0	0.0–20.6	1	10.0	0.3–44.5
Because of the remuneration	0	0.0	0.0–20.6	0	0.0	0.0–30.8
Other reason	1	6.3	0.2–30.2	1	10.0	0.3–44.5
What's your preferred frequency of testing the water?						
Once per week (*p* = 0.508)	2	12.5	0.0–39.7	0	0.0	0.0–28.7
Once all two weeks (*p* = 0.399)	9	56.3	37.5–83.4	8	80.0	70.0–100.0
Once each month (*p* = 0.668)	5	31.3	12.5–58.4	2	20.0	10.0–48.7
No time	0	0.0	0.0–27.2	0	0.0	0.0–28.7
Other	0	0.0	0.0–27.2	0	0.0	0.0–28.7
In which steps do you have difficulties in testing the water quality with Aquagenx®?						
No difficulties (*p* = 0.677)	5	31.3	11.0–58.7	2	50.0	18.7–81.3
Collecting the water sample (*p* = 1.000)	2	12.5	1.6–38.3	1	20.0	2.5–55.6
Adding the growth medium (*p* = 0.060)	6	37.5	15.2–64.6	8	60.0	26.2–87.8
Incubating the sample	0	0.0	0.0–20.6	0	0.0	0.0–30.8
Score and send the results	0	0.0	0.0–20.6	0	0.0	0.0–30.8
Other	5	31.3	11.0–58.7	0	50.0	18.7–81.3
How difficult was the training to understand how to test the water quality?[a]						
Very easy (*p* = 1.000)	1	6.3	0.0–34.2	1	10.0	0.0–47.4
Easy (*p* = 1.000)	6	37.5	18.8–65.4	4	40.0	20.0–77.4
Neutral (*p* = 0.702)	8	50.0	31.3–77.9	4	40.0	20.0–77.4
Difficult (*p* = 1.000)	1	6.3	0.0–34.2	1	10.0	0.0–47.4
Very difficult (*p* = 1.000)	0	0.0	0.0–27.9	0	0.0	0.0–37.4
How difficult is the test to use?[b]						
Very easy (*p* = 1.000)	1	6.3	0.0–34.2	1	1.0	0.0–44.7
Easy (*p* = 1.000)	6	37.5	18.8–65.4	3	30.0	10.0–64.7
Neutral (*p* = 0.702)	8	50.0	31.3–77.9	6	60.0	40.0–94.7
Difficult (*p* = 1.000)	1	6.3	0.0–34.2	0	0.0	0.0–34.7
Very difficult (*p* = 1.000)	0	0.0	0.0–27.9	0	0.0	0.0–34.7

[a]Fisher's exact *p*-value *p* = 1.000 for no difficulties (very easy, easy, neutral) versus difficulties (difficult, very difficult) in understanding the training.
[b]Fisher's exact *p*-value *p* = 1.000 for no difficulties (very easy, easy, neutral) versus difficulties (difficult, very difficult) in using the test.

reason being to learn about drinking water quality and prioritize their family's health. The post-survey showed that most participants who didn't drop out were willing to continue monitoring the water quality given the opportunity (94%, Supplementary S1 Table A3). Also, willingness to pay an amount for continued water quality monitoring was likely; 38% expressed a willingness to pay for continued water quality testing as likely, 56% as neutral, and 6% as unlikely. The majority of participants that completed the monitoring were women with responsibility for doing the tests being changed by two participants (12%) during the monitoring period (Table 2 and Supplementary S1 Table A3). Learning about drinking water quality and caring about personal and family's health were the most important reasons for participation. Recognition or respect from others was an important reason for three participants who completed the monitoring. Other reasons mentioned were the support of students who were involved in the project. The majority of participants were satisfied with the frequency of testing, which was once every two weeks. However, about 30% preferred less frequent testing of once a month. Adding the growth medium was the most difficult part of testing the water quality with Aquagenx®. The water quality testing training was easy to neutral for most households to understand, with two participants rating it as difficult and two as very easy. Similarly, the use of the water quality tests was easy to neutral for most households, with one participant rating it as difficult and two as very easy in the pre-survey (Table 2).

Outputs – water quality results

Self-supply samples at source and point-of-use were frequently contaminated with *E. coli* with the proportions of contaminated samples varying during the study period. The proportion of contaminated source samples each month ranged between 10.5% and 70.0% while the proportion of contaminated point-of-use samples ranged between 15.0% and 43.8% (Figure 3). Quality control samples showed 90.0% ($n = 27$), 84.6% ($n = 22$) and 94.1% ($n = 16$) accuracy after the first, third, and twelfth sampling rounds, respectively. The measured ambient temperature ranged between 27.5°C and 31.2°C in Jatiluhur, 27.5°C and 32.1°C in Jatirangga and 29.2°C and 31.6°C in Sumur Batu, which is within the recommended incubation temperature range without the need for an incubator. Most participants tested the water from boreholes ($n = 26$, round 1), while one household tested the water from an unprotected dug well and three tested water from a protected well (Supplementary S1 Table A5). During the study period, the number of source types changed due to the dropout of participants or the use of alternative drinking water sources such as refill water at household level (Supplementary S1 Table A6). The range of contaminated self-supply samples was similar for participants that did not drop out from testing and completed the monitoring (Supplementary S1 Figure A1). Considering only participants that did not drop out from testing, the proportion of contaminated source samples ranged between 12.5% and 68.8% while the proportion of contaminated point-of-use samples ranged between 12.5% and 37.5% (Supplementary S1 Figure A1). Over the entire study period, *E. coli* was detected in 42.5% of the 214 samples from 26 boreholes, in 36.4% of the eleven samples from one unprotected dug well and in 26.1% of the 23 samples from three protected wells (Supplementary S1 Table A5). At point-of-use, *E. coli* was present in 29.3% of the 184 borehole samples, in 25.0% of the twelve samples from protected wells and in 27.5% of the 51 refill water samples (Supplementary S1 Table A6).

Outcomes – awareness and understanding of water quality

Participatory monitoring might have improved participants' understanding of self-supply water quality. When asked about the perceived source water and drinking water safety, the water quality was less frequently rated as good at the endline compared with the baseline (Table 3). Stuart-Maxwell test showed a statistically significant change in perception of self-supply safety at source ($p = 0.046$) when ratings were collapsed into two categories of good (excellent, very good, good) and poor (fair, poor). No significant change was observed in perception of drinking water safety at point-of-use ($p = 0.317$). Before and after the monitoring, all participants selected taste as an important water safety indicator. However, water storage method was the least frequently selected, with around one-third of respondents selecting it before and after the monitoring. In the post-monitoring survey, statements to test understanding of water quality were more frequently selected correctly, with more frequent selection of the correct statement 'microbial

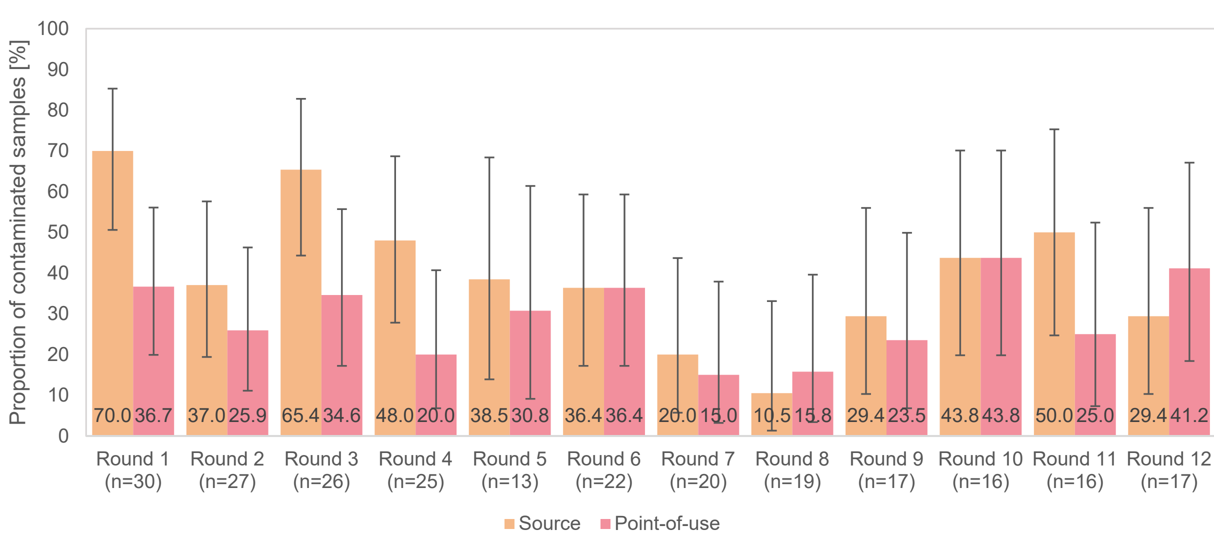

Figure 3. Proportion of source and point-of-use samples with positive *E. coli* detection in each sampling round during the six months monitoring period.

Table 3. Change in awareness and understanding on water quality before and after the monitoring of participants who completed the monitoring.

	Pre-survey			Post-survey		
Variables	n	[%]	95% CI [%]	n	[%]	95% CI [%]
Total	16	100.0	-	16	100.0	-
Which of the following factors do you think are important indicators of whether water is safe to drink?						
Taste	16	100.0	79.4–100.0	16	100.0	79.4–100.0
Appearance – Particles	10	62.5	35.4–84.8	7	43.8	19.8–70.1
Appearance – Colour	15	93.8	69.8–99.8	14	87.5	61.7–98.4
Odour	14	87.5	61.7–98.4	15	93.8	69.8–99.8
Recent flooding/rain	11	68.8	41.3–89.0	14	87.5	61.7–98.4
Proximity of sanitation facilities	9	56.3	29.9–80.2	12	75.0	47.6–92.7
Previous experience (have/have not previously been sick)	5	31.3	11.0–58.7	12	75.0	47.6–92.7
Whether water has been treated	12	75.0	47.6–92.7	10	62.5	35.4–84.8
How water is stored	6	37.5	15.2–64.6	6	37.5	15.2–64.6
Please select the following statements which you think are true.						
Microbial contamination in drinking water can cause diarrheal diseases	15	93.8	69.8–99.8	16	100.0	79.4–100.0
Boiling water is an effective method of removing pathogens in drinking water	16	100.0	79.4–100.0	16	100.0	79.4–100.0
Groundwater is always safe to drink	3	18.8	4.0–45.6	1	6.3	0.2–30.2
How would you rate the safety of your tested self-supply at the source before treatment?						
Excellent	0	0.0	0.0–10.5	0	0.0	0.0–28.4
Very good	0	0.0	0.0–10.5	3	18.8	0.0–47.2
Good	15	93.8	87.5–100.0	8	50.0	31.3–78.4
Fair	1	6.3	0.0–16.7	5	31.3	12.5–59.7
Poor	0	0.0	0.0–10.5	0	0.0	0.0–28.4
How would you rate the safety of your tested drinking water at home after treatment?						
Excellent	0	0.0	0.0–18.3	0	0.0	0.0–27.1
Very good	1	6.3	0.0–24.6	4	25.0	6.3–52.1
Good	14	87.5	81.3–100.0	9	56.3	37.5–83.4
Fair	1	6.3	0.0–24.6	3	18.8	0.0–45.9
Poor	0	0.0	0.0–18.3	0	0.0	0.0–27.1
What will/did you do in response to a contaminated water test result?						
Do nothing	2	12.5	1.6–38.3	2	12.5	1.6–38.3
Choose an alternative water source for drinking	8	50.0	24.7–75.3	13	81.3	54.4–96.0
Boil the water before consumption	13	81.3	54.4–96.0	13	81.3	54.4–96.0
Clean the storage containers	10	62.5	35.4–84.8	12	75.0	47.6–92.7
Running my tap water before using it each day	1	6.3	0.2–30.2	10	62.5	35.4–84.8
How likely are you to talk the following groups of people about drinking water quality? [Family]						
Never	3	18.8	0.0–47.4	4	25.0	6.3–52.7
Rarely	1	6.3	0.0–34.9	2	12.5	0.0–40.2
Sometimes	7	43.8	25.0–72.4	8	50.0	31.3–77.7
Often	5	31.3	12.5–59.9	2	12.5	0.0–40.2
Every time	0	0.0	0.0–28.6	0	0.0	0.0–27.7
Not relevant	0	0.0	0.0–28.6	0	0.0	0.0–27.7
How likely are you to talk the following groups of people about drinking water quality? [Friends]						
Never	5	31.3	12.5–60.1	6	37.5	18.8–66.4
Rarely	4	25.0	6.3–53.8	6	37.5	18.8–66.4
Sometimes	5	31.3	12.5–60.1	3	18.8	0.0–47.7
Often	2	12.5	0.0–41.3	1	6.3	0.0–35.2
Every time	0	0.0	0.0–28.8	0	0.0	0.0–28.9
Not relevant	0	0.0	0.0–28.8	0	0.0	0.0–28.9
How likely are you to talk the following groups of people about drinking water quality? [Neighbours]						
Never	6	37.5	18.8–66.4	7	43.8	25.0–72.3
Rarely	3	18.8	0.0–47.7	4	25.0	6.3–53.6
Sometimes	6	37.5	18.8–66.4	4	25.0	6.3–53.6
Often	1	6.3	0.0–35.2	1	6.3	0.0–34.8
Every time	0	0.0	0.0–28.9	0	0.0	0.0–28.6
Not relevant	0	0.0	0.0–28.9	0	0.0	0.0–28.6
How likely are you to talk the following groups of people about drinking water quality? [Colleagues]						
Never	7	43.8	25.0–72.3	15	93.8	87.5–100.0
Rarely	1	6.3	0.0–34.8	1	6.3	0.0–16.7
Sometimes	2	12.5	0.0–41.1	0	0.0	0.0–10.5
Often	0	0.0	0.0–28.6	0	0.0	0.0–10.5
Every time	0	0.0	0.0–28.6	0	0.0	0.0–10.5
Not relevant	6	37.5	18.8–66.1	0	0.0	0.0–10.5

contamination in drinking water can cause diarrheal diseases', and less frequent selection of the incorrect statement that groundwater is always safe to drink. All respondents selected the statement 'Boiling water is an effective method of removing pathogens in drinking water' as correct, before and after the monitoring. All participants except one responded that participating in the monitoring improved understanding about the quality of drinking water (Supplementary S1 Table A4). In addition, all participants responded that the tested water quality was as expected. Boiling the water before consumption was the most frequent response to a test result showing contamination at both baseline and endline (81%).

Table 4. GEE analysis shows that testing water over time did not have a significant effect on water quality at source or point-of-use. *E. coli* presence in self-supply sources was significantly influenced by rainfall. No significant effect of rainfall on water quality was observed in drinking water at point-of-use. Cumulative rainfall was considered as three days (Model I), one week (Model II) and two weeks (Model III) prior to the water quality testing date. Model III has the smallest QIC value indicating that it provides the best fit to the data among the three models.

	Model I: Three days			Model II: One week			Model III: Two weeks		
Predictor	OR	95% CI	*p*-value	OR	95% CI	*p*-value	OR	95% CI	*p*-value
Source[a]									
Cumulative rainfall [cm]	1.09	1.03–1.16	0.005*	1.07	1.01–1.13	0.029*	1.07	1.02–1.13	0.008*
Sampling round	0.94	0.80–1.11	0.467	1.01	0.85–1.19	0.940	0.97	0.79–1.19	0.769
Point-of-use[b]									
Cumulative rainfall [cm]	1.03	0.95–1.13	0.466	1.02	0.97–1.08	0.438	1.05	1.00–1.11	0.062
Sampling round	0.98	0.82–1.18	0.837	0.97	0.80–1.17	0.729	0.89	0.75–1.06	0.205

*Significant predictor $p < 0.05$.
[a]Model I: QIC = 31.306, Model II: QIC = 29.585, Model III: QIC = 27.458.
[b]Model I: QIC = 29.728, Model II: QIC = 28.884, Model III: QIC = 27.401.

After the monitoring, choosing an alternative water source for drinking was more frequently selected as a response to a contaminated water test (81%), as well as cleaning the storage container (75%). In response to a test for contaminated water, the practice of running tap water before daily use had become common after the monitoring (63%). After monitoring, participants commonly reported a change in treatment, as well as water storage practice. A change in hygiene practice and water source choice was reported by almost half of respondents. All respondents of the post-monitoring survey saw benefits from testing the water quality in better understanding of drinking water quality and more trust in water quality. Other benefits such as different perception of water quality, support in water source choice and improvement of health were also commonly selected.

Even if participatory monitoring might have improved the understanding on water quality, testing water over time did not have a significant effect on the presence of *E. coli* in self-supply sources or drinking water at point-of-use. This suggests corrective actions were either not taken or not effective. GEE analysis showed that, after adjusting for rainfall, testing water over time was not a significant predictor of *E. coli* presence at source and point-of-use (Table 4). *E. coli* in self-supply sources was, however, found to be significantly associated with rainfall, regardless of whether the models considered cumulative rainfall over a period of three days, one week, or two weeks prior to the water quality testing date. However, no significant effect of rainfall on water quality was observed in drinking water at point-of-use. Effects of rainfall were also observed on groundwater levels of private unprotected dug wells, with lower groundwater water levels observed during dry season months (Supplementary S1 Figure A2).

Discussion

This study of household-led water quality monitoring in urban Indonesia demonstrated a number of positive outcomes, including increased awareness, knowledge gain and behaviour change. Participants who fully engaged in the environmental monitoring were motivated to continue the testing, with driving factors including an interest to learn about drinking water quality and caring about personal and family's health. The participatory monitoring led citizens to develop a more realistic perception of water quality, a better understanding of drinking water quality, and to change their behaviour regarding water treatment and storage. However, as noted by Walker et al., (2021), citizens who volunteer for a project are typically targeted for participation, such as the participants of this study, and might be already aware of the issue, hence their interest. Despite this, the study of Walker et al., (2021) suggests that citizen science projects can still be effective in increasing awareness and knowledge when engagement leads to learning, as observed in our study. Given that self-supply services are the responsibility of individual households, it is important that self-supplying households have an understanding of water quality and risks for contamination, along with knowledge about household water treatment and safe storage options.

However, our study observed demotivation to engage in citizen science amongst a sub-set of participants, which is consistent with previous studies. Engagement of citizens, especially in the form of regular monitoring, may impose a non-trivial burden on participants (Walker, Smigaj, and Tani 2021). In our study, it was difficult to find 30 interested participants and almost half of them dropped out during the trial of six months, mostly due to time constraints. Demotivation among participants was also evidenced by instances where households falsified results. In other studies, excessive complexity, lengthy and overly detailed instructions in conducting participatory monitoring have been found to be off-putting participants (Forrest et al. 2019). However, in our study, most participants did not report any difficulties in understanding the instructions or the water quality test. Those who dropped out of the program mostly cited being too busy as their reason. To make participatory monitoring of self-supply attractive and minimize negative impacts for participants, it is important to make water quality testing as simple and time efficient as possible, and also to emphasize its importance in a way that resonates with households.

The results of this study suggest that Aquagenx® presence/absence tests may be suitable for participatory monitoring, albeit with some caveats. Selecting the appropriate technology is of importance in facilitating the monitoring of self-supply water services by citizens, at it requires simple, reliable, and low-cost water quality tests, as highlighted by (Bain et al. 2020). The Aquagenx® presence/absence test was relatively straightforward for participants to carry out, water quality results were reliable, and no incubator was required due to the study site's climate with an ambient temperature above 25°C. However, testing microbial water quality in more temperate climates with ambient temperatures below 25°C requires an incubator or heat source, complicating and increasing the costs of the participatory monitoring approach. Limitations of the testing method used included the difficulties that were reported with adding the growth medium, the qualitative nature of the results and unit costs which may be prohibitive for lower-income households. Cost per Aquagenx® presence/absence test was about US$ 5.70. The cost of fortnightly source and point-of-use testing (four tests per month) is estimated at 6.8% of the minimum monthly wage of Bekasi City (US$ 334), and 17.7% of the minimum monthly wage for West Java Province (US$ 129) in 2023 (WageIndicator 2023). Hence, while Aquagenx® presence/absence tests may be on the lower end of the cost spectrum for microbial drinking water tests, without subsidies they would be prohibitively expensive for lower-income households to use with a frequency that was trialled in this study. Reducing the frequency of testing would improve affordability. For example, the cost of testing at a single location (either source or point-of-use) on a monthly or annual basis would equate to 1.7% and 0.14% of the minimum wage in Bekasi City, respectively. Reducing the frequency of household-led testing may still provide valuable data for governments to track and oversee overall trends in self-supply water quality over time.

While less frequent testing would reduce the cost and time burden, the trade-off is a reduced capacity to capture temporal variation in water quality. If a participatory approach to monitoring self-supply water quality were to be rolled out at greater scale, balancing these opposing considerations would be critical. Another consideration is whether testing method might assess presence/absence of a faecal indicator (as it did in this study) or whether a quantitative method is needed. A limitation of the presence/absence method used in this study is that it could not fully capture the extent or variability of *E. coli* concentration during the monitoring period. However, the quantification of *E. coli* relies on more complex assays, such as MPN assays, which are more expensive and involve additional processes, which makes them more challenging to implement in resource – limited contexts (Bain et al. 2012; Brown, Bir, and Bain 2020, Genter et al. 2019; Schertenleib et al. 2019).

In order to ensure the long-term success of household-led monitoring, it is crucial to consider the relationship between the CPI dimensions 'power dynamics' and 'participation', which includes both intra-household dynamics among participants as well as dynamics between institutional actors and participants. While participatory monitoring can have a range of positive long-term impacts on participants, such as empowerment and improved livelihoods (Gharesifard, Wehn, and van der Zaag 2019; Walker, Smigaj, and Tani 2021), efforts required to participate should be kept to a minimum and adequate support should be provided, as citizens bear the burden of labour and responsibility for doing the testing. In this study, mostly women were responsible for doing the testing. It is unclear how the additional workload of the testing affects intra-household dynamics of households, as the labour associated with self-supply management is already tiring for some households (Genter et al. 2023). In this study, the regular communication with enumerators was a key factor in maintaining participation, and it is unlikely this could be sustained as part of a long-term monitoring programme. It is also important to consider who controls and influences the initiative in the long-term, as well as the funding needed to sustain it. In order to put water quality monitoring by households into practice, the question needs to be addressed of whether households can report their water quality results to the competent authority and whether the authority can actively follow up and respond. This study showed that some participants were willing to pay some amount to continue the testing, however, given the technology and testing costs, financial support would likely be needed for lower-income households. The involvement of more actors such as government and non-profit organizations would require monitoring of actor-specific goals and objectives, and changes in those objectives over time. Ultimately, the long-term success of household-led monitoring depends on careful consideration of power dynamics, participation and institutional arrangements to sustain the initiative over the long-term.

Although participatory monitoring increased awareness about water quality, this study shows that monitoring alone was insufficient to improve the safety of self-supply water services. The study found no significant improvement in water quality at the self-supply source or point-of-use after the participatory monitoring. The prevalence of *E. coli* contamination at point-of-use remained a frequent concern for self-supply drinking water in the area, despite the common practice of boiling water. This suggests that further improvements in source water quality and safe water treatment and storage practices at the household level are critical for improving the safety of self-supply services. The relationship between rainfall and *E. coli* concentration at the self-supply source also suggests targeted efforts to improve household water treatment are most important during wetter periods.

Based on the study's findings, it is suggested that an adaption of the CPI framework be considered to better account for the interrelation between its dimensions (Figure 4). The previously outlined framework in this study already includes some adaptions of Gharesifard et al., (2019) CPI framework, such as placing the dimension of 'participation' at the centre and indicating the relationships between the key dimensions (Figure 1). It is further suggested that bi-directional interrelations be established between the dimensions of 'goals and objectives' to the dimensions of 'power dynamics', 'participation' and 'technology' (Figure 4). For example, the overarching goal of evaluating the feasibility of a participatory monitoring approach for self-supply services was influenced by various aspects, including the current institutional context (monitoring is by default the responsibility of households themselves), the willingness of households to participate, and the access to relevant necessary technologies. Additionally, it is suggested that the adaptation of the CPI framework should allow for the interrelation of aspects between dimensions, rather than rigid categorization in a single dimension (Figure 4). To give some examples, the research showed that the results were highly influenced by the efforts required for participation and the pattern of communication between participants and enumerators. The choice of communication technology, such as WhatsApp, resulted in the exclusion of some groups. The geographic scope not only influenced the dimension of 'participation' but also affected the 'goals and objectives'. For instance, the study focused on urban

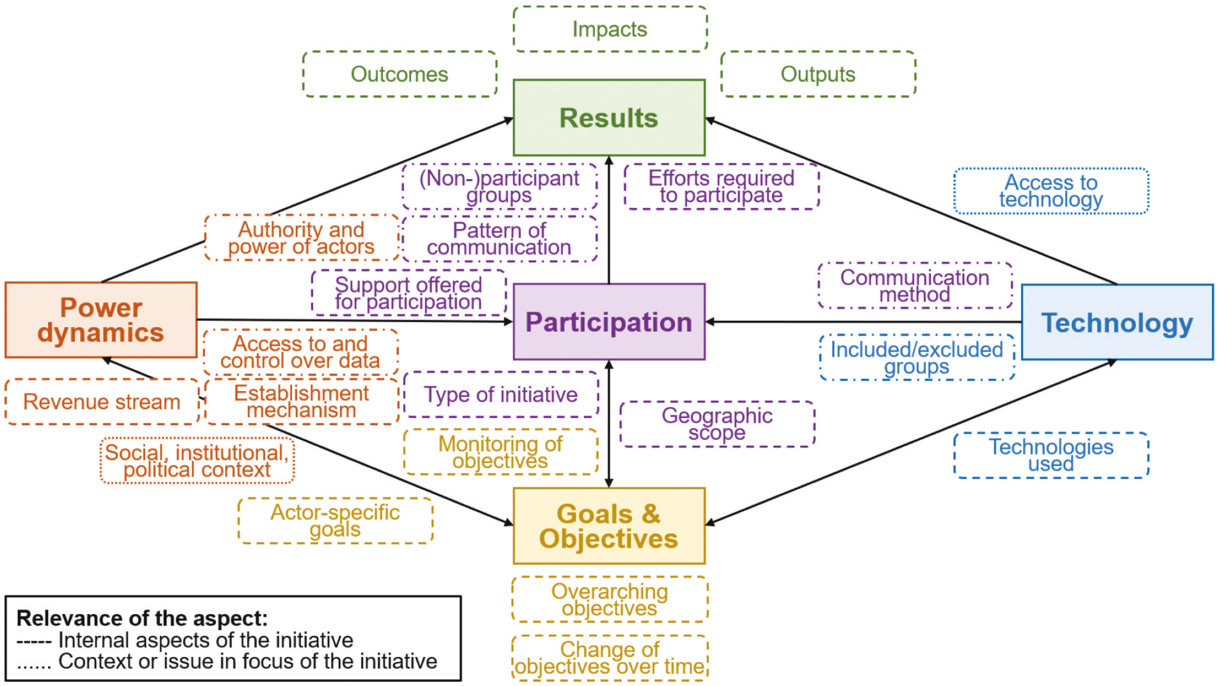

Figure 4. Adapted CPI framework of Gharesifard et al., (2019) accounting for interrelations between its dimensions and aspects.

groundwater self-supply, which may differ from other settings. Lastly, the support offered for participation highly influenced both 'participation' and 'power dynamics', as available resources were crucial factors. An adapted approach taking into account the interrelation between dimensions and the aspects that influence them prove a more comprehensive understanding of initiatives.

While the findings of this study contribute valuable insights into a participatory monitoring approach for microbial water quality in self-supply water services, it is important to acknowledge the limitations of this research. The relatively low number of participants limited the ability to fully explore the relationship between pre- and post-survey findings. Additionally, the participatory monitoring was conducted over a time period of six months, which limited the ability to assess long-term impacts beyond this timeframe. Therefore, future research should further investigate the effectiveness and sustainability of participatory monitoring approaches for self-supply services.

Conclusion

This study addresses a critical knowledge gap by establishing and evaluating a participatory monitoring approach for microbial water quality in self-supplied urban areas of Indonesia. The results have important implications for informing government decisions regarding self-supply in urban areas. This study highlights the potential benefits and limitations of participatory monitoring by citizens using field-based microbial water quality tests for self-supply services. While the approach can provide useful data for identifying the presence of microbial contamination in drinking water and raise awareness and understanding about water quality, participants can find it burdensome and lack motivation to test their water on a regular basis. As such, household-led testing conducted at reduced frequencies may be less demanding on households' workloads and still provide valuable data for governments to oversee trends in self-supply water quality over time. To make participatory monitoring attractive and feasible, water quality testing should be simple, inexpensive, and time-efficient, and needs complementary education or social marketing strategies for households. If participatory monitoring were to be scaled up or sustained, establishing an appropriate institutional architecture would be necessary. Finally, the study underscores the need for support strategies that prioritize safe water treatment and storage practices in urban areas where self-supply is common, as monitoring alone is unlikely to lead to water quality improvements.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

References

Aquagenx. 2013. *Aquagenx® CBT EC+TC Presence/Absence (P/A) Kit Instructions for Use: Drinking Water*.

Bain, R., J. Bartram, M. Elliott, R. Matthews, L. Mcmahan, R. Tung, P. Chuang, and S. Gundry. 2012. "A Summary Catalogue of Microbial Drinking Water Tests for Low and Medium Resource Settings." *International Journal of Environmental Research and Public Health* 9 (5): 1609–1625. https://doi.org/10.3390/ijerph9051609.

Bain, R., R. Johnston, and T. Slaymaker. 2020. "Drinking Water Quality and the SDGs." *NPJ Clean Water* 3 (1): 37. https://doi.org/10.1038/s41545-020-00085-z.

Bartram, J., L. Corrales, A. Davison, D. Deere, D. Drury, B. Gordon, G. Howard, A. Rinehold, and M. Stevens. 2009. *Water Safety Plan Manual: Step-By-Step Risk Management for Drinking-Water Suppliers*. Geneva: World Health Organization.

BPS Kota Bekasi. 2021. Bekasi Municipality in Figures 2021. *BPS Kota Bekasi*. 1907.3763.

Brouwer, S., P. W. J. J. van der Wielen, M. Schriks, M. Claassen, and J. Frijns. 2018. "Public Participation in Science: The Future and Value of Citizen Science in the Drinking Water Research." *Water (Switzerland)* 10 (3). https://doi.org/10.3390/w10030284.

Brown, J., A. Bir, and R. E. S. Bain. 2020. "Novel Methods for Global Water Safety Monitoring: Comparative Analysis of Low-Cost, Field-Ready E. Coli Assays." *NPJ Clean Water* 3 (1). https://doi.org/10.1038/s41545-020-0056-8.

Buytaert, W., Z. Zulkafli, S. Grainger, L. Acosta, T. C. Alemie, J. Bastiaensen, and B. De Bièvre. 2014. "Citizen Science in Hydrology and Water Resources: Opportunities for Knowledge Generation, Ecosystem Service Management, and Sustainable Development." In *Frontiers in Earth Science*, Vol. 2. Frontiers Media S.A. https://doi.org/10.3389/feart.2014.00026

Chávez García Silva, R., J. Grönwall, J. Van Der Kwast, K. Danert, and J. W. Foppen. 2020. "Estimating Domestic Self-Supply Groundwater Use in Urban Continental Africa." *Environmental Research Letters* 15 (10): 1040b2. https://doi.org/10.1088/1748-9326/ab9af9.

Conrad, C. C., and K. G. Hilchey. 2011. "A Review of Citizen Science and Community-Based Environmental Monitoring: Issues and Opportunities." *Environmental Monitoring and Assessment* 176 (1–4): 273–291. https://doi.org/10.1007/s10661-010-1582-5.

Crocker, J., and J. Bartram. 2014. "Comparison and Cost Analysis of Drinking Water Quality Monitoring Requirements versus Practice in Seven Developing Countries." *International Journal of Environmental Research and Public Health* 11 (7): 7333–7346. https://doi.org/10.3390/ijerph110707333.

Forrest, S. A., L. Holman, M. Murphy, and J. C. Vermaire. 2019. "Citizen Science Sampling Programs as a Technique for Monitoring Microplastic Pollution: Results, Lessons Learned and Recommendations for Working with Volunteers for Monitoring Plastic Pollution in Freshwater Ecosystems." *Environmental Monitoring and Assessment* 191 (3). https://doi.org/10.1007/s10661-019-7297-3.

Foster, S., R. Hirata, M. Eichholz, and M. F. Alam. 2022. "Urban Self-Supply from Groundwater—An Analysis of Management Aspects and Policy Needs." *Water* 14 (4): 575. https://doi.org/10.3390/w14040575.

Foster, T., C. Priadi, K. K. Kotra, M. Odagiri, E. C. Rand, and J. Willetts. 2021. "Self-Supplied Drinking Water in Low- and Middle-Income Countries in the Asia-Pacific." *NPJ Clean Water* 4 (1): 1–10. https://doi.org/10.1038/s41545-021-00121-6.

Genter, F., S. J. Marks, G. Clair-Caliot, D. S. Mugume, R. B. Johnston, R. E. Bain, and T. R. Julian. 2019. "Evaluation of the Novel Substrate RUG™ for the Detection of Escherichia coli in Water from Temperate (Zurich, Switzerland) and Tropical (Bushenyi, Uganda) Field Sites." *Environmental Science: Water Research & Technology* 5 (6): 1082–1091. https://doi.org/10.1039/C9EW00138G.

Genter, F., G. L. Putri, M. A. Pratama, C. Priadi, J. Willetts, and T. Foster. 2022. "Microbial Contamination of Groundwater Self-Supply in Urban Indonesia: Assessment of Sanitary and Socio-Economic Risk Factors." *Water Resources Research* 58 (10). https://doi.org/10.1029/2021wr031843.

Genter, F., G. L. Putri, E. Suleeman, L. Darmajanti, C. Priadi, T. Foster, J. Willetts, and M. Herrera. 2023. "Understanding Household Self-Supply Use and Management Using a Mixed-Methods Approach in Urban Indonesia." *PLOS Water* 2 (1): e0000070. https://doi.org/10.1371/journal.pwat.0000070.

Genter, F., J. Willetts, and T. Foster. 2021. "Faecal Contamination of Groundwater Self-Supply in Low- and Middle Income Countries: Systematic Review and Meta-Analysis." *Water Research* 201:117350. https://doi.org/10.1016/j.watres.2021.117350.

Gharesifard, M., U. Wehn, and P. van der Zaag. 2019. "What Influences the Establishment and Functioning of Community-Based Monitoring Initiatives of Water and Environment? A Conceptual Framework." *Canadian Journal of Fisheries and Aquatic Sciences* 579:124033. https://doi.org/10.1016/j.jhydrol.2019.124033.

Grönwall, J. T., M. Mulenga, and G. McGranahan. 2010. *Groundwater, self-supply and poor urban dwellers: A review with case studies of Bangalore and Lusaka* (No. 26). IIED.

Khatibi, F. S., and S. M. Yamakanamardi. 2010. *Microbial Water Quality Examination by H 2 S Strip in Mysore City and Training Women for Decrease of Water Pollution*. www.neptjournal.com.

MacLeod, C., R. Peletz, F. Kere, A. M'Baye, M. Onyango, S. Aw, M. E. H. Issabre, R. Tung, and R. Khush. 2019. "Are presence/absence microbial tests appropriate for monitoring large urban water supplies in sub-Saharan Africa?" *Water (Switzerland)* 11 (3): 491. https://doi.org/10.3390/w11030491.

Matwewe, F., K. Hyland, and J. Thomas. 2018. "Locally Produced Hydrogen Sulphide Detecting Water Quality Test Kits Increase Household Level Monitoring in Rural Tanzania." *Journal of Water and Health* 16 (3): 359–368. https://doi.org/10.2166/wh.2018.220.

National Population and Family Planning Board (BKKBN), Statistics Indonesia (BPS), Ministry of Health (Kemenkes), & ICF. 2018. *Indonesia Demographic and Health Survey* 2017. https://dhsprogram.com/pubs/pdf/FR342/FR342.pdf.

Pan, W. 2001. "Akaike's Information Criterion in Generalized Estimating Equations." *Biometrics* 57 (1): 120–125. https://doi.org/10.1111/j.0006-341X.2001.00120.x.

Peckenham, J. M., T. Thornton, and P. Peckenham. 2012. "Validation of Student Generated Data for Assessment of Groundwater Quality." *Journal of Science Education and Technology* 21 (2): 287–294. https://doi.org/10.1007/s10956-011-9317-0.

Priadi, C., L. Darmajanti, E. Suleeman, G. Putri, F. Genter, T. Foster, and J. Willetts. 2023. "Policy and regulatory context for self-supplied drinking water services in two cities in Indonesia: Priorities for managing risks." *Environmental Development* 100940. https://doi.org/10.1016/j.envdev.2023.100940.

Schertenleib, A., J. Sigrist, M. N. D. Friedrich, C. Ebi, F. Hammes, and S. J. Marks. 2019. "Construction of a Low-Cost Mobile Incubator for Field and Laboratory Use." *Journal of Visualized Experiments* 145 (145). https://doi.org/10.3791/58443.

WageIndicator. 2023. "Minimum Wage West Java." https://gajimu.com/garment/Salaries-in-Garment/minimum-wage-garment/provincial-and-regencies-minimum-wage-in-west-java.

Walker, D. W., M. Smigaj, and M. Tani. 2021. "The Benefits and Negative Impacts of Citizen Science Applications to Water as Experienced by Participants and Communities." *Wiley Interdisciplinary Reviews: Water* 8 (1). https://doi.org/10.1002/wat2.1488.

WHO. 2017. "Safely managed drinking water - thematic report on drinking water." http://apps.who.int/bookorders.

WHO. 2022. "Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First and Second Addenda."

WHO, & UNICEF. 2017. "Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First Addendum." (Vol. 53, Issue 9). https://doi.org/10.1017/CBO9781107415324.004.

WHO, & UNICEF. 2022. "Laboratory Assessment: Aquagenx CBT EC+TC MPN Kit."

Wright, J. A., H. Yang, K. Walker, S. Pedley, J. Elliott, and S. W. Gundry. 2012. "The H2S Test versus Standard Indicator Bacteria Tests for Faecal Contamination of Water: Systematic Review and Meta-Analysis." *Tropical Medicine & International Health* 17 (1): 94–105. https://doi.org/10.1111/j.1365-3156.2011.02887.x.

6.3 Summary

Chapter VI addresses RQ3 by evaluating an established household-led monitoring approach aimed at testing the microbial water quality of self-supply services. The findings suggest that the participatory monitoring approach can provide useful data for detecting faecal contamination in drinking water and raise awareness and understanding about water quality among households. However, households may perceive the monitoring process as burdensome, leading to a lack of motivation to test their water regularly. In order to transition self-supply services towards a safely managed water service, the study highlights the necessity of additional support strategies, as monitoring alone is unlikely to significantly impact drinking water safety. These may include improvements in source protection and strengthening of household water treatment.

This chapter focused on monitoring, which is part of the 'Governance and institutions' component, as monitoring water service delivery is essential for government regulation. Since self-supply is not monitored or regulated, and water quality monitoring and management is by default the responsibility of households themselves, the focus shifts to the 'Users' component. The chapter provided insights on these components and interactions in terms of monitoring, which has implications for informing governance and institutional decision regarding self-supply monitoring in urban Indonesia.

Chapter VII

7. Discussion

7.1 Overview

The PhD research explored the microbial water quality, use, management, and monitoring of self-supply water services in urban areas of Indonesia. **Chapter VII** evaluates and discusses the delivery of self-supply services with regard to current global monitoring criteria and socio-economic and gender dynamics. It also highlights implications and offers suggestions for further research to advance our understanding and inform improvements in self-supply service delivery.

It is important to note that in urban Indonesia, millions of people depend on self-supply for their water needs. As such, self-supply will persist for decades to come and transitioning away from this practice would be a long-term process. Therefore, efforts should be made to enhance self-supply, regardless of whether it is deemed an acceptable mode of water provision or not.

To conceptualise this synthesis, the adapted social-ecological system framework presented in **Chapter II** was used. Based on the findings of the PhD research, this chapter explores the interrelations between the social-ecological system core components of 'Water resources', 'Infrastructure', 'Users' and 'Governance and Institutions' and the implications for moving self-supply towards a safely managed water service in urban Indonesia. The purpose of the synthesis using the social-ecological system framework was to identify and highlight implications based on the findings of the PhD research questions, intended to move self-supply services towards a safely managed drinking water service.

The synthesis in this chapter is structured around six key discussion topics, which have been conceptualised based on the interrelations between the relevant social-ecological system components. The seven key discussion topics were identified based on the main findings of the PhD research questions.

The introductory paragraph of each key discussion topic provides a summary of the synthesis in the following paragraphs. It highlights the relevant social-ecological system components of the discussion topic and provides a rationale for the importance of that discussion topic. Additionally, it highlights the relevant findings of the PhD research questions. The introductory paragraph concludes with a summary of the implications for governance and institutions.

The adapted social-ecological system framework with the relevant highlighted components is illustrated at the beginning of each discussion topic. The blue shaded components highlight the relevant discussion focus of the specific discussion topic, while the grey shaded components hold relevance across all the topics. The 'Governance and institutions' component encompass a monitoring focus, however, the implications of the synthesis will provide guidance to governance and institutions on how to respond to self-supply.

Building on these six discussion topics, the chapter critically reflects on the adaption and use of the social-ecological system approach in the final section.

7.2 Groundwater resources

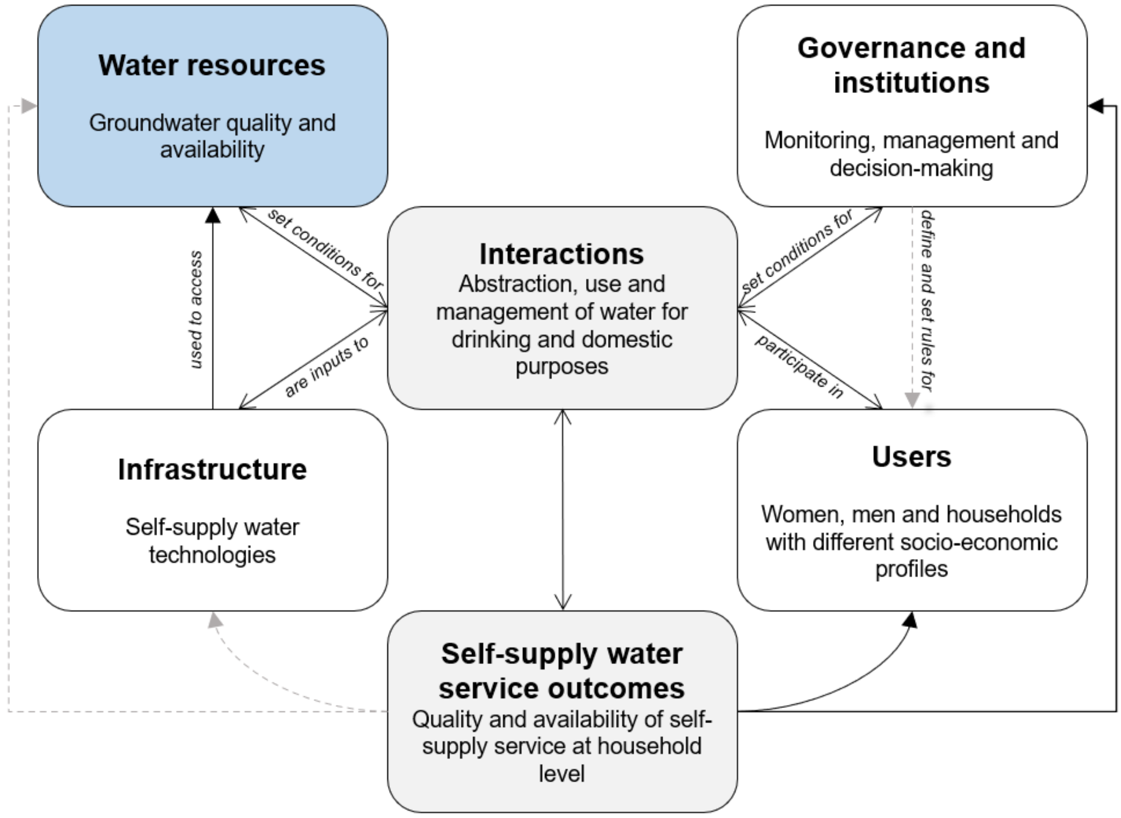


Figure 10: The 'Water resources' component includes the quality and availability of groundwater sources. All three research questions are situated within this component, with RQ1 and RQ2 having greater focus on that component.

The social-ecological system framework shows that water resources, encompassing both the quality and availability of groundwater, set conditions for the self-supply water service outcomes at household level (Figure 10). Therefore it is crucial to consider the 'Water resources' component and its interrelation to 'Self-supply water service outcomes' at household level to move self-supply towards a safely managed water service. Findings from RQ2 indicate that households prefer private groundwater sources to meet drinking and domestic needs, however, users also perceived declines in both the quality and availability of groundwater resources. Concomitantly, findings from RQ1 underscore the potential risk posed by on-site sanitation systems to the quality of groundwater resources. The implications of these findings are a call for increased efforts by governments and institutions to holistically manage groundwater resources. Efforts that include both quantity and quality management will be critical to the sustainable use of this water resource.

Groundwater is widely used as a preferred source of drinking water. In Southeast Asia and the Pacific, 62% of households in urban areas rely on groundwater as their primary drinking water source, with 90% of urban households in Indonesia depending on it (Carrard et al., 2019). In Indonesia, groundwater is supplied to urban households through point source facilities, piped systems, and packaged water (Carrard et al., 2019). Self-supply using groundwater was estimated to be the main drinking water source for a quarter of the urban Indonesian population (36 million people) (Foster et al., 2021). Also, the PhD research showed that groundwater self-supply was the preferred source of drinking water over alternative water sources in case study locations in Indonesia. In the cities of Bekasi and Metro, a significant proportion of the surveyed households relied on private boreholes (31%) or private dug wells (26%) as their primary drinking water sources. Groundwater self-supply was the preferred option due to its perceived safety, taste, and appearance at both study sites. It should be noted that the overall dependence on self-supply as a water source might be underestimated, when the secondary source of domestic water is not given (Sutton & Butterworth, 2021). For example, in urban areas, self-supply is often used alongside bottled water as a popular primary source of drinking water (Sutton & Butterworth, 2021). The high reliance on groundwater self-supply for drinking water in Bekasi and Metro emphasises the need for sustainable management and protection of the quality of this vital resource.

Groundwater serves a vital role not only as a drinking water source but also for domestic purposes. The PhD research showed that for domestic purposes, 47% used groundwater self-supply from private boreholes, and 35% from dug wells. In terms of choosing a domestic water source, appearance, reliability, and safety were the most important factors in Bekasi, while safety was followed by convenience and reliability in Metro. Groundwater can bring many benefits because it is often more consistent in quantity and quality than surface water sources (Howard et al., 2016). It can also be extracted using simple, low-cost technologies, making it accessible to households in areas where piped water systems are not available. Sutton and Butterworth (2021) highlighted the presence of a groundwater self-supply service on a household's premises as a key value of self-supply. This favours its expanded use for domestic purposes such as bathing, washing and cooking (Sutton & Butterworth, 2021). The widespread use of groundwater self-supply for domestic purposes underscores its value as an on-site accessible water source, and highlights the importance of considering the criteria of water availability when needed.

The regulation and integration of household self-supply within water management frameworks is essential for balancing its potential impact on groundwater resources with meeting the diverse water needs of urban communities. Small-scale household self-supply for multiple uses is assumed to have minimal impact on groundwater resources (Sutton & Butterworth, 2021). However, it needs to be regulated when the pressure on sources and scale of abstraction becomes too great (Sutton & Butterworth, 2021). As such, it is important to quantify and incorporate self-supply as an integral part of evolving urban water supply systems, ensuring its safety and sustainability alongside other supply options. Exploring the specific impacts of household self-supply on groundwater resources is crucial, including factors such as magnitude of withdrawals relative to other groundwater supplies. Additionally, attention should be directed towards developing regulatory frameworks and management strategies that integrate self-supply into the diverse range of available water supply options.

The sustainability of self-supply systems in urban Indonesia and elsewhere might be a growing concern due to perceived declines in both the quality and availability of groundwater by users, highlighting the need to understand the underlying causes and potential solutions to address this issue. Groundwater resources are at great environmental risk due to anthropogenic overexploitation and pollution in urban Indonesia and elsewhere (Carrard et al., 2019). Estimates suggest that globally 80% of aquifers are overexploited and that about 1.7 billion people live in areas where groundwater resources are under threat (Gleeson et al., 2012). This raises concerns about the sustainability of self-supply systems. Self-supply users in Bekasi and Metro have reported declines in both the quality and availability of water over time. The perceived declines in quality and availability of groundwater in urban Indonesia suggests a need to validate the perceived declines in groundwater quality and availability and to understand the underlying causes and potential solutions to address this issue.

On-site sanitation has been identified as a hazard factor for faecal contamination of groundwater, which may affect the quality of self-supply. In Bekasi City, 66% of the surveyed households have access to basic sanitation[1], while 29% and 2% have access to unimproved and limited sanitation, respectively (Septarini et al., 2021). In Bekasi city, most households use pour-flush latrines coupled with containment in the form of septic tanks or cubluks. Cubluks are septic tanks that are open bottomed pits without a concrete base (World Bank, 2013). Most of the tank facilities do not comply with the technical standards for septic tank design in Bekasi city, which were set by the Indonesia National Standard (Septarini et al., 2021). Additionally, containment was mostly unmanaged, with 71% of containment never being emptied, leading to accumulation of faecal sludge (Septarini et al., 2021). This can have implications for the groundwater quality of self-supply systems. Therefore, further investigation is required on how on-site sanitation affects the water quality of self-supply and whether improvements of sanitation facilities reduce faecal contamination of self-supply systems.

[1] Basic sanitation refers to the use of improved facilities that are not shared with other households (WHO, 2022). Improved sanitation facilities, such as septic tanks that store and treat excreta on-site, have on-site storage facilities that effectively separate excreta from users and the surface environment (containment) (WHO, 2022).

Results from Bekasi suggest that lateral separation between sanitation systems and self-supply wells may not be sufficient in preventing the transmission of faecal contamination. Regulations stipulate a minimum distance between shallow wells and a pollution source of 10 m, which is often not complied with (Appendix III of Minister of Public Works Reg. 33/PRT/M/2016). However, the recommended distance and appropriate siting of sanitation systems and groundwater wells may vary depending on the specific soil and hydrological conditions in the particular environment (Graham & Polizzotto, 2013). The results of the PhD research, which indicate that there may be insufficient lateral distance between sanitation systems and self-supply wells, should be interpreted with caution. These findings may have been influenced by confounding factors, such as population density. Additionally, it is important to note that the distances measured between sanitation systems and self-supply wells were based on households' estimates. Further evidence on the risk to groundwater from on-site sanitation and other hazards and pathway factors is needed, such as investigating the distance and density of on-site sanitation systems and self-supply wells, including the implications of groundwater levels and rainfall.

7.3 Infrastructure used to access water resources

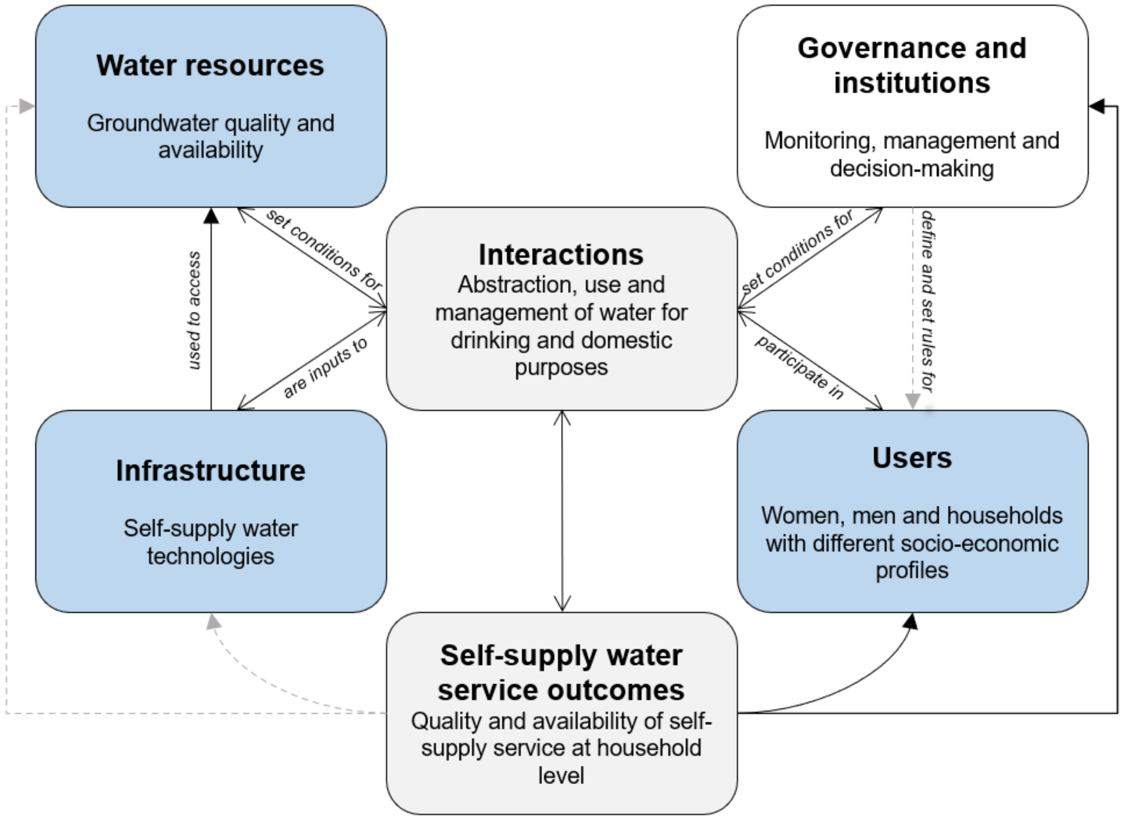


Figure 11: The 'Infrastructure' component includes self-supply technologies, which are used to access water resources.

The infrastructure, encompassing various self-supply water technologies such as boreholes and dug wells, is used to access groundwater resources. The interconnections within the social-ecological system highlight the pivotal role of the 'Infrastructure' component in determining groundwater quality and availability for users. The different socio-economic profiles of users may, in turn, affect the conditions for self-supply water technologies (Figure 11). As such, it is imperative to emphasise the importance of the infrastructure used for groundwater access in ensuring the quality and availability of self-supplied groundwater. Findings from RQ1 indicate that improved self-supply technologies yield better water quality than unimproved ones, and improper construction can increase the risk of contamination. RQ2 uncovers the users' desire to upgrade unimproved self-supply technologies, albeit hindered by financial constraints. Moreover, even when groundwater self-supply is preferred, infrastructure upgrades are sought to enhance the quality and availability of groundwater. These findings underscore the necessity of careful consideration of the roles of the private sector and local government in supporting and facilitating improvements in self-supply infrastructure.

Improved self-supply infrastructure plays a key role in ensuring better water quality. The microbial water quality of boreholes and dug wells vary greatly, with boreholes generally providing better quality water, suggesting the need to improve the infrastructure of self-supply sources. Dug wells, especially unimproved ones, are more susceptible to microbial contamination than boreholes due to their shallow depth and uncovered nature. Boreholes, on the other hand, are typically deeper, have more effective natural filtration with a more protected well head. However, improper construction or maintenance can still lead to contamination in boreholes, as observed in Metro and Bekasi, where boreholes lacking a concrete platform or having a shallow depth showed increased risk of contamination. Self-supply services in urban Indonesia predominantly consist of boreholes and dug wells that lack sanitary safeguards. Infrastructure improvements are critical to advancing self-supply towards a safely managed water service.

The shift by users from dug wells to boreholes based on water quality perceptions is constrained by cost barriers and underscores the imperative of improving self-supply sources, while addressing disparities and enhancing affordability through targeted financial support. Users generally perceive water from boreholes to be of better quality than that from dug wells, which has led many dug well owners to construct boreholes instead. However, the high construction costs of boreholes were a significant barrier for some dug well owners. In Metro, where many households still rely on unprotected dug wells, poorer households were found to have a higher likelihood of having contaminated self-supply water compared to wealthier households. To meet the criteria for safely managed water services, self-supply sources must be improved, and unprotected dug wells should be replaced with boreholes or upgraded. Insights need to be gained to make such infrastructure upgrades more affordable and accessible to a broader range of households, including consideration of targeted financial support.

Improving infrastructure for self-supply water sources requires adherence to construction standards, education and training for well drillers, and regulatory compliance. Inadequate infrastructure is a significant risk factor for the contamination of self-supply water sources in urban Indonesia, such as the absence of concrete platforms and insufficient borehole depth. Therefore, it is crucial to follow proper construction standards for borehole drilling and provide education and training to well drillers. Self-supply water systems in urban Indonesia involve many informal and small industry service providers, including suppliers and vendors of equipment and materials, well diggers, and pump technicians. These actors can be educated on borehole construction and groundwater conservation by local implementing agencies (Priadi et al., 2023). In rural sub-Saharan Africa, for instance, well-digging training has been implemented in different regions, with documented examples of successful training for water supply entrepreneurs and enterprises (Sutton & Butterworth, 2021). In urban Indonesia, specific construction standards and guidelines for boreholes and protected wells exist. However, in-depth interviews with well drillers showed that infrastructure does not comply with guidelines and regulations, and well drillers lack formal training or information about regulations (Priadi et al., 2023). To improve infrastructure and ensure compliance with regulations, it is recommended that regulations are properly enforced in consideration of self-supply, and training is offered to well diggers with potential registration and drilling permits for regulation.

Self-supply infrastructure has also been shown to have an influence on the availability of water to individual households. The availability of water when needed is crucial to meet the safely managed water service criteria, and while self-supply seems to generally provide this in urban Indonesia, there are still mixed perceptions of availability and consequent infrastructure improvements. Self-supply is an established fact in urban Indonesia and has been shown to play a vital role in meeting household water needs. According to the results of the quantitative household survey, it seems that households relying on self-supply generally have water available when needed. Nearly all households reported having water available in the previous two weeks. However, the closer qualitative examination revealed that households relying on dug wells reported mixed perceptions of water availability, with poor availability during the dry season. This often leads to the deepening or replacement of shallow dug wells with deeper boreholes of those households that could afford it.

The shift towards demanding higher-quality services in urban Indonesia highlights the need for government to consider the roles of the private sector in regulating self-supply. Fischer et al. (2020) viewed the shift in demand towards higher quality services in rural Bangladesh as an opportunity to align user demand and payments with regulated services, since it is more politically palatable to provide new infrastructure over regulating the use of existing infrastructure. In the rural sub-Saharan Africa self-supply context, the main actors are in the private sector with NGO advice supporting the building of markets, while government is not yet involved in the development of services (Sutton & Butterworth, 2021). In urban Indonesia, self-supply is the responsibility of individual households but may depend highly on the private sector, such as informal suppliers providing products and services in support of private water supply. This highlights the need to carefully examine the roles of the private sector in providing self-supply infrastructure and service in urban Indonesia.

In addition, the roles of the local government should be emphasised in supporting equitable environments for access to safe self-supply. Based on the human right to water, the government is obligated to ensure that the needs to access safe water for all is met (UN General Assembly, 2010). Accordingly, in the context of urban self-supply in Indonesia, the responsibility lies with local governments as the actor obligated to create the conditions to meet these needs. Gero and Willetts (2020) emphasised that if the private sector is to play an effective role in improving WASH coverage, it is important to consider more than just direct support to enterprises. To ensure sustainability, local governments and other actors should create an effective enabling environment for enterprises. Important local government roles include training and business development support to enterprises, linking demand and supply by promoting local enterprises, supporting associations of entrepreneurs, providing targeted subsidies or financing to catalyse private sector engagement or to facilitate access for poor and disadvantaged people, and setting and monitoring quality standards and accreditation of products and services (Gero & Willetts, 2020). With regard to self-supply in urban Indonesia, a stronger evidence base to develop strategic and targeted programmes is needed involving a range of actors including private sector actors, WASH markets and policymakers.

7.4 Consideration of water quality at point-of-use

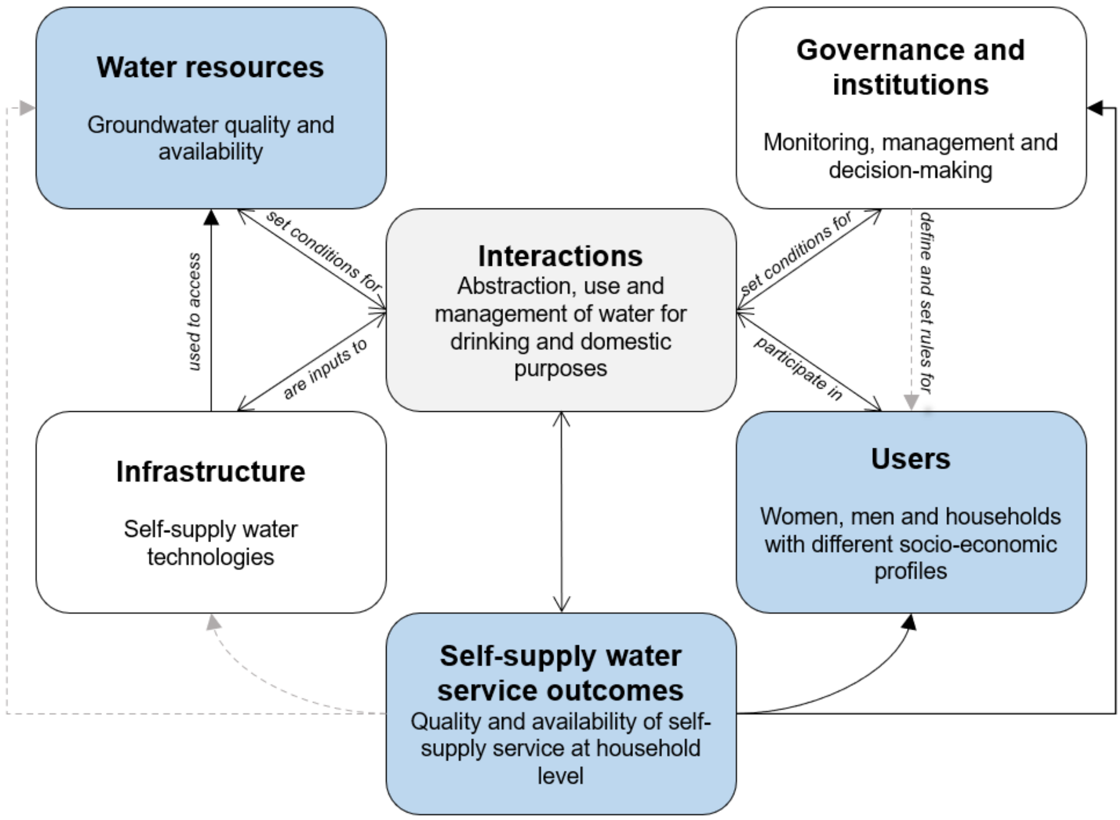


Figure 12: The 'Self-supply water service outcomes' component includes the quality and availability of self-supply service at household level. These are affected by users through interactions including abstraction, use and management of water resources.

Considering the quality and availability of self-supply at household level is crucial. The social-ecological system framework directly links 'Self-supply water service outcomes' with the 'Users' components, as the self-supply water at the household level is what users actually consume. Conversely, users exert influence on self-supplied water service outcomes through their interactions in the abstraction, use, and management of water resources. 'Water resources' set conditions for the interactions and are indirectly linked to the 'Self-supply water service outcomes' at household level (Figure 12). Findings from RQ1 indicate that water quality at the point-of-use remains at risk of faecal contamination despite the practice of boiling as a water treatment method. RQ2 reveals that boiling is labour intensive and challenging for some households to manage, raising the need to explore alternative household water treatment methods. Additionally, RQ2 underscores that many households still rely on wood for fuel, prompting questions about the reasons behind these fuel choices. These findings imply the critical importance of considering the household level in decision-making processes and providing education on proper household water treatment practices.

The PhD research findings revealed that groundwater self-supply quality improved at point-of-use but was still not entirely free from faecal contamination despite boiling practices, emphasising the importance of educating households on proper water treatment and storage. *E. coli* was detected in 66% of self-supply sources, but due to boiling practices, it was found less frequently at the household level, present in 30% of point-of-use sources. Self-supply users have adopted water treatment practices in response to the lack of access to safe water sources. However, sustained use is essential if household water treatment technology is to provide continued protection, which is difficult to achieve (Sobsey et al., 2008). Education about water quality needs to be provided to households to raise awareness regarding proper water treatment and storage. This is especially true in Bekasi, where despite water treatment, source water quality was still related to water quality at the point-of-use. In Metro, further knowledge is needed on the specific factors that contribute to the persistence of faecal contamination from the self-supply source to point-of-use, as water quality at point-of-use was not related to the quality at source.

To minimise the risk of self-supply contamination, local governments should take steps to protect water quality and monitor water quality both at the source and the point-of-use. While source water quality determines the criteria for being free from faecal contamination in the context of national monitoring, the question arises about whether point-of-use water is more important in determining the criteria for being free from faecal contamination for households. To meet the criteria of being free from contamination at household level, it is essential to minimise the risks of contamination at source, but also to consider treatment and point-of-use quality. Thus, it is vital to ensure that measures are in place to protect groundwater quality, and that households are educated on proper treatment and handling of water to reduce the risk of contamination. Investigations are needed on how monitoring and enforcement mechanisms can be employed by duty-bearers to ensure compliance with water quality standards.

Boiling was found to be the most common water treatment method in both Bekasi and Metro; however, this approach was found to be labour intensive, which highlights the need to consider alternative treatment technologies for wider adoption. Quantitative results of the household survey suggest that households almost always boil their self-supply water prior to consumption, however, qualitative in-depth interviews showed that the labour involved in boiling water could not always be managed. This is consistent with a study by Psutka et al. (2011) that suggested overreporting and inconsistent compliance. This raises the question about the promotion of alternative household water technologies that might be less labour intensive.

Besides boiling, there are other effective water treatment methods available; however, the adoption of these methods may be challenging. Analysis of household water treatment interventions showed a large degree of variation in the reported effectiveness of household water treatment solutions and has indicated that ceramic water filters are superior to other treatment technologies such as biosand filters and chlorine (Hunter, 2009). However, the study of Cohen et al. (2017) in the context of rural China highlighted the challenge of the poorly understood socio-cultural and behavioural determinants for household water treatment adoption and the cultural preference for boiling. Therefore, Cohen et al. (2017) suggested building upon existing preferences for boiled water and promoting the expanded use of electric kettles in areas which lack a safe centralised supply but have reliable electricity access. Electric kettles tend to be fast, easy and convenient means of continuing their pre-existing boiling behaviour (Cohen et al., 2017). The study also mentioned the potential barriers to adoption such as one-time investment costs and associated electricity costs.

The difficulty of adopting new household treatment technologies was also shown in a study by Fagerli et al. (2017) in Indonesia. The study compared traditional boiling practices with household water treatment using a commercial chlorination product, and found lower levels of *E. coli* contamination in water treated with chlorine compared with households that boiled their water (Fagerli et al., 2017). Even if chlorine treatment was associated with a lower median cost per day (US$0.26) than boiling using kerosene (US$0.01), adoption was very low, and the traditional boiling habit was preferred (Fagerli et al., 2017).

Analyses across different contexts to understand the effectiveness of successful household water treatment adoption conclude that the effectiveness of household water treatment adoption depends on a variety of complex interactions among socio-environmental conditions (Clasen et al., 2008; Daniel et al., 2018). The socio-environmental and behavioural determinants for household water treatment adoption might be highly context specific. Therefore, the determinants and cultural preferences for household water treatment adoption in the urban Indonesian self-supply context must first be understood before alternative household water technologies can be promoted.

Household fuel choices for water boiling and cooking in urban Indonesia, including the adoption of alternative technologies, are influenced by a range of factors, including household income, access to reliable electricity, and government programmes aimed at promoting clean energy. In the study sites in Bekasi and Metro, liquified petroleum gas (LPG) was the most frequently used fuel for water boiling by 96% of households. Despite being a potential source of household air pollution and harmful to health, wood was still used as a fuel by 28% of households in Metro. The findings are consistent with a study by (Andadari et al., 2014), that evaluated the impact of a large government programme to substitute LPG for kerosene in Indonesia and found that the programme was very effective in causing a large-scale shift from kerosene to LPG, and that higher income households in suburban areas benefitted disproportionally strong. However, there are still knowledge gaps regarding the underlying causes of the fuel choices for self-suppliers in urban areas of Indonesia.

The success of government initiatives and the adaption of alternative technologies may vary in different contexts. In 2021, the Indonesian government introduced the induction cooking conversion programme from LPG to an induction stove to reduce LPG subsidy (Hakam et al., 2022). The study of Hakam et al. (2022) concluded for various possible economic scenarios, that the application of induction stoves for cooking is more economical compared to LPG stoves (Hakam et al., 2022). However, a study in the context of peri-urban and rural Ecuador showed that the conversion programme from LPG to induction stove is considered as unsuccessful (Gould et al., 2020). LPG was still frequently used and 50% of rural households and 20% of peri-urban households still used firewood for cooking (Gould et al., 2020). Although the Indonesian government has introduced a conversion programme from LPG to induction stoves, the success of such initiatives may be context-specific, and additional research is needed to understand the challenges and opportunities for promoting cleaner and more affordable household energy sources that can benefit all households, regardless of income. Efforts to promote cleaner and more affordable household energy sources should consider the inclusion and financial support for low-income self-suppliers to ensure that all households can benefit from the adoption of alternative technologies.

7.5 Household participation and engagement in self-supply monitoring

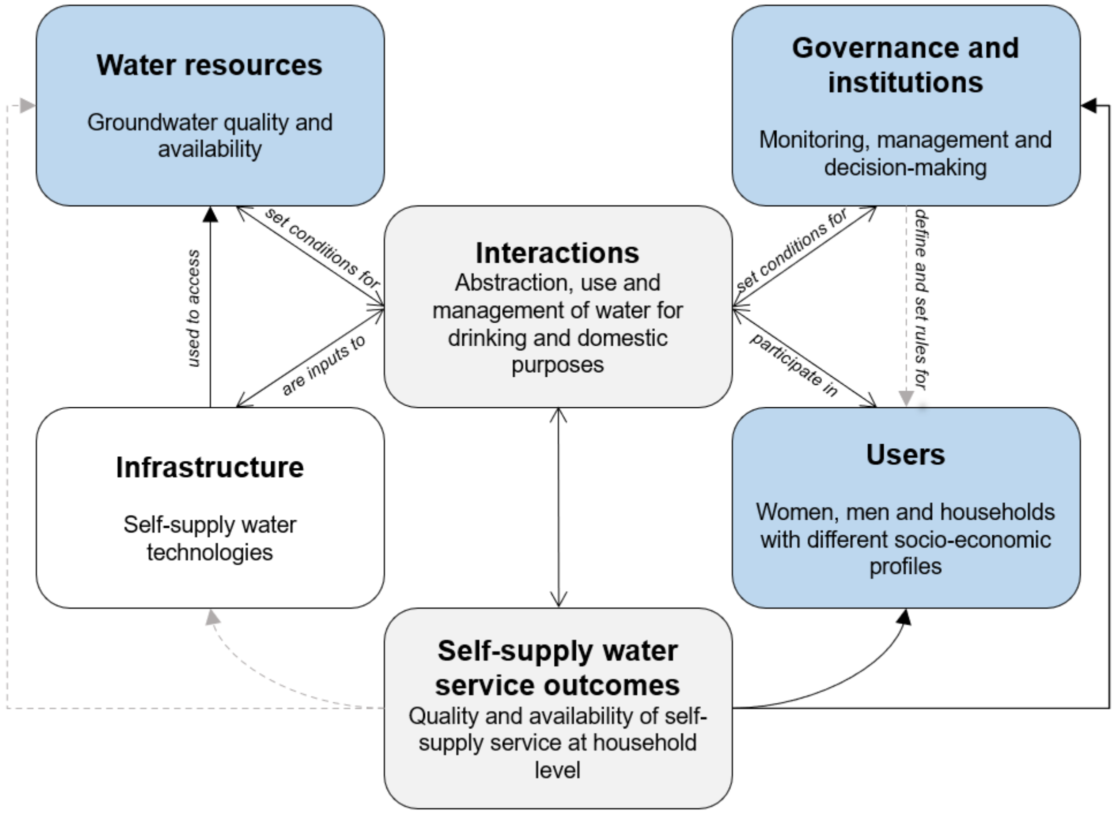


Figure 13: The 'Governance and institutions' component encompasses a monitoring focus, which is explored as part of the participatory monitoring approach. In the participatory monitoring approach, users test groundwater quality at the source and water quality of self-supply services at household level as a potential approach to offer governments ongoing oversight of trends.

Monitoring self-supply water quality is a critical yet under-researched area that plays an important role in understanding self-supply service outcomes and ensuring the provision of safe and reliable water services, and has implications for informing government decisions regarding self-supply. The social-ecological system component of 'Governance and institutions' encompasses a monitoring focus (Figure 13). Governance regulations on drinking water are often unrealistic for the large number of privately owned self-supply systems, as such self-supply is not monitored or regulated and, by default, monitoring water quality sits with households themselves. Therefore, the link in the social-ecological system framework between the components of 'Governance and institutions' and 'Users' is not clearly pronounced (Figure 13).

Monitoring serves a range of purposes within the context of water management in general, and within the context of this PhD research. Overall, the PhD research assesses the extent to which self-supply fulfills the SDG criteria of a safely managed water service in the context of global monitoring. The PhD research employed monitoring for research purposes to characterise and identify existing water quality problems related to self-supply in RQ1. RQ1 showed that water quality monitoring that accounts for seasonal variability is crucial to ensure safe water services at all times, and that regular water quality testing complemented by sanitary inspections is required to understand the contamination risks of self-supply sources.

On the other hand, RQ3 focused on a participatory approach for on-going water quality monitoring. Household-led testing of microbial water quality could fulfil an important monitoring role in self-supply contexts with potential relevance for health agencies and local governments to oversee levels of service and trends over time. In the participatory monitoring approach, users tested groundwater quality at the source and water quality of self-supply services at household level. RQ3 showed that the participatory monitoring approach provided reliable water quality results, and increased awareness of water quality, however, nearly half of the household dropped out of the monitoring and increased awareness did not translate into actions that improved water quality within the study period. Participants expressed varying levels of willingness to pay and more research is needed on cost-effective strategies to make monitoring affordable for households. RQ3 concluded that less frequent water quality testing by households might be valuable to oversee ongoing trends in self-supply water quality, but may have little impact on drinking water safety unless accompanied by support to improve source protection and strengthen household water treatment and safe storage practices.

Various water quality monitoring approaches exist, however, the literature currently lacks documentation on the methods of monitoring and reporting microbial water quality in self-supply services. Conducting frequent monitoring of self-supply services presents significant challenges, as self-supply serves individual households, which in urban Indonesia involves millions of water sources. Household responsibility for self-supply introduces additional barriers to monitoring, including limited access to laboratories, inadequate training, and budgetary constraints. One specific monitoring practice explored in this PhD research is participatory water quality monitoring.

For on-going monitoring to track levels and trends in self-supply water quality, involving households in the monitoring process may present a promising approach; however, critical concerns need to be addressed before implementation. In places like Kota Bekasi, where self-supply lacks formal monitoring and regulation, the responsibility for monitoring and managing water quality typically falls on households themselves. In accordance with Ministry of Health (MoH) regulation no. 492/2010, drinking water operators are obligated to ensure water quality standards, with support and oversight from local government and public health agencies (Priadi et al., 2023). According to MoH regulation no. 736/2010, central and local governments are required to conduct twice-yearly sanitary inspections of non-piped drinking water supplies, including dug wells and boreholes. Facilities at high and very high risk of contamination are expected to make improvements to their water and sanitation systems (Priadi et al., 2023). Those at low and medium risk should conduct monthly microbial and physical parameter tests and biannual tests for compulsory and optional chemical parameters (Priadi et al., 2023). However, these regulations are often impractical for the numerous privately owned self-supply systems in Indonesia and are frequently overlooked. The introduction of household-led water quality testing has the potential to aid in meeting regulatory standards and enhancing oversight of self-supply water quality. Yet, to implement household water quality monitoring effectively, critical questions must be addressed, including whether households can report their water quality results to the relevant authorities and whether the authorities can actively follow up and respond.

The PhD research demonstrated both the value and challenge of engaging self-supply users in the monitoring process, particularly through field-based microbial water quality tests. This approach yielded useful data for identifying microbial contamination in drinking water and revealed that the proportions of contaminated samples varied over time, suggesting that testing frequency should be sufficiently frequent to capture temporal variations in water quality. However, the high participant dropout rate suggests that the monitoring needs to be made more attractive, less time-consuming, and more affordable to achieve uptake at a larger scale. Conducting household-led testing at reduced frequencies may still be a viable solution that may be less demanding on households' workloads and provides valuable data for governments to oversee trends in self-supply water quality over time. Additionally, decreasing the frequency of testing can reduce costs, making water quality monitoring more affordable for households. Exploring optimal testing intervals that balance data significance, participant burden and resource constraints can provide valuable insights.

Cost-effective strategies need to be identified to make water quality monitoring more affordable for households. The findings of the PhD research revealed that participants who completed the monitoring expressed varying levels of willingness to pay for continued water quality testing. Willingness to pay anything (versus pay nothing) for continued water quality testing was expressed as likely by 38% of participants who completed the monitoring, as neutral by 56% of participants and as unlikely by 6% of participants. It should be noted that caution is needed in interpreting this indication as the number of participants who completed the monitoring was low. If self-supply users are expected to pay for water quality surveillance, it is necessary to understand their willingness to pay and determine the appropriate frequency of testing.

Self-supply monitoring approaches should be accompanied by targeted support strategies to improve water quality. The findings of the PhD research indicate that engaging self-supply users in the monitoring process through field-based microbial water quality tests has proven effective in raising awareness and enhancing understanding about water quality. However, participatory water quality monitoring alone may not directly improve water quality or have a significant impact on water resource management processes without additional support strategies. Additional support strategies and interventions are needed to complement participatory monitoring efforts and translate awareness into tangible improvements in water quality and resource management outcomes. This highlights the importance of integrating monitoring initiatives with targeted support measures, such as capacity-building programmes, regulatory interventions, and infrastructure enhancements.

However, participatory water quality monitoring without additional support strategies can still provide valuable guidance for governments to develop support strategies. Participatory monitoring could offer governments with an oversight of trends if water quality data is shared, and appropriate systems are put in place. Further, engaging households in the monitoring process can help build trust between authorities and society and ensure that the monitoring process reflects self-supply users' needs and concerns (Walker et al., 2021). As individual self-supply users are responsible for monitoring their own water quality, it is important to consider monitoring strategies, and while our approach of household-led testing at reduced frequencies may be a potential solution, further research is needed to determine its feasibility of implementation.

While a participatory monitoring approach could offer governments ongoing oversight of trends, it is essential to recognise that frequent water quality monitoring, extending beyond single, one-time *E. coli* tests, is imperative. Such monitoring is required to comprehensively assess the multifaceted risks associated with faecal contamination in self-supply, which are influenced by factors like seasonality and infrastructure types. Moreover, this comprehensive monitoring also helps to identify targeted support strategies, enabling authorities to address specific challenges in safeguarding water quality within self-supply systems.

Frequent water quality monitoring that accounts for seasonal variation is crucial to ensure safe water services at all times. Single one-time measurements of *E. coli* during wet and dry seasons showed that self-supply samples were frequently contaminated at the source and point-of-use. However, the associations between seasonality and microbial water quality yielded mixed results. This suggests that single one-time water quality results are insufficient to represent the safety of self-supply sources. The results of the PhD research are consistent with other studies that emphasise the need for frequent water quality monitoring to go beyond single one-time *E. coli* tests to make a statement about water safety (Charles et al., 2020; Kostyla et al., 2015). Longitudinal monitoring involving frequent water quality monitoring over an extended period would be beneficial to capture seasonal variations and investigate the underlying factors that contribute to the mixed results in the associations between seasonality and microbial water quality in self-supply sources.

Water quality monitoring of self-supply services could be accompanied by sanitary inspections. In the literature, evidence on the correlation between sanitary risk score and microbial water quality is mixed (E. Kelly et al., 2020, 2021). However, sanitary inspections and water quality analysis are distinct and complementary tools, serving important purposes in the on-going process of ensuring water safety (E. Kelly et al., 2020, 2021). The PhD research findings suggest that seasonality plays a greater role in influencing water quality for certain infrastructure types such as improved sources, while unimproved sources pose a high risk of contamination irrespective of seasonality. These findings underscore the importance of incorporating sanitary inspections into monitoring approaches, complementing water quality testing. By combining these two aspects, the specific challenges associated with different infrastructure types and the potential risks of contamination, including the impact of seasonality, can be considered.

There is a need for more comprehensive monitoring in global monitoring databases such as the JMP to accurately capture progress on household drinking water services, including consideration of self-supply. The findings from this PhD research, which highlight an overlooked water service model and consider gender dimensions, wealth factors, and point-of-use water quality, extend global monitoring frameworks by adding depth to the understanding of water services. In the context of Indonesia, these results can inform national monitoring efforts by providing a more comprehensive view of water access, which is essential for accurate reporting and policy decisions. Official monitoring can benefit from integrating data on self-supply sources to capture a more inclusive picture of water access. This highlights the importance of nationally representative surveys, which can enable monitoring of service levels for self-supply, in contrast to relying solely on administrative data from utilities.

7.6 Self-supply use and management by households

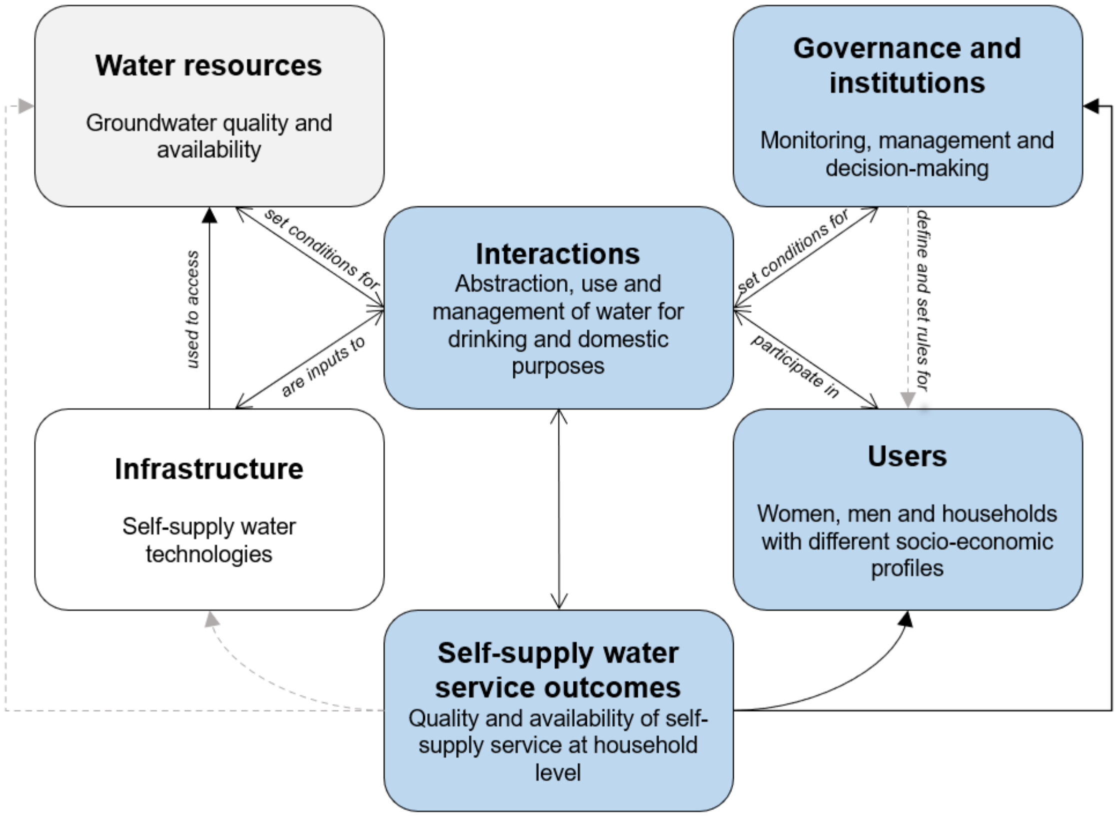


Figure 14: The 'Interactions' component includes the abstraction, use and management of water for drinking and domestic purposes. Users abstract, use, and manage self-supplied water, directly impacting the self-supply water service outcomes, including quality and availability at household level, which, in turn, influences the users. The 'Governance and institutions' component includes management and decision-making processes. In the context of self-supply, these processes are conducted by the users themselves.

Use and management of self-supply services is crucial as it determines water service outcomes at household levels, which has an influence on users. The social-ecological system framework component of 'Interactions', including water management practices such as abstracting, using and managing of water for drinking and domestic purposes, occupies a central position within the framework because it has a direct influence on all components of the framework. Users include women, men and households who benefit from and interact with water resources and service outcomes (Figure 14). Management and decision-making processes are relevant to governance, which in the case of self-supply, is the responsibility of the users themselves. RQ2 emphasises the user's perspective and their interactions with water resources and service outcomes. As self-supply services are privately owned, management practices might be different from other water supplies. The PhD research showed that households had a clear preference for their own self-supply water. Moreover, collaboration between women and men in terms of responsibilities, management, and decision-making was common in the self-supply context, indicating mutual strong interest in its success. Although self-supply was the preferred water source, alternative sources such as refill water and public piped systems played an important role in supplementing inadequate supplies, and hence their safety and reliability should be considered in self-supply contexts. The findings have implications on how to support self-supply towards a safely managed service, and show that investing in public piped services in self-supply contexts may face resistance from self-supply users that must first be overcome.

A sense of ownership may play a crucial role on how users take responsibility for sourcing and managing their own self-supply water supply. Marks and Davis (2012) investigated the sense of ownership in communal water systems in rural Kenya and found a strong sense of ownership and having an individual water connection, as well as including households' involvement in decisions about service delivery and investing oneself. Marks and Davis (2012) defined the sense of ownership for the water system as households' expressed attitudes of ownership and commitment related to the infrastructure. Based on Pierce et al. (2001), the three main causal pathways for developing a sense of ownership for an object are controlling, intimately knowing, and investing oneself into it. There is a potential high sense of ownership of self-supply systems in urban Indonesia, which can be attributed to the fact that self-supply is on-premises, self-invested and the household's own responsibility. Understanding the linkages between ownership and user behaviour in self-supply water systems could inform strategies to promote sustainable water management practices among users.

A sense of ownership may be closely linked to the service outcomes of self-supply water systems. A sense of ownership is suggested to have an influence on management effectiveness and ultimately on the sustainability and functioning of water supplies (Sutton & Butterworth, 2021). Indicators for effectiveness are functioning, reliability and adequacy of water supplies which are outputs of management practices (Sutton & Butterworth, 2021). For example, Foster et al. (2018) found that the likelihood of a privately owned handpump being functional was significantly associated with private ownership in Cambodia. The PhD research revealed that households in Bekasi and Metro had a clear preference for their own private self-supply over alternative water sources, and that cooperation between household members in terms of management and their shared interest in its success was common. Understanding the mechanisms by which a sense of ownership influences management effectiveness and service outcomes in self-supply water systems is crucial, as it can uncover specific behaviours, decision-making processes, and resource allocation strategies that lead to improved functionality, reliability, and adequacy of water supplies.

Exploring the gender dynamics of decision-making, responsibilities and user involvement in self-supply water systems can provide valuable insights for enhancing ownership and improving system outcomes. The PhD research on household management of self-supply in urban Indonesia showed that gendered intra-household dynamics varied across self-supply households, but showed cooperation between women and men and certain clearly defined roles in terms of responsibilities and decision-making. Since women are often the main users of water service delivery in the household, it is often assumed that they have a vested interest in its success and their involvement in decision-making lead to better performance (Mommen et al., 2017). Examining gender dynamics within self-supply water systems, including the roles, responsibilities, and decision-making power of men and women, is essential for understanding their influence on ownership, management effectiveness, and service outcomes, and can contribute to fostering more equitable and inclusive water management practices.

When supporting self-supply, the safety and reliability of alternative water supplies should be considered, as these supplies serve as a supplement to address groundwater quality and availability issues. According to the PhD research, households in Bekasi and Metro coped with quality, availability, and management issues of self-supply by using multiple water sources, with refill water being particularly important. The main source of drinking water for 21% of households in the study sites in urban Indonesia was refill water. On the other hand, the use of packaged branded water was less common, with 12% of households in Bekasi and 6% in Metro relying on it as a primary source of drinking water. The lack of trust in the quality of refill water was common, and it was perceived to have a poor taste and health issues such as bloating after consumption. In contrast, packaged branded water was perceived to have good quality. However, packaged branded water has a higher cost compared to refill water. There is a need to investigate the potential for alternative water sources to supplement groundwater quality and availability issues, and to explore the safety and reliability of these alternative water sources.

To address challenges with self-supply safety, it is crucial to explore the potential of public piped water as an alternative water source and identify and overcome the barriers that hinder its adoption. Most households in Bekasi and Metro did not have the possibility to connect to public piped services because they were not available in these regions, and if available, public piped services were generally not used. The PhD research found that several factors contributed to the non-use of public piped services, including a lack of trust, concerns about reliability, the high costs and the preference for self-supply water.

The findings are consistent with a study by Foster et al. (2022) that found the initial private investment in self-supply construction as a common coping strategy to improve water-supply reliability as a response to the inadequate public piped water supply from municipal utilities. According to Foster et al. (2022), while self-supply systems may incur higher initial construction costs, the long-term operational costs of private self-supply are often lower than those of an equivalent public water supply on an unsubsidised tariff. This may lead to a continued use of self-supply as a cost-reduction strategy even with improved public supply (Foster et al., 2022). However, this can have significant impacts on cash flows and investment cycles, as self-supply practice by wealthier households reduces utility revenue collection and hinders water utilities' ability to invest in infrastructure and maintain subsidised water tariffs for lower-income residents (Foster et al., 2022).

Given the significant investments made by self-suppliers in their supply arrangements, one potential approach is to incentivise them to connect to public piped systems through a combination of behavioural and economic measures (Sutton & Butterworth, 2021). To promote the adoption of public service connections, it is crucial to address users' perceptions of the benefits associated with such connections. This entails ensuring the reliability of public piped systems and addressing users' concerns regarding the safety of water quality. Additionally, targeted financial support may be necessary to overcome the barrier of high connection costs to public piped water.

Other identified factors contributing to the non-use of public piped services included a perceived unpleasant smell of chlorine and the preference for self-supply water. The PhD research showed that households often viewed taste as the most important attribute for drinking water. This raises the chance of households rejecting chlorinated water in favour of the unsafe option, as the chlorine taste from public water services was generally perceived as unpleasant. There is a need to educate self-supply users about the taste of chlorine and the effectiveness of water treatment methods. Palatability should be considered when establishing chlorination dosing guidelines and implementing chlorination in water supplies, as it is well known that people reject chlorinated water in favour of untreated water (Smith et al., 2021). Overall, to promote the acceptance and utilisation of public piped systems, addressing the factors hindering the use of public piped services should be addressed and further researched.

7.7 Equity considerations of self-supply

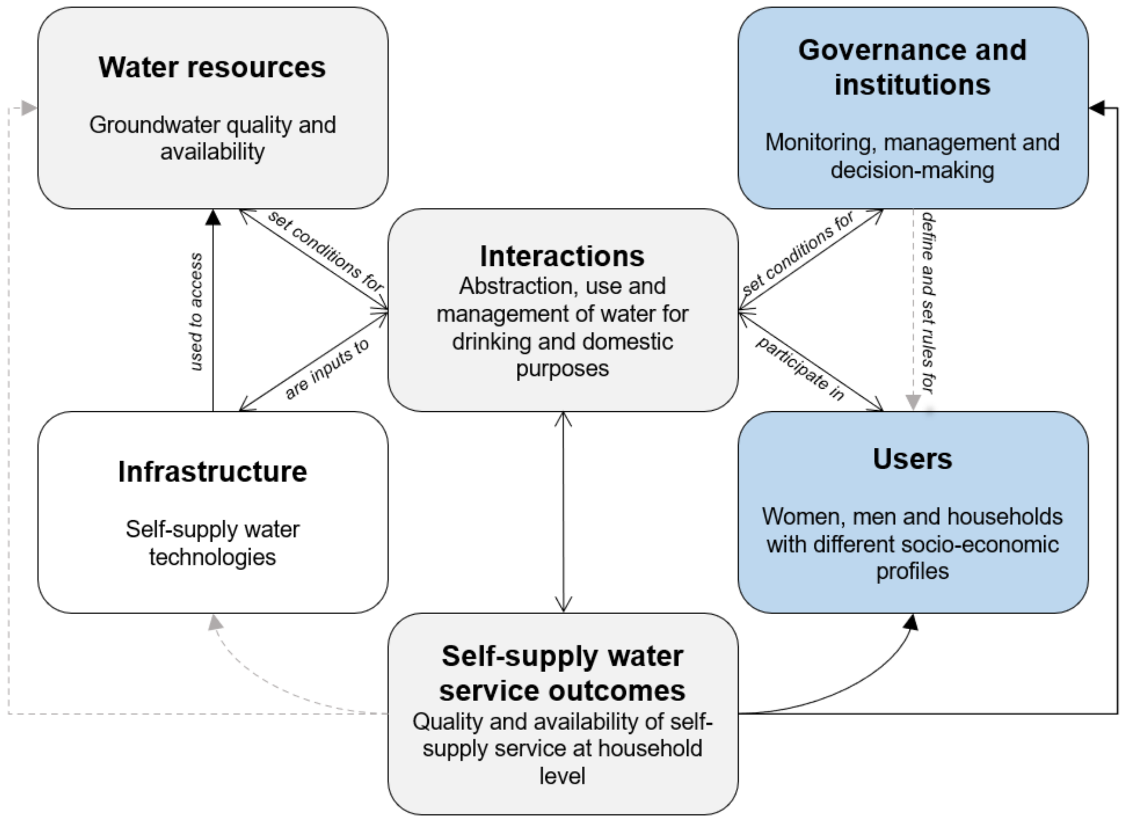


Figure 15: The 'Users' component includes women, men, and households with different socio-economic profiles. The implications regarding the equity aspect of the 'Users' component need to be considered when governments and institutions develop support strategies.

The role of equity considerations of self-supply is of paramount importance, given that self-supply places the responsibility directly on households. The 'Users' component within the social-ecological system framework assumes a central role in identifying equity-related aspects. This component encompasses women, men, and households with different socio-economic profiles (Figure 15). Several socio-economic inequities have been uncovered in the PhD research, which should be considered when establishing support strategies. RQ1 revealed that wealth emerged as a significant risk factor for faecal contamination. Additionally, RQ2 uncovered that self-supply use was connected with the practice of water boiling as a point-of-use water treatment method with many households still relying on the use of fuel which is harmful to health. Moreover, RQ2 shed light on varying intra-household dynamics across different households. Uncovering equity aspects of self-supply has implications for governance and institutions, particularly in the pursuit of 'leaving no one behind' when establishing support strategies.

First, wealth was a significant risk factor for faecal contamination in Metro, where many households rely on unprotected dug wells. Qualitative data further revealed that cost was a major barrier for households that could not afford to construct boreholes, indicating that poorer households may be less willing or less able to invest in improved self-supply infrastructure. The finding that poorer households may be unwilling or unable to pay for improved self-supply infrastructure highlights the need for research and support strategies to address equity issues in self-supply. It is necessary to explore affordable and sustainable options for households with limited financial resources to improve their water supply. Support strategies could focus on increasing access to financing options, subsidies, or other financial incentives for households to invest in improved self-supply infrastructure. Additionally, support strategies could aim to increase awareness and knowledge among vulnerable households about the importance of safe water supply and the potential health risks associated with contaminated water sources.

Secondly, the prevalence of wood as fuel for boiling was common in Metro. The reasons why households in Metro continue to use wood as a fuel for boiling, despite the government-led programme to promote the use of LPG as a safer and more sustainable alternative, need to be clarified. This has important equity implications for the recently introduced government-led conversion programme from LPG to induction stoves, as it suggests that some households may face barriers to accessing and using this new technology. It is important to ensure that the conversion programme is designed and implemented in a way that considers the needs and challenges of all households, particularly those that may be more vulnerable or marginalised.

Thirdly, despite the responsibility for self-supply management was mostly shared between household members, qualitative results indicated that gendered norms still played a significant role in shaping self-supply roles regarding management. Additionally, while decision-making was mostly shared between household members in Metro, in Bekasi the dominant decision-making role was held by men. Further research could explore how gender dynamics influence self-supply management including sustainability, efficiency and effectiveness. Understanding the linkages between gender dynamics and system outcomes could inform strategies to enhance overall system performance. Moreover, exploring the intersectionality of gender with other social factors, such as socio-economic status, age or marital status, could provide a more nuanced understanding of the experiences, challenges and opportunities faced by different groups. Examining the interactions between gender and other dimensions of equity can inform strategies for promoting social inclusion addressing the needs of marginalised or vulnerable groups within self-supply contexts.

7.8 Critical reflection of the social-ecological system approach

Based on the social-ecological system framework used in the PhD research, this section builds on the adaptions of the social-ecological system approach (Section 2.2.4). This section reflects on the use of the social-ecological system framework in the PhD research and focuses on its strengths, limitations and challenges, and recommendations for future use. Finally, this section highlights our collective study Priadi et al. (2023), in which we adapted and applied the social-ecological system framework of Hoque et al. (2019) to the policy and regulatory context for self-supply in urban Indonesia. I was involved in and contributed to this work beyond the scope of this PhD research.

The use of the social-ecological system approach, and specifically Hoque's framework, in the PhD research demonstrated several strengths. Firstly, it proved instrumental in addressing and conceptualizing the interdisciplinary nature of the research questions, providing a comprehensive framework that encompassed diverse perspectives. The conceptualization offered valuable support in the interpretation and analysis of results. One notable strength of the social-ecological system framework lies in its ability to differentiate between the components of 'Water resources' and 'Self-supply water service outcomes'. This distinction is particularly crucial when evaluating water quality, as water quality may vary significantly between the source and the household level. Another noteworthy strength is Hoque's incorporation of a distinct component dedicated to 'Infrastructure' within the framework. This inclusion acknowledges the critical role that infrastructure plays in the provision of water services. The inclusion of infrastructure sets it apart from Ostrom's well-known social-ecological system framework, which highlights the adaptability of the social-ecological system approach to the complexities of assessing water services.

While employing the social-ecological system approach in the PhD research brought valuable insights, it also presented certain limitations and challenges. To align with the PhD research's scope and research questions, the study replaced 'Water security outcomes' with 'Water service outcomes,' focusing specifically on self-supply water quality and availability. While suitable for the PhD research objectives, this modification constrains the analysis within these parameters. The exclusion of 'Water security' in the framework limits a broader consideration of sustainability factors and exploration of alternative water sources.

The future use of the social-ecological system framework may benefit from an integration of water security, if the boundaries of the self-supply evaluation are to be extended. Water security, as defined by Charles et al. (2020), means ensuring that safe services are sustained. To make a statement about the water security of households relying on self-supply, a more holistic understanding of long-term factors affecting self-supply water service outcomes, such as demographic pressure and climate change, is required. In addition, gaining a thorough understanding of the alternative water sources used by households relying on self-supply, including the quality and availability of these sources, is essential. Considering water security outcomes within the social-ecological system approach could broaden the perspectives and assessment of self-supply water services.

Another limitation concerns the placement of the ‘Governance and institution’ component in the social-ecological system framework of the PhD research. Positioning this component is challenging in the context of self-supply, given that self-supply is currently under-regulated with no clear roles and responsibilities for the government, and consequently falls under households' individual responsibility. In self-supply, governance, including decision-making and management, rests with the users themselves. Users are playing dual roles as beneficiaries of the service and service providers. Therefore, users and governance are essentially synonymous in the realm of self-supply, raising questions about the stand-alone positioning of ‘Governance and institutions’ as a separate component.

Future use of the social-ecological system framework could consider a repositioning of the ‘Governance and institutions’ component within the social-ecological system approach. In our collective study Priadi et al. (2023), we situated the ‘Governance’ component around the components of ‘Water resources’, ‘Infrastructure’, and ‘Users’, with water security outcomes serving as the central focus (Priadi et al., 2023). By integrating the ‘Users’ component as an integral part of the ‘Governance and institutions’, the governance of self-supply can be further strengthened.

Moreover, another notable challenge encountered was the deliberation on whether to incorporate a risk perspective in the social-ecological system framework of the PhD research. The social-ecological system framework in the PhD research does not specifically outline different risks associated with water security, as proposed by Hoque et al. (2019). Hoque et al. (2019) uses the definition of water security based on Grey and Sadoff (2007), which in the context of drinking and domestic uses comprises a provision and a risk perspective. Given the PhD research’s scope and focus on water service outcomes rather than water security, the inclusion of a risk perspective was deemed less useful. Additionally, the acceptability of self-supply as a mode of water provision might be debatable. The acceptance of self-supply as a mode of water provision may vary depending on regional policies, regulations, and cultural contexts. In urban Indonesia, millions of people rely on self-supply; however, significant challenges exist in implementing the existing laws and regulations regarding self-supply (Priadi et al., 2023). If self-supply is considered an acceptable form of provision, future application of the social-ecological system framework could benefit from incorporating a risk perspective to drinking water security to conceptualize and understand the challenges related to water security outcomes of self-supply.

In future applications of the framework, incorporating a risk perspective, it is suggested to include and consider technical risks associated with the 'Infrastructure' component. Hoque et al. (2019) links the four core components of the social-ecological system framework to the environmental, institutional, financial and social risks. In the framework of Hoque et al. (2019), financial risks are solely linked to the 'Infrastructure' component. However, in the self-supply context, financial risks can also be associated with both the 'Infrastructure' and 'Users' components. For example, users of self-supply services may face financial risks in improving their self-supply infrastructure. In this scenario, financial risks could be indicative of the socio-economic wealth status of users, which can be considered within the realm of social risks. Therefore, instead of using financial risks specifically tied to the infrastructure, it is proposed to employ the term "technical risk", taking into account sanitary risk factors. This adaptation allows for a more comprehensive understanding of the multifaceted risks involved in self-supply systems, integrating technical considerations such as construction standards, operation and maintenance.

We used an adapted version of the framework developed by Hoque et al. (2019) in a collaborative study Priadi et al. (2023) to analyse the policy and regulatory context of self-supplied water services in Bekasi and Metro. In this research, which was beyond the scope of this PhD research, we used the framework to investigate the influence of governance and institutions on social-ecological dynamics of self-supply water service delivery. In the adapted framework, the 'Governance' component was situated around the components of 'Water resources', 'Infrastructure', and 'Users', with water security outcomes serving as the central focus (Priadi et al., 2023). The adapted framework linked financial risks to the 'Users' component, and included technical risks associated with the 'Infrastructure' component. Health and water security risks, such as the inability to access safe drinking and domestic water supply, was included as an additional risk aspect.

7.9 Summary

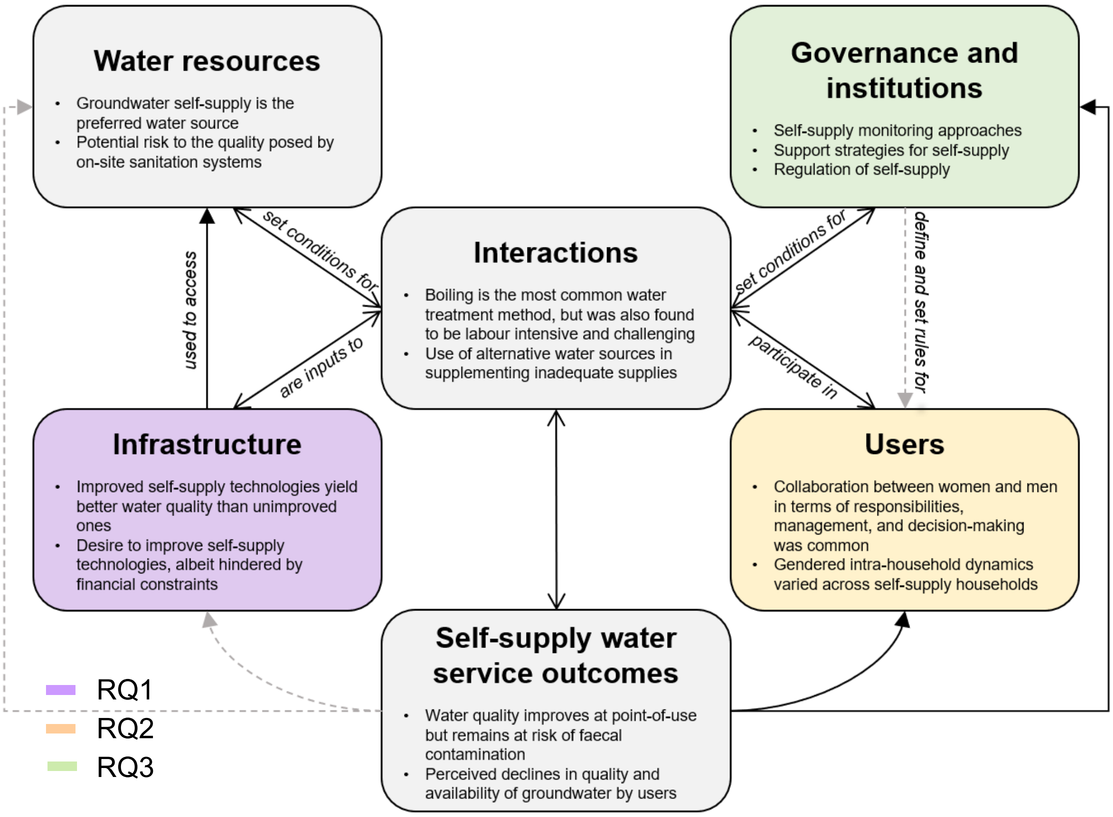


Figure 16: Summary of the key findings conceptualised based on the interrelations between the relevant components of the adapted social-ecological system framework.

Chapter VII provided a synthesis and discussion of the findings of the PhD research on the understanding of self-supply water services in urban Indonesia and highlighted implications and research gaps with regard to moving self-supply services towards a safely managed water service. The chapter was structured around six key discussion topics, which have been conceptualised based on the interrelations between the relevant components of the adapted social-ecological system framework (Figure 16).

The first key discussion topic focused on groundwater resources as the preferred source for drinking water and domestic use among self-suppliers. It emphasises the imperative of recognising and tackling the challenges confronting this valuable source in terms of both quality and availability.

The second key discussion topic highlighted the critical role of the self-supply infrastructure used to access groundwater resources to ensure adequate quality and availability. It is suggested to support and improve the self-supply infrastructure to advance self-supply towards a safely managed water service.

The third key discussion topic pointed to the need to consider water quality at point-of-use, as self-supply water at the household level was still not free from faecal contamination, despite boiling practices. To move self-supply towards a safely managed water service, the consideration of the household level is required, including promotion of safe water treatment and storage practices at the household level.

The fourth discussion topic centred around monitoring of self-supply water quality. It discussed the challenges and implications of self-supply monitoring with a focus on the established and evaluated participatory monitoring approach. The discussion distinguished between ongoing, less regular monitoring to oversee water quality trends to inform government and institutions, and frequent water quality monitoring to comprehensively assess the multifaceted risks associated with water quality deterioration of self-supply.

The fifth discussion topic focused on the self-supply use and management by households. It emphasised the need to take into account gender dynamics and the sense of ownership associated with the management of self-supply. Additionally, it recognised the importance of considering the use of multiple water sources when establishing support strategies for self-supply.

The sixth discussion topic highlighted and discussed three equity considerations for self-supply that were uncovered in the PhD research. It focused on the household wealth in improving self-supply infrastructure and accessing safe water, the uptake of safe fuel for water boiling, and the gender norms in managing self-supply.

Lastly, this chapter critically reflected on the adaption and use of the social-ecological system approach and suggested potential considerations for its use in future research.

Chapter VIII

8. Conclusion

8.1 Overview

The concluding chapter provides an overview of the contributions made by the PhD research to the field and introduces potential areas for future research. First, the research outputs, including journal publications and conference presentations, are presented (Appendices **A1** and **A7**). This is followed by a description of the contributions that the PhD research has made to the area. Subsequently, the chapter suggests and summarises areas for future research, drawing insights from the findings and acknowledging the limitations of the current PhD research. Finally, the chapter concludes with an overarching summary of the PhD research.

8.2 Research outputs

To contribute to the dissemination of new knowledge, progress and findings on self-supply in urban contexts, five publications were published as a first author in peer-reviewed academic journals, and presented at five international conferences throughout the PhD research phase from 2020 to 2023. Conference presentations were held at the UNC Water and Health Conference in 2021, at the Water-WISER Early Career Researcher Conference in 2022, at the SIWI World Water Week in 2022, and at the Indonesian Water, Sanitation and Hygiene Symposium in 2023. Additionally, research outputs were presented in form of a conference poster at the WEDC International Conference in 2021. In addition, a publication on the policy and regulatory context for self-supply was released in a peer-reviewed academic journal, with my involvement as a co-author (Priadi et al., 2023).

8.3 Contributions

The PhD research has sought to understand self-supply services in urban Indonesia with regard to safely managed water services criteria. Despite the global prevalence of self-supply practices, this water service delivery model has received little attention not only by governance and institutions but also in academic research. It has been an under-researched topic, marked by its highly context-specific nature. As such, the PhD research makes a substantial contribution to the understanding of this overlooked water service provision.

By evaluating the microbial water quality of self-supply services at both source and point-of-use and its associated risk factors of faecal contamination (RQ1), the PhD research has added significant knowledge to the field. By addressing RQ1, the PhD research has rigorously assessed the links between groundwater quality and contamination risks in self-supply and thereby provided understanding about the level of service that self-supply delivers in terms of water quality and to whom. Given that risks of water contamination and related pathways are context specific and poorly understood, the PhD research has played a crucial role in enhancing understanding within the urban Indonesian context. An additional contribution lies in the consideration of point-of-use water quality in the context of self-supply, an aspect hitherto overlooked. Beyond examining water quality solely at the source, the PhD research has extended its focus to include assessments at the point-of-use. Moreover, the research delved into equity dimensions by incorporating socio-economic factors into the analysis of water quality, providing a more comprehensive understanding of the disparities that may exist.

The PhD research has advanced the understanding of the use and management of groundwater self-supply considering intra-household dynamics (RQ2). By addressing RQ2, the PhD research has contributed significantly to the understanding of household-level management practices and the use of multiple water sources in the context of self-supply, which has been an under-researched topic. While previous research on gender and water supply service delivery has mainly focused on community-level interactions, the PhD research has provided new insights into how gender dynamics operate within households in the context of self-supply. Moreover, the PhD research has contributed to a better understanding on how users perceive quality and availability of self-supply service at household level.

The PhD research has developed and evaluated a monitoring approach for self-supply water quality (RQ3), an approach that has not yet been widely used in microbial water quality testing. The findings of RQ3 contribute to address a critical knowledge gap regarding the feasibility and effectiveness of self-supply water quality monitoring approaches. Moreover, the monitoring approach provides potential benefits and limitations of participatory monitoring by citizens using field-based microbial water quality tests, and thereby provides relevant knowledge if the monitoring approach were to be scaled up or sustained.

By using and adapting the social-ecological system framework of Hoque et al. (2019), the PhD research assessed self-supply based on social-ecological thinking. While social-ecological approaches are increasingly applied in water resource management, there are limited examples of their application to drinking water services (Hoque et al., 2019), and in particular to self-supply services (Priadi et al., 2023). The social-ecological system approach applied in the PhD research has shown to be valuable for the evaluation of self-supply in terms of safely managed water services through interdisciplinary research.

Overall, the PhD research has not only expanded the knowledge base in the field by addressing critical research questions but has also shed light on the practical implications for governance and institutions. Findings of all research questions are relevant for governance and institutions, offering insights on how to respond to the challenges associated with self-supply in order to move self-supply towards a safely managed water service.

8.4 Further research priorities

This section offers a summary of the key suggestions for further research based on the findings and limitations of the PhD research. While approaches for additional research are alluded to in **Chapter VII**, the focus in this section is on providing a concise summary of the identified research priorities.

It is important to note that the PhD research focuses specifically on self-supply settings in urban Indonesia. As such, it is possible that the findings and implications of the PhD research may not be directly applicable to other settings, such as self-supply prevalence in rural areas. Therefore, caution should be exercised when considering the implications of this research for other contexts. Exploring the relevance of the PhD research findings beyond urban self-supply contexts in Indonesia, for example in rural areas, is essential for a more comprehensive understanding of the broader implications of the PhD research.

The findings of the PhD research indicated that faecal contamination was common in self-supply water systems. While the PhD research was limited to the use of indicator bacteria *E. coli*, further research is needed to explore contamination in self-supply water systems beyond the use of faecal indicator bacteria *E. coli*. This may involve investigating other potential contaminants, such as microbial pathogens, to gain a more comprehensive understanding of the extent and nature of contamination in self-supply water sources.

Moreover, further research could investigate the sources and pathways of contamination in self-supply water systems more deeply. While the assessment of faecal contamination risk factors in the PhD research was limited to information based on sanitary inspections, household surveys and water quality testing, future research may involve conducting microbial source tracking or other advanced techniques to determine the origins of contaminants. Important hazard and pathways factors to consider include sanitation systems, groundwater levels and rainfall. Understanding the sources of contamination can guide targeted management strategies to reduce and prevent contamination in self-supply water sources.

The findings from the PhD research suggested that self-supply infrastructure used to access groundwater influenced both water quality and availability. These results emphasise the importance of improving infrastructure to enhance the water quality and availability and to explore potential support strategies. Further research could conduct a comprehensive analysis of the various stakeholders involved in self-supply systems, including users, government agencies and the private sector to investigate their roles, responsibilities, and capacities regarding infrastructure improvements to understand potential barriers, collaboration opportunities and strategies for effective engagement. Different financial mechanisms and funding options to support infrastructure improvements should be considered and explored. Furthermore, action research approaches could focus on capacity building and knowledge sharing, including the exploration of training programmes, awareness campaigns, and platforms for exchanging best practices, technical expertise, and experiences related to self-supply infrastructure.

The research highlights the concerning persistence of faecal contamination in self-supply water at the point-of-use, despite the common practice of boiling as a water treatment method. Additionally, findings reveal the labour-intensive nature associated with boiling water. To further address these issues, there is a need to investigate the underlying reasons for the ongoing faecal contamination in self-supply water. This may involve conducting in-depth assessments of household water treatment and storage practices among self-supply households, exploring the potential adoption of alternative or complementary treatment options, and investigating the effectiveness of strategies for education and awareness regarding household water treatment and safe water storage practices.

The findings of the PhD research indicate that self-supply is the preferred water source, while alternative water sources are used as a supplement to address groundwater quality and availability concerns. To build upon these findings, further research is essential to assess the safety and reliability of alternative water supplies, with particular emphasis on refill water and public piped water. This assessment can help to identify potential strategies for promoting and encouraging the adoption of safe alternative water sources. Additionally, it is important to investigate the socio-economic impacts associated with the use of self-supply and alternative water sources. This entails assessing the costs, affordability, benefits, and trade-offs of different water sources to gain a comprehensive understanding of their socio-economic implications.

Furthermore, the findings of the PhD research offer valuable insights into the gender dynamics involved in managing self-supply water systems, highlighting responsibilities and decision-making. More detailed qualitative research is required to understand the interest in maintaining or shifting current gender norms and roles. Moreover, further research is needed to explore how the management of private self-supply, particularly considering gender dynamics, is linked to the sense of ownership and water service outcomes.

The PhD research focused on addressing the challenge of monitoring water quality in self-supply systems and trialled and evaluated a participatory monitoring approach. The findings suggest that household-led testing at reduced frequencies could be a potential solution. However, further research is necessary to assess the feasibility of scaling up or sustaining this approach, including factors such as willingness to pay and strategies to mitigate drop-out rates. Furthermore, while the PhD research was limited to the participatory monitoring approach, alternative monitoring strategies with strengthened roles for local authorities should be explored and evaluated.

8.5 Summary

The PhD research addressed important gaps in the understanding of self-supply services in urban Indonesia by providing insights into the water quality, household-level use and management, and the development and evaluation of a participatory monitoring approach. The PhD research has made a significant contribution to the understanding of self-supply services in urban Indonesia by demonstrating the common presence of faecal contamination at both the source and point-of-use, and by identifying potential risk factors associated with this contamination. This fills an important gap in the existing evidence regarding the level of service provided by self-supply systems.

Furthermore, the PhD research has provided significant insights into the use and management of self-supply by individual households, shedding light on intra-household gender dynamics and revealing that while self-supply is the preferred water source, alternative sources are still commonly used alongside self-supply. By considering the household level, this research fills a critical gap in the available evidence, as there has been limited understanding of how self-supply is used and managed within individual households.

Finally, the PhD research developed and assessed a participatory monitoring approach for evaluating the microbial water quality of self-supply sources. This contribution is significant as monitoring approaches for microbial water quality in self-supply systems have been underused and poorly understood. The findings highlight both the potential of and the challenges associated with participatory monitoring.

Bibliography

Aboelnga, H. T., Ribbe, L., Frechen, F. B., & Saghir, J. (2019). Urban water security: Definition and assessment framework. *Resources*, *8*(4). https://doi.org/10.3390/resources8040178

Acey, C. (2010). Gender and community mobilisation for urban water infrastructure investment in southern Gender and community mobilisation for urban water infrastructure investment in southern Nigeria. *Gender & Development*, *18*(1). https://doi.org/10.1080/13552071003599970

Adams, E. A., Boateng, G. O., & Amoyaw, J. A. (2016). Socioeconomic and Demographic Predictors of Potable Water and Sanitation Access in Ghana. *Social Indicators Research*, *126*(2), 673–687. https://doi.org/10.1007/s11205-015-0912-y

Ali, R., Bünzli, M. A., Colombo, L., Khattak, S. A., Pera, S., Riaz, M., & Valsangiacomo, C. (2019). Water quality before and after a campaign of cleaning and disinfecting shallow wells: A study conducted during and after floods in Khyber Pakhtunkhwa, Pakistan. *Journal of Water Sanitation and Hygiene for Development*, *9*(1), 28–37. https://doi.org/10.2166/WASHDEV.2018.272

Allan, J. V, Kenway, S. J., & Head, B. W. (2018). Urban water security - what does it mean? *Urban Water Journal*, *15*(9), 899–910. https://doi.org/10.1080/1573062X.2019.1574843

Andadari, R. K., Mulder, P., & Rietveld, P. (2014). Energy poverty reduction by fuel switching. Impact evaluation of the LPG conversion program in Indonesia. *Energy Policy*, *66*, 436–449. https://doi.org/10.1016/j.enpol.2013.11.021

ARGOSS. (2001). Guidelines for Assessing the Risk to Groundwater from On-Site Sanitation. *British Geological Survey*, *01*(142), Art. CR/01/142.97pp.

Aven, T., & Renn, O. (2009). On risk defined as an event where the outcome is uncertain. *Journal of Risk Research*, *12*(1), 1–11. https://doi.org/10.1080/13669870802488883

Bain, R., Bartram, J., Elliott, M., Matthews, R., Mcmahan, L., Tung, R., Chuang, P., & Gundry, S. (2012). A summary catalogue of microbial drinking water tests for low and medium resource settings. *International Journal of Environmental Research and Public Health*, *9*(5), 1609–1625. https://doi.org/10.3390/ijerph9051609

Bain, R., Cronk, R., Wright, J., Yang, H., Slaymaker, T., & Bartram, J. (2014a). Fecal Contamination of Drinking-Water in Low- and Middle-Income Countries: A Systematic Review and Meta-Analysis. *PLoS Medicine*, *11*(5). https://doi.org/10.1371/journal.pmed.1001644

Bain, R., Cronk, R., Wright, J., Yang, H., Slaymaker, T., & Bartram, J. (2014b). Fecal Contamination of Drinking-Water in Low- and Middle-Income Countries: A Systematic Review and Meta-Analysis. *PLoS Medicine*, *11*(5). https://doi.org/10.1371/journal.pmed.1001644

Bappeda Kota Bekasi. (2018). *Rencana Pembangunan Jangka Menengah Daerah Kota Bekasi 2018-2023*.

Bartram, J., Brocklehurst, C., Fisher, M. B., Luyendijk, R., Hossain, R., Wardlaw, T., & Gordon, B. (2014). Global monitoring of water supply and sanitation: History, methods and future challenges. In *International Journal of Environmental Research and Public Health* (Vol. 11, Issue 8, pp. 8137–8165). MDPI. https://doi.org/10.3390/ijerph110808137

Bartram, J., Corrales, L., Davison, A., Deere, D., Drury, D., Gordon, B., Howard, G., Rinehold, A., & Stevens, M. (2009). *Water Safety Plan Manual: Step-by-step risk management for drinking-water suppliers*.

BPS Kota Bekasi. (2021). Bekasi Municipality in Figures 2021. *BPS Kota Bekasi*, *1907.3763*.

BPS Kota Metro. (2019). *Metro Municipality in Figures 2019*. *1907–4751*, 262.

Bradley, D. J., & Bartram, J. K. (2013). Domestic water and sanitation as water security: Monitoring, concepts and strategy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *371*(2002). https://doi.org/10.1098/rsta.2012.0420

Brouwer, S., van der Wielen, P. W. J. J., Schriks, M., Claassen, M., & Frijns, J. (2018). Public participation in science: The future and value of citizen science in the drinking water research. *Water (Switzerland)*, *10*(3). https://doi.org/10.3390/w10030284

Butterworth, J., Sutton, S., & Mekonta, L. (2013). Self-supply as a complementary water services delivery model in Ethiopia. *Water Alternatives*, *6*(3), 405–423.

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T. C., Bastiaensen, J., De Bièvre, B., Bhusal, J., Clark, J., Dewulf, A., Foggin, M., Hannah, D. M., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandeya, B., Paudel, D., Sharma, K., Steenhuis, T., … Zhumanova, M. (2014). Citizen science in hydrology and water resources: Opportunities for knowledge generation, ecosystem service management, and sustainable development. In *Frontiers in Earth Science* (Vol. 2). Frontiers Media S.A. https://doi.org/10.3389/feart.2014.00026

Carrard, N., Crawford, J., Halcrow, G., & Rowland, C. (2013). A framework for exploring gender equality outcomes from WASH programmes. *Waterlines*, *32*(4).

Carrard, N., MacArthur, J., Leahy, C., Soeters, S., & Willetts, J. (2022). The water, sanitation and hygiene gender equality measure (WASH-GEM): Conceptual foundations and domains of change. *Women's Studies International Forum*, *91*. https://doi.org/10.1016/j.wsif.2022.102563

Carrard, N., Madden, B., Chong, J., Grant, M., Nghiêm, T. P., Bùi, L. H., Hà, H. T. T., & Willetts, J. (2019). Are piped water services reaching poor households? Empirical evidence from rural Viet Nam. *Water Research*, *153*, 239–250. https://doi.org/10.1016/j.watres.2019.01.026

Chao, K. K., Chao, C. C., & Chao, W. L. (2004). Evaluation of Colilert-18 for Detection of Coliforms and Eschericha coli in Subtropical Freshwater. *Applied and Environmental Microbiology*, *70*(2), 1242–1244. https://doi.org/10.1128/AEM.70.2.1242-1244.2004

Charles, K. J., Nowicki, S., & Bartram, J. K. (2020). A framework for monitoring the safety of water services: from measurements to security. *Npj Clean Water*, *3*(1), 1–6. https://doi.org/10.1038/s41545-020-00083-1

Chávez García Silva, R., Grönwall, J., Van Der Kwast, J., Danert, K., & Foppen, J. W. (2020). Estimating domestic self-supply groundwater use in urban continental Africa. *Environmental Research Letters*, *15*(10). https://doi.org/10.1088/1748-9326/ab9af9

Clasen, T. F., & Bastable, A. (2003). Faecal contamination of drinking water during collection and household storage: The need to extend protection to the point of use. *Journal of Water and Health*, *1*(3), 109–115. https://doi.org/10.2166/wh.2003.0013

Clasen, T. F., Do, H. T., Boisson, S., & Shipin, O. (2008). Microbiological effectiveness and cost of boiling to disinfect drinking water in rural Vietnam. *Environmental Science and Technology*, *42*(12), 4255–4260. https://doi.org/10.1021/es7024802

Cohen, A., Zhang, Q., Luo, Q., Tao, Y., Colford, J. M., & Ray, I. (2017). Predictors of Drinking Water Boiling and Bottled Water Consumption in Rural China: A Hierarchical Modeling Approach. *Environmental Science and Technology*, *51*(12), 6945–6956. https://doi.org/10.1021/acs.est.7b01006

Conrad, C. C., & Hilchey, K. G. (2011). A review of citizen science and community-based environmental monitoring: Issues and opportunities. *Environmental Monitoring and Assessment*, *176*(1–4), 273–291. https://doi.org/10.1007/s10661-010-1582-5

Crocker, J., & Bartram, J. (2014). Comparison and cost analysis of drinking water quality monitoring requirements versus practice in seven developing countries. *International Journal of Environmental Research and Public Health*, *11*(7), 7333–7346. https://doi.org/10.3390/ijerph110707333

Cronin, A. A., Odagiri, M., Arsyad, B., Nuryetty, M. T., Amannullah, G., Santoso, H., Darundiyah, K., & Nasution, N. A. (2017). Piloting water quality testing coupled with a national socioeconomic survey in Yogyakarta province, Indonesia, towards tracking of Sustainable Development Goal 6. *International Journal of Hygiene and Environmental Health*, *220*(7), 1141–1151. https://doi.org/10.1016/j.ijheh.2017.07.001

Daniel, D., Marks, S. J., Pande, S., & Rietveld, L. (2018). Socio-environmental drivers of sustainable adoption of household water treatment in developing countries. *Npj Clean Water*, *1*(1). https://doi.org/10.1038/s41545-018-0012-z

Davoodi, R., Pirsaheb, M., Karimyan, K., Gupta, V. K., Takhtshahi, A. R., Sharafi, H., & Moradi, M. (2018). Data for distribution of various species of fecal coliforms in urban, rural and private drinking water sources in ten years period – A case study: Kermanshah, Iran. *Data in Brief*, *18*, 1544–1550. https://doi.org/10.1016/j.dib.2018.04.053

DerSimonian, R., & Laird, N. (1986). Meta-analysis in clinical trials. *Controlled Clinical Trials*. https://doi.org/10.1016/0197-2456(86)90046-2

Egger, M., Smith, G. D., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected by a simple, graphical test. *British Medical Journal*. https://doi.org/10.1136/bmj.315.7109.629

Eisenhauer, I. F., Hoover, C. M., Remais, J. V., Monaghan, A., Celada, M., & Carlton, E. J. (2016). Estimating the risk of domestic water source contamination following precipitation events. *American Journal of Tropical Medicine and Hygiene*, *94*(6), 1403–1406. https://doi.org/10.4269/ajtmh.15-0600

Ejechi, E. O., & Ejechi, B. O. (2008). Safe drinking water and satisfaction with environmental quality of life in some oil and gas industry impacted cities of Nigeria. *Social Indicators Research*, *85*(2), 211–222. https://doi.org/10.1007/s11205-007-9086-6

Elliott, M., MacDonald, M. C., Chan, T., Kearton, A., Shields, K. F., Bartram, J. K., & Hadwen, W. L. (2017). Multiple household water sources and their use in remote communities with evidence from Pacific Island Countries. *Water Resources Research*, *54*, 9106–9117.

Fagerli, K., Trivedi, K. K., Sodha, S. V., Blanton, E., Ati, A., Nguyen, T., Delea, K. C., Ainslie, R., Figueroa, M. E., Kim, S., & Quick, R. (2017). Comparison of boiling and chlorination on the quality of stored drinking water and childhood diarrhoea in Indonesian households. *Epidemiology and Infection*, *145*(15), 3294–3302. https://doi.org/10.1017/S0950268817002217

Fischer, A., Hope, R., Manandhar, A., Hoque, S., Foster, T., Hakim, A., Islam, M. S., & Bradley, D. (2020). Risky responsibilities for rural drinking water institutions: The case of unregulated self-supply in Bangladesh. *Global Environmental Change*, *65*(June 2019). https://doi.org/10.1016/j.gloenvcha.2020.102152

Fisher, J. (2008). Women in water supply , sanitation and hygiene programmes. *Municipal Engineer*, *161*(ME4), 223–229. https://doi.org/10.1680/muen.2008.161.4.223

Fisher, J., Cavill, S., & Reed, B. (2017). Mainstreaming gender in the WASH sector: dilution or distillation? *Gender and Development*, *25*(2), 185–204. https://doi.org/10.1080/13552074.2017.1331541

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). *Resilience Thinking: Integrating Resilience, Adaptability and Transformability*. https://www.jstor.org/stable/26268226?seq=1&cid=pdf-

Foster, S., Hirata, R., Eichholz, M., & Alam, M. F. (2022). Urban Self-Supply from Groundwater—An Analysis of Management Aspects and Policy Needs. *Water (Switzerland)*, *14*(4). https://doi.org/10.3390/w14040575

Foster, T., Priadi, C., Kotra, K. K., Odagiri, M., Rand, E. C., & Willetts, J. (2021). Self-supplied drinking water in low- and middle-income countries in the Asia-Pacific. *Npj Clean Water*, *4*(1), 1–10. https://doi.org/10.1038/s41545-021-00121-6

Foster, T., Shantz, A., Lala, S., & Willetts, J. (2018). Factors associated with operational sustainability of rural water supplies in Cambodia. *Environmental Science: Water Research and Technology*, *4*(10), 1577–1588. https://doi.org/10.1039/c8ew00087e

Furlong, K., & Kooy, M. (2017). Worlding Water Supply: Thinking Beyond the Network in Jakarta. *International Journal of Urban and Regional Research*, *41*(6), 888–903. https://doi.org/10.1111/1468-2427.12582

Genter, F., Marks, S. J., Clair-Caliot, G., Mugume, D. S., Johnston, R. B., Bain, R. E. S., & Julian, T. R. (2019). Evaluation of the novel substrate RUG^{TM} for the detection of: Escherichia coli in water from temperate (Zurich, Switzerland) and tropical (Bushenyi, Uganda) field sites. *Environmental Science: Water Research and Technology*, *5*(6), 1082–1091. https://doi.org/10.1039/c9ew00138g

Genter, F., Putri, G. L., Handayani, R., Priadi, C., Willetts, J., & Foster, T. (2023). Evaluation of a participatory citizen approach to monitor microbial water quality of self-supply in urban Indonesia. *Urban Water Journal*, 1–13. https://doi.org/10.1080/1573062X.2023.2285438

Genter, F., Putri, G. L., Maysarah, S., Rolia, E., Pratama, M. A., Priadi, C., Willetts, J., & Foster, T. (2023). Associations between seasonality and faecal contamination of self-supply sources in urban Indonesia. *Journal of Water, Sanitation and Hygiene for Development*. https://doi.org/10.2166/washdev.2023.060

Genter, F., Putri, G. L., Suleeman, E., Darmajanti, L., Priadi, C., Foster, T., & Willetts, J. (2023). Understanding household self-supply use and management using a mixed-methods approach in urban Indonesia. *PLOS Water*, *2*(1), e0000070. https://doi.org/10.1371/journal.pwat.0000070

Genter, F., Putri, G., Pratama, M., Priadi, C., Willetts, J., & Foster, T. (2022). Microbial Contamination of Groundwater Self-supply in urban Indonesia: Assessment of Sanitary and Socio-economic Risk factors. *Water Resources Research*, *58*. https://doi.org/https://doi.org/10.1029/2021WR031843

Genter, F., Willetts, J., & Foster, T. (2021). Faecal contamination of groundwater self-supply in low- and middle income countries: Systematic review and meta-analysis. In *Water Research*. https://doi.org/10.1016/j.watres.2021.117350

Gero, A., & Willetts, J. (2020). Securing a conducive environment for WASH markets: The role of local government. *Waterlines*, *39*(1), 44–60.

Gharesifard, M., Wehn, U., & van der Zaag, P. (2019). What influences the establishment and functioning of community-based monitoring initiatives of water and environment? A conceptual framework. *Journal of Hydrology*, *579*. https://doi.org/10.1016/j.jhydrol.2019.124033

Gleeson, T., Wada, Y., Bierkens, M. F. P., & Van Beek, L. P. H. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature*, *488*(7410), 197–200. https://doi.org/10.1038/nature11295

Gorter, A. C., Alberts, J. H., Gago, J. F., & Sandiford, P. (1995). A randomized trial of the impact of rope-pumps on water quality. *Journal of Tropical Medicine and Hygiene*, *98*, 247–255.

Gould, C. F., Schlesinger, S. B., Molina, E., Bejarano, M. L., Valarezo, A., & Jack, D. W. (2020). Household fuel mixes in peri-urban and rural Ecuador: Explaining the context of LPG, patterns of continued firewood use, and the challenges of induction cooking. *Energy Policy*, *136*. https://doi.org/10.1016/j.enpol.2019.111053

Graham, J. P., & Polizzotto, M. L. (2013). Pit latrines and their impacts on groundwater quality: A systematic review. *Environmental Health Perspectives*, *121*(5), 521–530. https://doi.org/10.1289/ehp.1206028

Grant, M., Huggett, C., Willetts, J., & Wilbur, J. (2017). *Gender Equality & Goal 6 : The Critical Connection*. Australian Water Partnership.

Grey, D., & Sadoff, C. W. (2007). Sink or Swim? Water security for growth and development. *Water Policy*, *9*(6), 545–571. https://doi.org/10.2166/wp.2007.021

Grönwall, J., & Danert, K. (2020). Regarding Groundwater and Drinking Water Access through A Human Rights Lens : Self-Supply as A Norm. *Water*, *12*(419), 21.

Grönwall, J., Mulenga, M., & Mcgranahan, G. (2010). Groundwater, self-supply and poor urban dwellers - A review with case studies of Bangalore and Lusaka. *Human Settlements Working Paper Series - Water and Sanitation*, *26*, 87.

Gundry, S. W., Wright, J. A., Conroy, R., Du Preez, M., Genthe, B., Moyo, S., Mutisi, C., Ndamba, J., & Potgieter, N. (2006). Contamination of drinking water between source and point-of-use in rural households of South Africa and Zimbabwe: implications for monitoring the Millennium Development Goal for water. *Water Practice and Technology*, *1*(2). https://doi.org/10.2166/wpt.2006.032

Hadipuro, W. (2010). Indonesia’s water supply regulatory framework: Between commercialisation and public service? *Water Alternatives*, *3*(3), 475–491.

Hakam, D. F., Nugraha, H., Wicaksono, A., Rahadi, R. A., & Kanugrahan, S. P. (2022). Mega conversion from LPG to induction stove to achieve Indonesia’s clean energy transition. *Energy Strategy Reviews*, *41*. https://doi.org/10.1016/j.esr.2022.100856

Healy, A. (2019). The Rise of the Off-Grid City. *GeoDrilling International*.

Higgins, J. P. T., & Thompson, S. G. (2002). Quantifying heterogeneity in a meta-analysis. *Statistics in Medicine*. https://doi.org/10.1002/sim.1186

Hope, R., & Rouse, M. (2013). Risks and responses to universal drinking water security. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *371*(2002). https://doi.org/10.1098/rsta.2012.0417

Hoque, S. F., Hope, R., Arif, S. T., Akhter, T., Naz, M., & Salehin, M. (2019). A social-ecological analysis of drinking water risks in coastal Bangladesh. *Science of the Total Environment*, *679*, 23–34. https://doi.org/10.1016/j.scitotenv.2019.04.359

Howard, G. (2002). Water quality surveillance - a practical guide. *Environmental Science and Technology*, *5*(2), 114–119.

Howard, G., Calow, R., Macdonald, A., & Bartram, J. (2016). Climate Change and Water and Sanitation: Likely Impacts and Emerging Trends for Action. *Annual Review of Environment and Resources*, *41*, 253–276. https://doi.org/10.1146/annurev-environ-110615-085856

Hulland, K. R. S., Chase, R. P., Caruso, B. A., Swain, R., Biswal, B., Sahoo, K. C., Panigrahi, P., & Dreibelbis, R. (2015). Sanitation, stress, and life stage: A systematic data collection study among women in Odisha, India. *PLoS ONE*, *10*(11). https://doi.org/10.1371/journal.pone.0141883

Hunter, P. R. (2009). Household water treatment in developing countries: Comparing different intervention types using meta-regression. *Environmental Science and Technology*, *43*(23), 8991–8997. https://doi.org/10.1021/es9028217

IDEXX Laboratories. (2015). Colilert-18 Procedure. In *Idexx Laboratories* (Issue 0). https://www.lagaay.com/Catalogus/Product information/279555/Colilert -18 E-coli detection Manual.pdf

Kelly, E., Cronk, R., Fisher, M., & Bartram, J. (2021). Sanitary inspection, microbial water quality analysis, and water safety in handpumps in rural sub-Saharan Africa. *Npj Clean Water*, *4*(1), 3. https://doi.org/10.1038/s41545-020-00093-z

Kelly, E. R., Cronk, R., Kumpel, E., Howard, G., & Bartram, J. (2020). How we assess water safety: A critical review of sanitary inspection and water quality analysis. *Science of The Total Environment*, *718*, 137237. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.137237

Kilsby, D. (2012). “ Now we feel like respected adults ” - Positive change in gender roles and relations in a Timor-Leste WASH program. *ACFID Research in Development Series*, *6*.

Kooy, M., Walter, C. T., & Prabaharyaka, I. (2018). Inclusive development of urban water services in Jakarta: The role of groundwater. *Habitat International*, *73*, 109–118. https://doi.org/10.1016/j.habitatint.2016.10.006

Korfali, S. I., & Jurdi, M. (2009). Provision of safe domestic water for the promotion and protection of public health: A case study of the city of Beirut, Lebanon. *Environmental Geochemistry and Health*, *31*(2), 283–295. https://doi.org/10.1007/s10653-008-9218-1

Kostyla, C., Bain, R., Cronk, R., & Bartram, J. (2015). Seasonal variation of fecal contamination in drinking water sources in developing countries: A systematic review. In *Science of the Total Environment* (Vol. 514, pp. 333–343). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2015.01.018

Kumpel, E., Cock-Esteb, A., Duret, M., Waal, O. De, & Khush, R. (2017). Seasonal variation in drinking and domestic water sources and quality in port harcourt, Nigeria. *American Journal of Tropical Medicine and Hygiene*, *96*(2), 437–445. https://doi.org/10.4269/ajtmh.16-0175

Kurniasih, H. (2008). Water Not for All: The Concequences of Water Privitisation in Jakarta, Indonesia. *The 17th Biennial Conference of the Asian Studies Association of Australia*, 1–19.

Larson, B., Minten, B., & Razafindralambo, R. (2006). Unravelling the linkages between the Millennium Development Goals for poverty, education, access to water and household water use in developing countries: Evidence from Madagascar. *Journal of Development Studies*, *42*(1), 22–40. https://doi.org/10.1080/00220380500356258

MacArthur, J., Carrard, N., & Willetts, J. (2020). Wash and gender: A critical review of the literature and implications for gender-transformative wash research. In *Journal of Water Sanitation and Hygiene for Development* (Vol. 10, Issue 4, pp. 818–827). IWA Publishing. https://doi.org/10.2166/washdev.2020.232

MacCarthy, M. F., Annis, J. E., & Mihelcic, J. R. (2013). Unsubsidised self-supply in eastern Madagascar. *Water Alternatives*, *6*(3), 424–438.

Macdonald, A., Davies, J., Calow, R., & Chilton, J. (2005). Developing groundwater. A Guide fro Rural Water Supply. In *Public Works*.

Magro, G., Bain, R. E. S., Woodall, C. A., Matthews, R. L., Gundry, S. W., & Davis, A. P. (2014). Synthesis and application of resorufin β- D -glucuronide, a low-cost chromogenic substrate for detecting Escherichia coli in drinking water. *Environmental Science and Technology*, *48*(16), 9624–9631. https://doi.org/10.1021/es502319n

Manafi, M. (1996). Fluorogenic and chromogenic enzyme substrates in culture media and identification tests. *International Journal of Food Microbiology*, *31*(1–3), 45–58. https://doi.org/10.1016/0168-1605(96)00963-4

Marks, S. J., & Davis, J. (2012). Does User Participation Lead to Sense of Ownership for Rural Water Systems? Evidence from Kenya. *World Development*, *40*(8), 1569–1576. https://doi.org/10.1016/j.worlddev.2012.03.011

Martel, P. (2016). Review of Options for Reporting Water, Sanitation and Hygiene Coverage By Wealth Quintile. In *MICS Methodological Papers* (Data and Analytics Section, Division of Data, Research and Policy, Issue 4). http://mics.unicef.org/files?job=W1siZiIsIjIwMTcvMDYvMTUvMTYvMzMvMzAvMzE2L01JQ1NfTWV0aG9kb2xvZ2ljYWxfUGFwZXJfNC5wZGYiXV0&sha=adfd855d58aa27ea

Martínez-Santos, P., Martín-Loeches, M., García-Castro, N., Solera, D., Díaz-Alcaide, S., Montero, E., & García-Rincón, J. (2017). A survey of domestic wells and pit latrines in rural settlements of Mali: Implications of on-site sanitation on the quality of water supplies. *International Journal of Hygiene and Environmental Health*, *220*(7), 1179–1189. https://doi.org/10.1016/j.ijheh.2017.08.001

McGinnis, M. D., & Ostrom, E. (2014). Social-ecological system framework: Initial changes and continuing challenges. *Ecology and Society*, *19*(2). https://doi.org/10.5751/ES-06387-190230

McGuinness, S. L., O'Toole, J., Barker, S. F., Forbes, A. B., Boving, T. B., Giriyan, A., Patil, K., D'Souza, F., Vhaval, R., Cheng, A. C., & Leder, K. (2020). Household Water Storage Management, Hygiene Practices, and Associated Drinking Water Quality in Rural India. *Environmental Science & Technology*, *54*(8), 4963–4973. https://doi.org/10.1021/acs.est.9b04818

Meierhofer, R., Bänziger, C., Deppeler, S., Kunwar, B. M., & Bhatta, M. (2018). From water source to tap of ceramic filters—factors that influence water quality between collection and consumption in rural households in Nepal. *International Journal of Environmental Research and Public Health*, *15*(11). https://doi.org/10.3390/ijerph15112439

Metwali, R. M. (2003). Water quality of some wells in Taiz City (Yemen Republic) and its surroundings. *Folia Microbiologica*, *48*(1), 90–94. https://doi.org/10.1007/BF02931282

Ministry of Public Works, Indonesia Habitat National Team, & Housing Republic of Indonesia. (2016). *Indonesia National Report for Habitat III*.

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009a). PRISMA - Review guidelines. *Annals of Internal Medicine*.

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009b). PRISMA - Review guidelines. *Annals of Internal Medicine*.

Mommen, B., Humphries-Waa, K., & Gwavuya, S. (2017). Does women's participation in water committees affect management and water system performance in rural Vanuatu? *Waterlines*, *36*(3), 216–232. https://doi.org/10.3362/1756-3488.16-00026

National Population and Family Planning Board (BKKBN), Statistics Indonesia (BPS), Ministry of Health (Kemenkes), & ICF. (2018). *Indonesia Demographic and Health Survey 2017*. https://dhsprogram.com/pubs/pdf/FR342/FR342.pdf

Ngasala, T. M., Masten, S. J., & Phanikumar, M. S. (2019). Impact of domestic wells and hydrogeologic setting on water quality in peri-urban Dar es Salaam, Tanzania. *Science of the Total Environment*, *686*, 1238–1250. https://doi.org/10.1016/j.scitotenv.2019.05.202

Okotto, L., Okotto-Okotto, J., Price, H., Pedley, S., & Wright, J. (2015). Socio-economic aspects of domestic groundwater consumption, vending and use in Kisumu, Kenya. *Applied Geography*, *58*(March), 189–197. https://doi.org/10.1016/j.apgeog.2015.02.009

Ostrom, E. (2009). A General Framework for Analyzing Sustainability of Social-Ecological Systems. In *Science* (Vol. 325, Issue 5939, pp. 416–419). https://doi.org/10.1126/science.1170749

Özdemir, S., Elliott, M., Brown, J., Nam, P. K., Hien, V. T., & Sobsey, M. D. (2011). Rainwater harvesting practices and attitudes in the mekong delta of Vietnam. *Journal* *of Water Sanitation and Hygiene for Development*. https://doi.org/10.2166/washdev.2011.024

Peckenham, J. M., Thornton, T., & Peckenham, P. (2012). Validation of Student Generated Data for Assessment of Groundwater Quality. *Journal of Science Education and Technology*, *21*(2), 287–294. https://doi.org/10.1007/s10956-011-9317-0

Pierce, J. L., Kostova, T., & Dirks, K. T. (2001). Toward a theory of psychological ownership in organizations. *Academy of Management*, *26*(2).

Poirier, M. J. P., Grépin, K. A., & Grignon, M. (2020). Approaches and Alternatives to the Wealth Index to Measure Socioeconomic Status Using Survey Data: A Critical Interpretive Synthesis. In *Social Indicators Research* (Vol. 148, Issue 1). Springer Netherlands. https://doi.org/10.1007/s11205-019-02187-9

Priadi, C., Darmajanti, L., Suleeman, E., Putri, G., Genter, F., Foster, T., & Willetts, J. (2023). Policy and regulatory context for self-supplied water services in two cities Indonesia: Priorities for managing socio-ecological risks [manuscript submitted for publication]. *Environmental Development*. https://doi.org/10.1016/j.envdev.2023.100940

Psutka, R., Peletz, R., Michelo, S., Kelly, P., & Clasen, T. (2011). Assessing the microbiological performance and potential cost of boiling drinking water in urban Zambia. *Environmental Science and Technology*, *45*(14), 6095–6101. https://doi.org/10.1021/es2004045

Ravenscroft, P., Mahmud, Z. H., Islam, M. S., Hossain, A. K. M. Z., Zahid, A., Saha, G. C., Zulfiquar Ali, A. H. M., Islam, K., Cairncross, S., Clemens, J. D., & Islam, M. S. (2017). The public health significance of latrines discharging to groundwater used for drinking. *Water Research*, *124*, 192–201. https://doi.org/10.1016/j.watres.2017.07.049

Schmidlin, T., Hürlimann, E., Silué, K. D., Yapi, R. B., Houngbedji, C., Kouadio, B. A., Acka-Douabélé, C. A., Kouassi, D., Ouattara, M., Zouzou, F., Bonfoh, B., N'Goran, E. K., Utzinger, J., & Raso, G. (2013). Effects of Hygiene and Defecation Behavior on Helminths and Intestinal Protozoa Infections in Taabo, Côte d'Ivoire. *PLoS ONE*, *8*(6), 1–12. https://doi.org/10.1371/journal.pone.0065722

Septarini, A., Islami, B. B., Putri, G. L., Pratama, M. A., Foster, T., Willetts, J., & Priadi, C. R. (2021). Sanitation inspection of household fecal containment in Bekasi, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *776*(1). https://doi.org/10.1088/1755-1315/776/1/012004

Smith, D. W., Islam, M., Furst, K. E., Mustaree, S., Crider, Y. S., Akter, N., Islam, S. A., Sultana, S., Mahmud, Z. H., Rahman, M., Mitch, W. A., & Davis, J. (2021). Chlorine taste can increase simulated exposure to both fecal contamination and disinfection byproducts in water supplies. *Water Research*. https://doi.org/10.1016/j.watres.2021.117806

Sobsey, M. D., Stauber, C. E., Casanova, L. M., Brown, J. M., & Elliott, M. A. (2008). Point of use household drinking water filtration: A practical, effective solution for providing sustained access to safe drinking water in the developing world. *Environmental Science and Technology*, *42*(12), 4261–4267. https://doi.org/10.1021/es702746n

Srikanth, R. (2013). Access, monitoring and intervention challenges in the provision of safe drinking water in rural Bihar, India. *Journal of Water Sanitation and Hygiene for Development*, *3*(1), 61–69. https://doi.org/10.2166/washdev.2013.033

Sutton, S. (2009). An Introduction to Self Supply: Putting the User First - Incremental improvements and private investment in rural water supply. *Rural Water Supply Series*, *February*, 1–7. http://www.rwsn.ch/documentation/skatdocumentation.2009-07-27.8158674790/file

Sutton, S., & Butterworth, J. (2021). *Self-Supply: Filling the gaps in public water supply provision*. Practical ACtion Publishing. https://doi.org/http://dx.doi.org/10.3362/9781780448190

Sweeting, M. J., Sutton, A. J., & Lambert, P. C. (2004). What to add to nothing? Use and avoidance of continuity corrections in meta-analysis of sparse data. *Statistics in Medicine*. https://doi.org/10.1002/sim.1761

Trevett, A. F., Carter, R. C., & Tyrrel, S. F. (2005). The importance of domestic water quality management in the context of faecal-oral disease transmission. *Journal of Water and Health*, *3*(3), 259–270. https://doi.org/10.2166/wh.2005.037

Tucker, J., MacDonald, A., Coulter, L., & Calow, R. C. (2014). Household water use, poverty and seasonality: Wealth effects, labour constraints, and minimal consumption in Ethiopia. *Water Resources and Rural Development*, *3*, 27–47. https://doi.org/10.1016/j.wrr.2014.04.001

UN General Assembly. (2010). *The human right to water and sanitation : resolution / adopted by the General Assembly*. A/RES/64/292. https://www.refworld.org/docid/4cc926b02.html

UN Water. (2013). Eliminating discrimination and inequalities in access to water and sanitation. *UN Water*, *May*, 1–56. http://hrbaportal.org/wp-content/files/UN-Water_Policy_Brief_Anti-Discrimination.pdf

U.S. EPA. (2009). *Method 1603: Escherichia coli (E. coli) in Water by Membrane Filtration Using modified membrane-thermotolerant Escherichia coli Agar (Modified mTEC)*.

Vaccari, M., Collivignarelli, C., Tharnpoophasiam, P., & Vitali, F. (2010). Wells sanitary inspection and water quality monitoring in Ban Nam Khem (Thailand) 30 months after 2004 Indian Ocean tsunami. *Environmental Monitoring and Assessment*, *161*(1–4), 123–133. https://doi.org/10.1007/s10661-008-0732-5

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software*, *36*(3), 1–48.

Vollaard, A. M., Ali, S., Smet, J., Van Asten, H., Widjaja, S., Visser, L. G., Surjadi, C., & Van Dissel, J. T. (2005). A survey of the supply and bacteriologic quality of drinking water and sanitation in Jakarta, Indonesia. *Southeast Asian Journal of Tropical Medicine and Public Health*, *36*(6), 1552–1561.

Walker, D. W., Smigaj, M., & Tani, M. (2021). The benefits and negative impacts of citizen science applications to water as experienced by participants and communities. *Wiley Interdisciplinary Reviews: Water*, *8*(1). https://doi.org/10.1002/wat2.1488

Water Governance Facility. (2014). Mainstreaming Gender in Water Governance Programmes: From Design to Results. *WGF Report*, *4*.

WHO. (2011). Guidelines for drinking-water quality. *World Health Organization*.

WHO. (2017). *Safely managed drinking water - thematic report on drinking water 2017*. https://doi.org/ISBN 978 92 4 156542 4

WHO. (2022). *Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda*.

WHO and UNICEF. (2018). Core questions on water, sanitation and hygiene for household surveys. *Joint Monitoring Programme*.

WHO, & UNICEF. (2010). *Progress on sanitation and drinking water - 2010 update*. http://whqlibdoc.who.int/publications/2010/9789241563956_eng_full_text.pdf

WHO, & UNICEF. (2017a). *Guidelines for drinking-water quality: fourth edition incorporating the first addendum* (Vol. 53, Issue 9). https://doi.org/10.1017/CBO9781107415324.004

WHO, & UNICEF. (2017b). *Guidelines for drinking-water quality: fourth edition incorporating the first addendum* (Vol. 53, Issue 9). https://doi.org/10.1017/CBO9781107415324.004

WHO, & UNICEF. (2019). *Progress on household drinking water, sanitation and hygiene 2000-2017. Special focus on inequalities.* 140.

WHO, & UNICEF. (2020). *Inequalities*. https://washdata.org/monitoring/inequalities

WHO, & UNICEF. (2021). *Five years into the SDGs - Progress on household drinking water, sanitation and hygiene*. https://www.oecd.org/dac/

Willetts, J., Halcrow, G., Carrard, N., Rowland, C., & Crawford, J. (2014). *Making the Invisible Visible : Gender and Pacific Water , Sanitation and Hygiene Initiatives*. 1–15.

World Bank. (2013). *Urban Sanitation Review: Indonesia Country Study*.

World Bank. (2020). *World Bank Country and Lending Groups*. https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-group

Wright, J., Gundry, S., & Conroy, R. (2004). Household drinking water in developing countries: A systematic review of microbiological contamination between source and point-of-use. *Tropical Medicine and International Health*, *9*(1), 1. https://doi.org/10.1046/j.1365-3156.2003.01160.x

Yang, H., Bain, R., Bartram, J., Gundry, S., Pedley, S., & Wright, J. (2013). Water safety and inequality in access to drinking-water between rich and poor households. *Environmental Science and Technology*, *47*(3), 1222–1230. https://doi.org/10.1021/es303345p

Appendix

A1 Supplementary materials of the publications

The supplementary materials of the PhD research can be accessed online from the corresponding publication.

Publication I

Genter, F., Willetts, J., & Foster, T. (2021). Faecal contamination of groundwater self-supply in low-and middle income countries: Systematic review and meta-analysis. *Water Research, 201,* 117350. https://doi.org/10.1016/j.watres.2021.117350

Publication II

Genter, F., Putri, G. L., Pratama, M. A., Priadi, C., Willetts, J., & Foster, T. (2022). Microbial contamination of groundwater self-supply in urban Indonesia: Assessment of sanitary and socio-economic risk factors. Water Resources Research, 58, e2021WR031843. https://doi.org/10.1029/2021WR031843

Publication III

Genter, F., Putri, G.L., Maysarah, S., Rolia, E., Pratama, M. A., Priadi, C., Willetts, J., Foster, T. (2023). Associations between seasonality and faecal contamination of self-supply sources in urban Indonesia. Water Sanitation and Hygiene for Development. https://doi.org/10.2166/washdev.2023.060

Publication IV

Genter, F., Putri, G.L., Suleeman, E., Darmajanti, L., Priadi, C., Foster, T., Willetts, J. (2023). Understanding household self-supply use and management using a mixed-methods approach in urban Indonesia. PLOS Water 2(1): e0000070. https://doi.org/10.1371/journal.pwat.0000070

Publication V

Genter, F., Putri, G. L., Handayani, R., Priadi, C., Willetts, J., & Foster, T. (2023). Evaluation of a participatory citizen approach to monitor microbial water quality of self-supply services in urban Indonesia. Urban Water Journal. https://doi.org/10.1080/1573062X.2023.2285438

A2 Protocol literature review

Objectives

The systematic review with meta-analysis aims to provide insight on the safety of groundwater self-supply in LMICs regarding faecal contamination. The study seeks to understand the extent to which groundwater self-supply is free from faecal contamination and addresses three research questions:

1. To what extent is groundwater self-supply contaminated with faecal indicator bacteria (FIB) in LMIC?

2. How does faecal contamination vary between source types, countries, rural and urban areas, seasons and study designs?

3. How does self-supply compare to public supply in terms of faecal contamination?

The focus of the study is self-supply based on groundwater sources. Rainwater is beyond the scope of this study. Further, the literature review focuses on microbial water quality as reported by FIB. Other microbial parameters such as pathogens or chemical water quality are not addressed.

Methods

This review is conducted according to the PRISMA statement (Moher et al., 2009b). Methods for search strategy, study eligibility and data extraction were adapted from (Bain et al., 2014)

Search Strategy

Studies were identified from peer-reviewed literature between the years 1990 and April 2020. The following databases were consulted: Web of Science (topic including title, abstract, author keywords and keywords plus), PubMed (all fields), SciELO (all fields), ProQuest (anywhere except full text) including Environmental Science, Public Health, Science, Biological Science, Agriculture Science databases) and Environmental Complete (Abstract or author supplied abstract, full text) (Table). Search terms were developed by combining the topic "water quality" with terms to restrict the search to self-supply water and low and middle-income countries using a list of country names (

Table)

Table . Searches were conducted between April and June 2020.

Eligibility and selection

Studies were included in the review provided they: (i) sufficient detail about the water samples to be related to self-supply groundwater sources; (ii) contain extractable data on thermotolerant coliform (TTC) or *Escherichia coli (E. coli)*; (iii) were published between 1990 and April 2020, (iv) include at least 10 separate water samples; (v) report data from LMICs as defined by felt into the classification LMIC (World Bank, 2020) and, (vi) were published in English. Indicators such as total coliform, coliphage and direct pathogen detection are not included in the review. The indicator total coliforms lacks international comparability (Bain et al. 2014) and pathogen and coliphage indicators have not been widely used yet. This review focuses on self-supply based on groundwater, therefore rainwater and surface water self-supply are not included. Studies were selected by screening of titles and abstracts followed by screening of full texts for selected studies. Duplicates were identified and removed.

Data extraction and matching

Basic descriptive data from eligible studies (author, year of publication etc.) and additional study characteristics thought to influence water quality (e.g. setting, season) were extracted into a Microsoft Office Excel 2016 spreadsheet.

Basic descriptive data includes author, year of publication, title, country, country income group and urban or rural setting. The country income group was identified as “low”, “lower-middle”, “upper-middle”, and “high” income based on the World Bank classification (World Bank, 2020). Additional characteristics thought to influence water quality include source type, type of water lifting device, source depth and seasons. To investigate the influence of source type on the water quality, each type of water source was recorded and matched with the corresponding JMP source definition and classified as improved or unimproved (WHO & UNICEF, 2017b). Groundwater sources from studies that did not distinguish between protected and unprotected wells were categorised as unclassified dug well, groundwater sources that did not distinguish between borehole and dug wells were categorised as unclassified.

To explore the influence of seasons, those studies that refer to water quality during “wet”, “rainy” or “dry” periods or equivalent were recorded. It was recorded whether studies took place during or shortly after emergencies or natural disasters. If available, information to the contamination risks provided, corresponding evidence and recommendations were extracted. It was recorded whether the study conducted household surveys or sanitary risk inspections.

Where possible, the following water quality information for each source type in the studies were extracted: non-compliance (presence of *E. coli* or TTC); mean, geometric mean and/or median level of contamination (*E. coli* or TTC per 100 ml); standard deviation, variance or standard errors (*E. coli* or TTC per 100 ml); risk categories of microbial contamination (<1, 1-10, 10-100, 10-50, >50 and >100 *E. coli* or TTC per 100 ml); number of samples tested; analytical method used to detect FIB.

Study Quality and Bias

Quality control criteria extracted include information on the selection (selection described, selection randomized, randomized selection described), region described, season reported, quality control, method described, point of sampling defined, handling described, handling minimum criteria met (Table A2.3: Quality criteria and description. Quality control criteria were selected based on (Bain et al., 2014). Unlike the study of Bain et al. 2014, the criteria accredited laboratory, trained technician and external review were not included. A quality score between 0 and 10 for each study was determined on the basis of the number of affirmative responses. Studies were classified based on study design as this is thought to affect the extent to which they are affected by bias, classification includes: Case-control, intervention, cross-sectional survey, longitudinal survey (>6 months, >2 repeated samples at each water point) and diagnostic study.

Analysis

Data for analysis

Only studies reporting noncompliance results were used for meta-analysis. Measures of central tendency from studies were not included in the meta-analysis because of limited reporting. For studies reporting both *E. coli* and TTC data, only the *E. coli* results were used. For studies reporting summarised results from sub-results, only the sub-results were used. For studies which assessed water quality at both, source and point-of-use, only results from the water source were included in the analysis. For the intervention study, only the dataset several years after the emergency event and intervention was used for analysis.

Qualitative synthesis

To qualitatively assess the proportion of studies reporting frequent and high levels of microbial contamination, cumulative density functions (CDFs) of the proportion of samples with ≥1 FIB per 100 mL and >100 FIB per 100 mL were plotted for each water source type using the “ggplot2” function in the statistical analysis software RStudio (version 1.2.5001, R Foundation for Statistical Computing, Vienna, Austria). Results of unclassified water sources were not included in the CDFs. FIB concentrations from datasets reporting results in risk classification were plotted using Microsoft Office excel 2016. The extent of FIB contamination of self-supply was calculated based on the included datasets used for meta-analysis.

Between study analysis

To investigate heterogeneity between studies in faecal contamination, random effects meta-regression was used to test *a priori* defined subgroups such as setting, season, source type and other study characteristics as possible explanations. Continuity correction of 0.5 was employed in Microsoft Office Excel 2016 for proportions of 0 or 1 (Sweeting et al., 2004). For studies with zero positive samples, 0.5 was substituted for the number of positive samples and for studies where all samples were positive, 0.5 was subtracted from the total number of positive samples. The “metafor” package in the statistical analysis software R (version 1.2.5001, R Foundation for Statistical Computing, Vienna, Austria) was used for meta-regression (Viechtbauer, 2010). A logit transformation for the analysis of proportion and was applied to the proportion of samples with >1 FIB per 100 mL and > 100 FIB per 100 mL using the “escalc” function. To compare the faecal contamination with the defined subgroups, random effects pooled odds ratio were calculated using the “rma” function. The DerSimonian-Laird estimator was used to estimate the amount of heterogeneity (DerSimonian & Laird, 1986).

Following subgroups were investigated:

- Setting: Urban vs. rural
- Income group: Low-income vs. upper-middle and lower-middle
- Source type: Dug well vs. borehole, protected vs. unprotected dug well, unimproved vs. improved, protected dug well vs. borehole
- Study characteristics: Wet vs. dry, TTC vs. *E. coli*, Random vs. non-random selection
- Study quality criteria
- Study design: Cross-sectional, longitudinal, intervention, cohort
- Study quality ranking: Lower (<6) vs higher (median), lower (<8) vs. higher (bottom two terciles vs. top terciles)

Within study analysis

Studies that included extractable water quality data from both self-supply and public water sources were combined using meta-analysis with the odds ratio as the effect measure to compare the faecal contamination based on the proportion of samples >1 FIB per 100 mL. Pooled estimates were calculated using the "escalc" and "rma" function in the R "metafor" package. Heterogeneity was estimated using Higgins I^2 (Higgins & Thompson, 2002). Forest plots were created using the "forest" function for self-supply compared to public water sources, self-supply compared to public piped water sources and improved self-supply water sources compared to improved public water sources. The influence of small study bias was assessed with the funnel plot method and Egger's regression test for odds ratio and standard error using the "funnel.rma" and "regtest" functions (Egger et al., 1997).

Following subgroups were investigated:

- Self-supply vs. public (excluding sachet water)
- Self-supply vs. public (including sachet water)
- Self-supply vs. piped
- Self-supply vs. public improved

Limited number of studies included extractable FIB data of both improved and unimproved self-supply water sources, therefore within study meta-analysis could not be conducted with these subgroups.

Definitions

Non-compliance: The proportion of samples (or sources) in which FIB (*E. coli* or thermotolerant coliform) are detected.

Risk level: The proportion of samples that are within the concentration ranges <1 ("not detected"), 1-10 ("low"), 10-100 ("moderate") and >100 ("high") FIB per 100 mL.

Tables

Table A2.1: Selected databases for the systematic review

Databases	Search
Web of Science	Topic including title, abstract, author keywords and keywords plus
PubMed	All fields
SciELO	All fields
ProQuest • Environmental Science • Public Health • Science • Biological Science • Agriculture Science	Anywhere except full text
Environmental Complete	Abstract or author supplied abstract, full text

Table A2.2: Search terms

(<water quality>) AND (<supply type>) AND (<low and middle income country list>)
((water) AND (safe OR quality)) AND (“self-supply” OR “self supply” OR “self-help” OR “private water” OR “private drinking water” OR “private well*” OR “private borehole*” OR “private tubewell*” OR “private protected well*” OR “on plot” OR “on premises” OR “on-premises” OR “family well*” OR “family borehole*” OR “family protected well*” OR “family water” OR “household well*” OR “household borehole*” OR “household protected well*” OR “domestic well*” OR “domestic borehole*” OR “domestic protected well*”) AND (Afghanistan OR Algeria OR Angola OR Anguilla OR Antigua OR Barbuda OR Argentina OR Armenia OR Armenian OR Aruba OR Azerbaijan OR Bahamas OR Bahrain OR Bangladesh OR Barbados OR Benin OR Byelarus OR Byelorussian OR Belarus OR Belorussian OR Belorussia OR Belize OR Bhutan OR Bolivia OR Botswana OR Brazil OR Brunei OR Burkina Faso OR Burkina Fasso OR Upper Volta OR Burundi OR Urundi OR Cambodia OR Khmer Republic OR Kampuchea OR Cameroon OR Cameroons OR Cameron OR Camerons OR Cape Verde OR Cayman Islands OR Central African Republic OR Chad OR Chile OR China OR Colombia OR Comoros OR Comoro Islands OR Comores OR Mayotte OR Congo OR Zaire OR Cook Islands OR Costa Rica OR Cote d'Ivoire OR Ivory Coast OR Croatia OR Cuba OR Cyprus OR Djibouti OR French Somaliland OR Dominica OR Dominican Republic OR East Timor OR East Timur OR Timor Leste OR Ecuador OR Egypt OR United Arab Republic OR El Salvador OR Eritrea OR Ethiopia OR Falkland Islands OR Las Malvinas OR Fiji OR Gabon OR Gabonese Republic OR Gambia OR Gaza OR Georgia Republic OR Georgian Republic OR Ghana OR Gold Coast OR Greece OR Grenada OR Guatemala OR Guinea OR Guam OR Guadeloupe OR Guiana OR Guyana OR Haiti OR Honduras OR Hong Kong OR India OR Maldives OR Indonesia OR Iran OR Iraq OR Jamaica OR Jordan OR Kazakhstan OR Kazakh OR Kenya OR Kiribati OR Korea OR Kosovo OR Kuwait OR Kyrgyzstan OR Kirghizia OR Kyrgyz Republic OR Kirghiz OR Kirgizstan OR Lao PDR OR Laos OR Lebanon OR Lesotho OR Basutoland OR Liberia OR Libya OR Macau OR Madagascar OR Malagasy Republic OR Maldives OR Malaysia OR Malaya OR Malay OR Sabah OR Sarawak OR Malawi OR Nyasaland OR Mali OR Malta OR Marshall Islands OR Martinique OR Mauritania OR Mauritius OR Agalega Islands OR Mexico OR Micronesia OR Middle East OR Mongolia OR Montserrat OR Morocco OR Ifni OR Mozambique OR Myanmar OR Myanma OR Burma OR Namibia OR Nauru OR Nepal OR Niui OR Netherlands Antilles OR New Caledonia OR Nicaragua OR Niger OR Nigeria OR Northern Mariana Islands OR Oman OR Mayotte OR Muscat OR Pakistan OR Palau OR Palestine OR Panama OR Paraguay OR Peru OR Philippines OR Philipines OR Phillipines OR Phillippines OR Polynesia OR Puerto Rico OR Qatar OR Reunion OR Rwanda OR Ruanda OR Saint Kitts OR St Kitts OR Nevis OR Saint Lucia OR St Lucia OR Saint Vincent OR St Vincent OR Grenadines OR Samoa OR Samoan Islands OR Navigator Island OR Navigator Islands OR Sao Tome OR Saudi Arabia OR Senegal OR Serbia OR Montenegro OR Seychelles OR Sierra Leone OR Singapore OR Sri Lanka OR Ceylon OR Solomon Islands OR Somalia OR South Africa OR Sudan OR Suriname OR Surinam OR Swaziland OR Syria OR Tajikistan OR Tadzhikistan OR Tadjikistan OR Tadzhik OR Tanzania OR Thailand OR Togo OR Togolese Republic OR Tokelau OR Tonga OR Trinidad OR Tobago OR Tunisia OR Turkey OR Turkmenistan OR Turkmen OR Turks Caicos OR Tuvalu Uganda OR United Arab Emirates OR Uruguay OR Uzbekistan OR Uzbek OR Vanuatu OR New Hebrides OR Venezuela OR Vietnam OR Viet Nam OR Virgin Islands OR West Bank OR Yemen OR Yugoslavia OR Zambia OR Zimbabwe)

Table A2.3: Quality criteria and description

Quality Criterion	Description
Selection described	Description of how the water samples were chosen, including how either the types of water source or their users were selected
Selection representative	Description of an approach that provides a representative picture of water quality in a given area
Selection randomized	Randomized sampling over a given study or population
Region described	Description of the geographic region within the country where the study was conducted
Season reported	Report of seasons or months of sampling
Quality control	Specification or reference of quality control procedures
Method described	Description or reference of well-defined and appropriate methods of microbial analysis
Point of sampling	Description of the point at which water was sampled
Handling described	Description of sample handling procedures, including sample collection, transport method and duration
Handling minimum criteria	Fulfilment of handling minimum criteria for sample handling and processing: transport on ice or between 2-8 °C, analysis within 6 hours of collection, and specified incubation temperature

References

Aboelnga, H. T., Ribbe, L., Frechen, F. B., & Saghir, J. (2019). Urban water security: Definition and assessment framework. *Resources*, *8*(4). https://doi.org/10.3390/resources8040178

Acey, C. (2010). Gender and community mobilisation for urban water infrastructure investment in southern Gender and community mobilisation for urban water infrastructure investment in southern Nigeria. *Gender & Development*, *18*(1). https://doi.org/10.1080/13552071003599970

Adams, E. A., Boateng, G. O., & Amoyaw, J. A. (2016). Socioeconomic and Demographic Predictors of Potable Water and Sanitation Access in Ghana. *Social Indicators Research*, *126*(2), 673–687. https://doi.org/10.1007/s11205-015-0912-y

Ali, R., Bünzli, M. A., Colombo, L., Khattak, S. A., Pera, S., Riaz, M., & Valsangiacomo, C. (2019). Water quality before and after a campaign of cleaning and disinfecting shallow wells: A study conducted during and after floods in Khyber Pakhtunkhwa, Pakistan. *Journal of Water Sanitation and Hygiene for Development*, *9*(1), 28–37. https://doi.org/10.2166/WASHDEV.2018.272

Allan, J. V, Kenway, S. J., & Head, B. W. (2018). Urban water security - what does it mean? *Urban Water Journal*, *15*(9), 899–910. https://doi.org/10.1080/1573062X.2019.1574843

Andadari, R. K., Mulder, P., & Rietveld, P. (2014). Energy poverty reduction by fuel switching. Impact evaluation of the LPG conversion program in Indonesia. *Energy Policy*, *66*, 436–449. https://doi.org/10.1016/j.enpol.2013.11.021

ARGOSS. (2001). Guidelines for Assessing the Risk to Groundwater from On-Site Sanitation. *British Geological Survey*, *01*(142), Art. CR/01/142.97pp.

Aven, T., & Renn, O. (2009). On risk defined as an event where the outcome is uncertain. *Journal of Risk Research*, *12*(1), 1–11. https://doi.org/10.1080/13669870802488883

Bain, R., Bartram, J., Elliott, M., Matthews, R., Mcmahan, L., Tung, R., Chuang, P., & Gundry, S. (2012). A summary catalogue of microbial drinking water tests for low and medium resource settings. *International Journal of Environmental Research and Public Health*, *9*(5), 1609–1625. https://doi.org/10.3390/ijerph9051609

Bain, R., Cronk, R., Wright, J., Yang, H., Slaymaker, T., & Bartram, J. (2014a). Fecal Contamination of Drinking-Water in Low- and Middle-Income Countries: A Systematic Review and Meta-Analysis. *PLoS Medicine*, *11*(5). https://doi.org/10.1371/journal.pmed.1001644

Bain, R., Cronk, R., Wright, J., Yang, H., Slaymaker, T., & Bartram, J. (2014b). Fecal Contamination of Drinking-Water in Low- and Middle-Income Countries: A Systematic Review and Meta-Analysis. *PLoS Medicine*, *11*(5). https://doi.org/10.1371/journal.pmed.1001644

Bappeda Kota Bekasi. (2018). *Rencana Pembangunan Jangka Menengah Daerah Kota Bekasi 2018-2023*.

Bartram, J., Brocklehurst, C., Fisher, M. B., Luyendijk, R., Hossain, R., Wardlaw, T., & Gordon, B. (2014). Global monitoring of water supply and sanitation: History, methods and future challenges. In *International Journal of Environmental Research and Public Health* (Vol. 11, Issue 8, pp. 8137–8165). MDPI. https://doi.org/10.3390/ijerph110808137

Bartram, J., Corrales, L., Davison, A., Deere, D., Drury, D., Gordon, B., Howard, G., Rinehold, A., & Stevens, M. (2009). *Water Safety Plan Manual: Step-by-step risk management for drinking-water suppliers*.

BPS Kota Bekasi. (2021). Bekasi Municipality in Figures 2021. *BPS Kota Bekasi*, *1907.3763*.

BPS Kota Metro. (2019). *Metro Municipality in Figures 2019*. *1907–4751*, 262.

Bradley, D. J., & Bartram, J. K. (2013). Domestic water and sanitation as water security: Monitoring, concepts and strategy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *371*(2002). https://doi.org/10.1098/rsta.2012.0420

Brouwer, S., van der Wielen, P. W. J. J., Schriks, M., Claassen, M., & Frijns, J. (2018). Public participation in science: The future and value of citizen science in the drinking water research. *Water (Switzerland)*, *10*(3). https://doi.org/10.3390/w10030284

Butterworth, J., Sutton, S., & Mekonta, L. (2013). Self-supply as a complementary water services delivery model in Ethiopia. *Water Alternatives*, *6*(3), 405–423.

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T. C., Bastiaensen, J., De Bièvre, B., Bhusal, J., Clark, J., Dewulf, A., Foggin, M., Hannah, D. M., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandeya, B., Paudel, D., Sharma, K., Steenhuis, T., … Zhumanova, M. (2014). Citizen science in hydrology and water resources: Opportunities for knowledge generation, ecosystem service management, and sustainable development. In *Frontiers in Earth Science* (Vol. 2). Frontiers Media S.A. https://doi.org/10.3389/feart.2014.00026

Carrard, N., Crawford, J., Halcrow, G., & Rowland, C. (2013). A framework for exploring gender equality outcomes from WASH programmes. *Waterlines*, *32*(4).

Carrard, N., MacArthur, J., Leahy, C., Soeters, S., & Willetts, J. (2022). The water, sanitation and hygiene gender equality measure (WASH-GEM): Conceptual foundations and domains of change. *Women's Studies International Forum*, *91*. https://doi.org/10.1016/j.wsif.2022.102563

Carrard, N., Madden, B., Chong, J., Grant, M., Nghiêm, T. P., Bùi, L. H., Hà, H. T. T., & Willetts, J. (2019). Are piped water services reaching poor households? Empirical evidence from rural Viet Nam. *Water Research*, *153*, 239–250. https://doi.org/10.1016/j.watres.2019.01.026

Chao, K. K., Chao, C. C., & Chao, W. L. (2004). Evaluation of Colilert-18 for Detection of Coliforms and Eschericha coli in Subtropical Freshwater. *Applied and Environmental Microbiology*, *70*(2), 1242–1244. https://doi.org/10.1128/AEM.70.2.1242-1244.2004

Charles, K. J., Nowicki, S., & Bartram, J. K. (2020). A framework for monitoring the safety of water services: from measurements to security. *Npj Clean Water*, *3*(1), 1–6. https://doi.org/10.1038/s41545-020-00083-1

Chávez García Silva, R., Grönwall, J., Van Der Kwast, J., Danert, K., & Foppen, J. W. (2020). Estimating domestic self-supply groundwater use in urban continental Africa. *Environmental Research Letters*, *15*(10). https://doi.org/10.1088/1748-9326/ab9af9

Clasen, T. F., & Bastable, A. (2003). Faecal contamination of drinking water during collection and household storage: The need to extend protection to the point of use. *Journal of Water and Health*, *1*(3), 109–115. https://doi.org/10.2166/wh.2003.0013

Clasen, T. F., Do, H. T., Boisson, S., & Shipin, O. (2008). Microbiological effectiveness and cost of boiling to disinfect drinking water in rural Vietnam. *Environmental Science and Technology*, *42*(12), 4255–4260. https://doi.org/10.1021/es7024802

Cohen, A., Zhang, Q., Luo, Q., Tao, Y., Colford, J. M., & Ray, I. (2017). Predictors of Drinking Water Boiling and Bottled Water Consumption in Rural China: A Hierarchical Modeling Approach. *Environmental Science and Technology*, *51*(12), 6945–6956. https://doi.org/10.1021/acs.est.7b01006

Conrad, C. C., & Hilchey, K. G. (2011). A review of citizen science and community-based environmental monitoring: Issues and opportunities. *Environmental Monitoring and Assessment*, *176*(1–4), 273–291. https://doi.org/10.1007/s10661-010-1582-5

Crocker, J., & Bartram, J. (2014). Comparison and cost analysis of drinking water quality monitoring requirements versus practice in seven developing countries. *International Journal of Environmental Research and Public Health*, *11*(7), 7333–7346. https://doi.org/10.3390/ijerph110707333

Cronin, A. A., Odagiri, M., Arsyad, B., Nuryetty, M. T., Amannullah, G., Santoso, H., Darundiyah, K., & Nasution, N. A. (2017). Piloting water quality testing coupled with a national socioeconomic survey in Yogyakarta province, Indonesia, towards tracking of Sustainable Development Goal 6. *International Journal of Hygiene and Environmental Health*, *220*(7), 1141–1151. https://doi.org/10.1016/j.ijheh.2017.07.001

Daniel, D., Marks, S. J., Pande, S., & Rietveld, L. (2018). Socio-environmental drivers of sustainable adoption of household water treatment in developing countries. *Npj Clean Water*, *1*(1). https://doi.org/10.1038/s41545-018-0012-z

Davoodi, R., Pirsaheb, M., Karimyan, K., Gupta, V. K., Takhtshahi, A. R., Sharafi, H., & Moradi, M. (2018). Data for distribution of various species of fecal coliforms in urban, rural and private drinking water sources in ten years period – A case study: Kermanshah, Iran. *Data in Brief*, *18*, 1544–1550. https://doi.org/10.1016/j.dib.2018.04.053

DerSimonian, R., & Laird, N. (1986). Meta-analysis in clinical trials. *Controlled Clinical Trials*. https://doi.org/10.1016/0197-2456(86)90046-2

Egger, M., Smith, G. D., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected by a simple, graphical test. *British Medical Journal*. https://doi.org/10.1136/bmj.315.7109.629

Eisenhauer, I. F., Hoover, C. M., Remais, J. V., Monaghan, A., Celada, M., & Carlton, E. J. (2016). Estimating the risk of domestic water source contamination following precipitation events. *American Journal of Tropical Medicine and Hygiene*, *94*(6), 1403–1406. https://doi.org/10.4269/ajtmh.15-0600

Ejechi, E. O., & Ejechi, B. O. (2008). Safe drinking water and satisfaction with environmental quality of life in some oil and gas industry impacted cities of Nigeria. *Social Indicators Research*, *85*(2), 211–222. https://doi.org/10.1007/s11205-007-9086-6

Elliott, M., MacDonald, M. C., Chan, T., Kearton, A., Shields, K. F., Bartram, J. K., & Hadwen, W. L. (2017). Multiple household water sources and their use in remote communities with evidence from Pacific Island Countries. *Water Resources Research*, *54*, 9106–9117.

Fagerli, K., Trivedi, K. K., Sodha, S. V., Blanton, E., Ati, A., Nguyen, T., Delea, K. C., Ainslie, R., Figueroa, M. E., Kim, S., & Quick, R. (2017). Comparison of boiling and chlorination on the quality of stored drinking water and childhood diarrhoea in Indonesian households. *Epidemiology and Infection*, *145*(15), 3294–3302. https://doi.org/10.1017/S0950268817002217

Fischer, A., Hope, R., Manandhar, A., Hoque, S., Foster, T., Hakim, A., Islam, M. S., & Bradley, D. (2020). Risky responsibilities for rural drinking water institutions: The case of unregulated self-supply in Bangladesh. *Global Environmental Change*, *65*(June 2019). https://doi.org/10.1016/j.gloenvcha.2020.102152

Fisher, J. (2008). Women in water supply , sanitation and hygiene programmes. *Municipal Engineer*, *161*(ME4), 223–229. https://doi.org/10.1680/muen.2008.161.4.223

Fisher, J., Cavill, S., & Reed, B. (2017). Mainstreaming gender in the WASH sector: dilution or distillation? *Gender and Development*, *25*(2), 185–204. https://doi.org/10.1080/13552074.2017.1331541

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). *Resilience Thinking: Integrating Resilience, Adaptability and Transformability*. https://www.jstor.org/stable/26268226?seq=1&cid=pdf-

Foster, S., Hirata, R., Eichholz, M., & Alam, M. F. (2022). Urban Self-Supply from Groundwater—An Analysis of Management Aspects and Policy Needs. *Water (Switzerland)*, *14*(4). https://doi.org/10.3390/w14040575

Foster, T., Priadi, C., Kotra, K. K., Odagiri, M., Rand, E. C., & Willetts, J. (2021). Self-supplied drinking water in low- and middle-income countries in the Asia-Pacific. *Npj Clean Water*, *4*(1), 1–10. https://doi.org/10.1038/s41545-021-00121-6

Foster, T., Shantz, A., Lala, S., & Willetts, J. (2018). Factors associated with operational sustainability of rural water supplies in Cambodia. *Environmental Science: Water Research and Technology*, *4*(10), 1577–1588. https://doi.org/10.1039/c8ew00087e

Furlong, K., & Kooy, M. (2017). Worlding Water Supply: Thinking Beyond the Network in Jakarta. *International Journal of Urban and Regional Research*, *41*(6), 888–903. https://doi.org/10.1111/1468-2427.12582

Genter, F., Marks, S. J., Clair-Caliot, G., Mugume, D. S., Johnston, R. B., Bain, R. E. S., & Julian, T. R. (2019). Evaluation of the novel substrate RUG^{TM} for the detection of: Escherichia coli in water from temperate (Zurich, Switzerland) and tropical (Bushenyi, Uganda) field sites. *Environmental Science: Water Research and Technology*, *5*(6), 1082–1091. https://doi.org/10.1039/c9ew00138g

Genter, F., Putri, G. L., Handayani, R., Priadi, C., Willetts, J., & Foster, T. (2023). Evaluation of a participatory citizen approach to monitor microbial water quality of self-supply in urban Indonesia. *Urban Water Journal*, 1–13. https://doi.org/10.1080/1573062X.2023.2285438

Genter, F., Putri, G. L., Maysarah, S., Rolia, E., Pratama, M. A., Priadi, C., Willetts, J., & Foster, T. (2023). Associations between seasonality and faecal contamination of self-supply sources in urban Indonesia. *Journal of Water, Sanitation and Hygiene for Development*. https://doi.org/10.2166/washdev.2023.060

Genter, F., Putri, G. L., Suleeman, E., Darmajanti, L., Priadi, C., Foster, T., & Willetts, J. (2023). Understanding household self-supply use and management using a mixed-methods approach in urban Indonesia. *PLOS Water*, *2*(1), e0000070. https://doi.org/10.1371/journal.pwat.0000070

Genter, F., Putri, G., Pratama, M., Priadi, C., Willetts, J., & Foster, T. (2022). Microbial Contamination of Groundwater Self-supply in urban Indonesia: Assessment of Sanitary and Socio-economic Risk factors. *Water Resources Research*, *58*. https://doi.org/https://doi.org/10.1029/2021WR031843

Genter, F., Willetts, J., & Foster, T. (2021). Faecal contamination of groundwater self-supply in low- and middle income countries: Systematic review and meta-analysis. In *Water Research*. https://doi.org/10.1016/j.watres.2021.117350

Gero, A., & Willetts, J. (2020). Securing a conducive environment for WASH markets: The role of local government. *Waterlines*, *39*(1), 44–60.

Gharesifard, M., Wehn, U., & van der Zaag, P. (2019). What influences the establishment and functioning of community-based monitoring initiatives of water and environment? A conceptual framework. *Journal of Hydrology*, *579*. https://doi.org/10.1016/j.jhydrol.2019.124033

Gleeson, T., Wada, Y., Bierkens, M. F. P., & Van Beek, L. P. H. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature*, *488*(7410), 197–200. https://doi.org/10.1038/nature11295

Gorter, A. C., Alberts, J. H., Gago, J. F., & Sandiford, P. (1995). A randomized trial of the impact of rope-pumps on water quality. *Journal of Tropical Medicine and Hygiene*, *98*, 247–255.

Gould, C. F., Schlesinger, S. B., Molina, E., Bejarano, M. L., Valarezo, A., & Jack, D. W. (2020). Household fuel mixes in peri-urban and rural Ecuador: Explaining the context of LPG, patterns of continued firewood use, and the challenges of induction cooking. *Energy Policy*, *136*. https://doi.org/10.1016/j.enpol.2019.111053

Graham, J. P., & Polizzotto, M. L. (2013). Pit latrines and their impacts on groundwater quality: A systematic review. *Environmental Health Perspectives*, *121*(5), 521–530. https://doi.org/10.1289/ehp.1206028

Grant, M., Huggett, C., Willetts, J., & Wilbur, J. (2017). *Gender Equality & Goal 6 : The Critical Connection*. Australian Water Partnership.

Grey, D., & Sadoff, C. W. (2007). Sink or Swim? Water security for growth and development. *Water Policy*, *9*(6), 545–571. https://doi.org/10.2166/wp.2007.021

Grönwall, J., & Danert, K. (2020). Regarding Groundwater and Drinking Water Access through A Human Rights Lens : Self-Supply as A Norm. *Water*, *12*(419), 21.

Grönwall, J., Mulenga, M., & Mcgranahan, G. (2010). Groundwater, self-supply and poor urban dwellers - A review with case studies of Bangalore and Lusaka. *Human Settlements Working Paper Series - Water and Sanitation*, *26*, 87.

Gundry, S. W., Wright, J. A., Conroy, R., Du Preez, M., Genthe, B., Moyo, S., Mutisi, C., Ndamba, J., & Potgieter, N. (2006). Contamination of drinking water between source and point-of-use in rural households of South Africa and Zimbabwe: implications for monitoring the Millennium Development Goal for water. *Water Practice and Technology*, *1*(2). https://doi.org/10.2166/wpt.2006.032

Hadipuro, W. (2010). Indonesia's water supply regulatory framework: Between commercialisation and public service? *Water Alternatives*, *3*(3), 475–491.

Hakam, D. F., Nugraha, H., Wicaksono, A., Rahadi, R. A., & Kanugrahan, S. P. (2022). Mega conversion from LPG to induction stove to achieve Indonesia's clean energy transition. *Energy Strategy Reviews*, *41*. https://doi.org/10.1016/j.esr.2022.100856

Healy, A. (2019). The Rise of the Off-Grid City. *GeoDrilling International*.

Higgins, J. P. T., & Thompson, S. G. (2002). Quantifying heterogeneity in a meta-analysis. *Statistics in Medicine*. https://doi.org/10.1002/sim.1186

Hope, R., & Rouse, M. (2013). Risks and responses to universal drinking water security. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *371*(2002). https://doi.org/10.1098/rsta.2012.0417

Hoque, S. F., Hope, R., Arif, S. T., Akhter, T., Naz, M., & Salehin, M. (2019). A social-ecological analysis of drinking water risks in coastal Bangladesh. *Science of the Total Environment*, *679*, 23–34. https://doi.org/10.1016/j.scitotenv.2019.04.359

Howard, G. (2002). Water quality surveillance - a practical guide. *Environmental Science and Technology*, *5*(2), 114–119.

Howard, G., Calow, R., Macdonald, A., & Bartram, J. (2016). Climate Change and Water and Sanitation: Likely Impacts and Emerging Trends for Action. *Annual Review of Environment and Resources*, *41*, 253–276. https://doi.org/10.1146/annurev-environ-110615-085856

Hulland, K. R. S., Chase, R. P., Caruso, B. A., Swain, R., Biswal, B., Sahoo, K. C., Panigrahi, P., & Dreibelbis, R. (2015). Sanitation, stress, and life stage: A systematic data collection study among women in Odisha, India. *PLoS ONE*, *10*(11). https://doi.org/10.1371/journal.pone.0141883

Hunter, P. R. (2009). Household water treatment in developing countries: Comparing different intervention types using meta-regression. *Environmental Science and Technology*, *43*(23), 8991–8997. https://doi.org/10.1021/es9028217

IDEXX Laboratories. (2015). Colilert-18 Procedure. In *Idexx Laboratories* (Issue 0). https://www.lagaay.com/Catalogus/Product information/279555/Colilert -18 E-coli detection Manual.pdf

Kelly, E., Cronk, R., Fisher, M., & Bartram, J. (2021). Sanitary inspection, microbial water quality analysis, and water safety in handpumps in rural sub-Saharan Africa. *Npj Clean Water*, *4*(1), 3. https://doi.org/10.1038/s41545-020-00093-z

Kelly, E. R., Cronk, R., Kumpel, E., Howard, G., & Bartram, J. (2020). How we assess water safety: A critical review of sanitary inspection and water quality analysis. *Science of The Total Environment*, *718*, 137237. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.137237

Kilsby, D. (2012). " Now we feel like respected adults " - Positive change in gender roles and relations in a Timor-Leste WASH program. *ACFID Research in Development Series*, *6*.

Kooy, M., Walter, C. T., & Prabaharyaka, I. (2018). Inclusive development of urban water services in Jakarta: The role of groundwater. *Habitat International*, *73*, 109–118. https://doi.org/10.1016/j.habitatint.2016.10.006

Korfali, S. I., & Jurdi, M. (2009). Provision of safe domestic water for the promotion and protection of public health: A case study of the city of Beirut, Lebanon. *Environmental Geochemistry and Health*, *31*(2), 283–295. https://doi.org/10.1007/s10653-008-9218-1

Kostyla, C., Bain, R., Cronk, R., & Bartram, J. (2015). Seasonal variation of fecal contamination in drinking water sources in developing countries: A systematic review. In *Science of the Total Environment* (Vol. 514, pp. 333–343). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2015.01.018

Kumpel, E., Cock-Esteb, A., Duret, M., Waal, O. De, & Khush, R. (2017). Seasonal variation in drinking and domestic water sources and quality in port harcourt, Nigeria. *American Journal of Tropical Medicine and Hygiene*, *96*(2), 437–445. https://doi.org/10.4269/ajtmh.16-0175

Kurniasih, H. (2008). Water Not for All: The Concequences of Water Privitisation in Jakarta, Indonesia. *The 17th Biennial Conference of the Asian Studies Association of Australia*, 1–19.

Larson, B., Minten, B., & Razafindralambo, R. (2006). Unravelling the linkages between the Millennium Development Goals for poverty, education, access to water and household water use in developing countries: Evidence from Madagascar. *Journal of Development Studies*, *42*(1), 22–40. https://doi.org/10.1080/00220380500356258

MacArthur, J., Carrard, N., & Willetts, J. (2020). Wash and gender: A critical review of the literature and implications for gender-transformative wash research. In *Journal of Water Sanitation and Hygiene for Development* (Vol. 10, Issue 4, pp. 818–827). IWA Publishing. https://doi.org/10.2166/washdev.2020.232

MacCarthy, M. F., Annis, J. E., & Mihelcic, J. R. (2013). Unsubsidised self-supply in eastern Madagascar. *Water Alternatives*, *6*(3), 424–438.

Macdonald, A., Davies, J., Calow, R., & Chilton, J. (2005). Developing groundwater. A Guide fro Rural Water Supply. In *Public Works*.

Magro, G., Bain, R. E. S., Woodall, C. A., Matthews, R. L., Gundry, S. W., & Davis, A. P. (2014). Synthesis and application of resorufin β- D -glucuronide, a low-cost chromogenic substrate for detecting Escherichia coli in drinking water. *Environmental Science and Technology*, *48*(16), 9624–9631. https://doi.org/10.1021/es502319n

Manafi, M. (1996). Fluorogenic and chromogenic enzyme substrates in culture media and identification tests. *International Journal of Food Microbiology*, *31*(1–3), 45–58. https://doi.org/10.1016/0168-1605(96)00963-4

Marks, S. J., & Davis, J. (2012). Does User Participation Lead to Sense of Ownership for Rural Water Systems? Evidence from Kenya. *World Development*, *40*(8), 1569–1576. https://doi.org/10.1016/j.worlddev.2012.03.011

Martel, P. (2016). Review of Options for Reporting Water, Sanitation and Hygiene Coverage By Wealth Quintile. In *MICS Methodological Papers* (Data and Analytics Section, Division of Data, Research and Policy, Issue 4). http://mics.unicef.org/files?job=W1siZiIsIjIwMTcvMDYvMTUvMTYvMzMvMzAvMzE2L01JQ1NfTWV0aG9kb2xvZ2ljYWxfUGFwZXJfNC5wZGYiXV0&sha=adfd855d58aa27ea

Martínez-Santos, P., Martín-Loeches, M., García-Castro, N., Solera, D., Díaz-Alcaide, S., Montero, E., & García-Rincón, J. (2017). A survey of domestic wells and pit latrines in rural settlements of Mali: Implications of on-site sanitation on the quality of water supplies. *International Journal of Hygiene and Environmental Health*, *220*(7), 1179–1189. https://doi.org/10.1016/j.ijheh.2017.08.001

McGinnis, M. D., & Ostrom, E. (2014). Social-ecological system framework: Initial changes and continuing challenges. *Ecology and Society*, *19*(2). https://doi.org/10.5751/ES-06387-190230

McGuinness, S. L., O'Toole, J., Barker, S. F., Forbes, A. B., Boving, T. B., Giriyan, A., Patil, K., D'Souza, F., Vhaval, R., Cheng, A. C., & Leder, K. (2020). Household Water Storage Management, Hygiene Practices, and Associated Drinking Water Quality in Rural India. *Environmental Science & Technology*, *54*(8), 4963–4973. https://doi.org/10.1021/acs.est.9b04818

Meierhofer, R., Bänziger, C., Deppeler, S., Kunwar, B. M., & Bhatta, M. (2018). From water source to tap of ceramic filters—factors that influence water quality between collection and consumption in rural households in Nepal. *International Journal of Environmental Research and Public Health*, *15*(11). https://doi.org/10.3390/ijerph15112439

Metwali, R. M. (2003). Water quality of some wells in Taiz City (Yemen Republic) and its surroundings. *Folia Microbiologica*, *48*(1), 90–94. https://doi.org/10.1007/BF02931282

Ministry of Public Works, Indonesia Habitat National Team, & Housing Republic of Indonesia. (2016). *Indonesia National Report for Habitat III*.

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009a). PRISMA - Review guidelines. *Annals of Internal Medicine*.

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009b). PRISMA - Review guidelines. *Annals of Internal Medicine*.

Mommen, B., Humphries-Waa, K., & Gwavuya, S. (2017). Does women's participation in water committees affect management and water system performance in rural Vanuatu? *Waterlines*, *36*(3), 216–232. https://doi.org/10.3362/1756-3488.16-00026

National Population and Family Planning Board (BKKBN), Statistics Indonesia (BPS), Ministry of Health (Kemenkes), & ICF. (2018). *Indonesia Demographic and Health Survey 2017*. https://dhsprogram.com/pubs/pdf/FR342/FR342.pdf

Ngasala, T. M., Masten, S. J., & Phanikumar, M. S. (2019). Impact of domestic wells and hydrogeologic setting on water quality in peri-urban Dar es Salaam, Tanzania. *Science of the Total Environment*, *686*, 1238–1250. https://doi.org/10.1016/j.scitotenv.2019.05.202

Okotto, L., Okotto-Okotto, J., Price, H., Pedley, S., & Wright, J. (2015). Socio-economic aspects of domestic groundwater consumption, vending and use in Kisumu, Kenya. *Applied Geography*, *58*(March), 189–197. https://doi.org/10.1016/j.apgeog.2015.02.009

Ostrom, E. (2009). A General Framework for Analyzing Sustainability of Social-Ecological Systems. In *Science* (Vol. 325, Issue 5939, pp. 416–419). https://doi.org/10.1126/science.1170749

Özdemir, S., Elliott, M., Brown, J., Nam, P. K., Hien, V. T., & Sobsey, M. D. (2011). Rainwater harvesting practices and attitudes in the mekong delta of Vietnam. *Journal of Water Sanitation and Hygiene for Development*. https://doi.org/10.2166/washdev.2011.024

Peckenham, J. M., Thornton, T., & Peckenham, P. (2012). Validation of Student Generated Data for Assessment of Groundwater Quality. *Journal of Science Education and Technology*, *21*(2), 287–294. https://doi.org/10.1007/s10956-011-9317-0

Pierce, J. L., Kostova, T., & Dirks, K. T. (2001). Toward a theory of psychological ownership in organizations. *Academy of Management*, *26*(2).

Poirier, M. J. P., Grépin, K. A., & Grignon, M. (2020). Approaches and Alternatives to the Wealth Index to Measure Socioeconomic Status Using Survey Data: A Critical Interpretive Synthesis. In *Social Indicators Research* (Vol. 148, Issue 1). Springer Netherlands. https://doi.org/10.1007/s11205-019-02187-9

Priadi, C., Darmajanti, L., Suleeman, E., Putri, G., Genter, F., Foster, T., & Willetts, J. (2023). Policy and regulatory context for self-supplied water services in two cities Indonesia: Priorities for managing socio-ecological risks [manuscript submitted for publication]. *Environmental Development*. https://doi.org/10.1016/j.envdev.2023.100940

Psutka, R., Peletz, R., Michelo, S., Kelly, P., & Clasen, T. (2011). Assessing the microbiological performance and potential cost of boiling drinking water in urban Zambia. *Environmental Science and Technology*, *45*(14), 6095–6101. https://doi.org/10.1021/es2004045

Ravenscroft, P., Mahmud, Z. H., Islam, M. S., Hossain, A. K. M. Z., Zahid, A., Saha, G. C., Zulfiquar Ali, A. H. M., Islam, K., Cairncross, S., Clemens, J. D., & Islam, M. S. (2017). The public health significance of latrines discharging to groundwater used for drinking. *Water Research*, *124*, 192–201. https://doi.org/10.1016/j.watres.2017.07.049

Schmidlin, T., Hürlimann, E., Silué, K. D., Yapi, R. B., Houngbedji, C., Kouadio, B. A., Acka-Douabélé, C. A., Kouassi, D., Ouattara, M., Zouzou, F., Bonfoh, B., N'Goran, E. K., Utzinger, J., & Raso, G. (2013). Effects of Hygiene and Defecation Behavior on Helminths and Intestinal Protozoa Infections in Taabo, Côte d'Ivoire. *PLoS ONE*, *8*(6), 1–12. https://doi.org/10.1371/journal.pone.0065722

Septarini, A., Islami, B. B., Putri, G. L., Pratama, M. A., Foster, T., Willetts, J., & Priadi, C. R. (2021). Sanitation inspection of household fecal containment in Bekasi, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *776*(1). https://doi.org/10.1088/1755-1315/776/1/012004

Smith, D. W., Islam, M., Furst, K. E., Mustaree, S., Crider, Y. S., Akter, N., Islam, S. A., Sultana, S., Mahmud, Z. H., Rahman, M., Mitch, W. A., & Davis, J. (2021). Chlorine taste can increase simulated exposure to both fecal contamination and disinfection byproducts in water supplies. *Water Research*. https://doi.org/10.1016/j.watres.2021.117806

Sobsey, M. D., Stauber, C. E., Casanova, L. M., Brown, J. M., & Elliott, M. A. (2008). Point of use household drinking water filtration: A practical, effective solution for providing sustained access to safe drinking water in the developing world. *Environmental Science and Technology*, *42*(12), 4261–4267. https://doi.org/10.1021/es702746n

Srikanth, R. (2013). Access, monitoring and intervention challenges in the provision of safe drinking water in rural Bihar, India. *Journal of Water Sanitation and Hygiene for Development*, *3*(1), 61–69. https://doi.org/10.2166/washdev.2013.033

Sutton, S. (2009). An Introduction to Self Supply: Putting the User First - Incremental improvements and private investment in rural water supply. *Rural Water Supply Series*, *February*, 1–7. http://www.rwsn.ch/documentation/skatdocumentation.2009-07-27.8158674790/file

Sutton, S., & Butterworth, J. (2021). *Self-Supply: Filling the gaps in public water supply provision*. Practical ACtion Publishing. https://doi.org/http://dx.doi.org/10.3362/9781780448190

Sweeting, M. J., Sutton, A. J., & Lambert, P. C. (2004). What to add to nothing? Use and avoidance of continuity corrections in meta-analysis of sparse data. *Statistics in Medicine*. https://doi.org/10.1002/sim.1761

Trevett, A. F., Carter, R. C., & Tyrrel, S. F. (2005). The importance of domestic water quality management in the context of faecal-oral disease transmission. *Journal of Water and Health*, *3*(3), 259–270. https://doi.org/10.2166/wh.2005.037

Tucker, J., MacDonald, A., Coulter, L., & Calow, R. C. (2014). Household water use, poverty and seasonality: Wealth effects, labour constraints, and minimal consumption in Ethiopia. *Water Resources and Rural Development*, *3*, 27–47. https://doi.org/10.1016/j.wrr.2014.04.001

UN General Assembly. (2010). *The human right to water and sanitation : resolution / adopted by the General Assembly*. A/RES/64/292. https://www.refworld.org/docid/4cc926b02.html

UN Water. (2013). Eliminating discrimination and inequalities in access to water and sanitation. *UN Water*, *May*, 1–56. http://hrbaportal.org/wp-content/files/UN-Water_Policy_Brief_Anti-Discrimination.pdf

U.S. EPA. (2009). *Method 1603: Escherichia coli (E. coli) in Water by Membrane Filtration Using modified membrane-thermotolerant Escherichia coli Agar (Modified mTEC)*.

Vaccari, M., Collivignarelli, C., Tharnpoophasiam, P., & Vitali, F. (2010). Wells sanitary inspection and water quality monitoring in Ban Nam Khem (Thailand) 30 months after 2004 Indian Ocean tsunami. *Environmental Monitoring and Assessment*, *161*(1–4), 123–133. https://doi.org/10.1007/s10661-008-0732-5

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software*, *36*(3), 1–48.

Vollaard, A. M., Ali, S., Smet, J., Van Asten, H., Widjaja, S., Visser, L. G., Surjadi, C., & Van Dissel, J. T. (2005). A survey of the supply and bacteriologic quality of drinking water and sanitation in Jakarta, Indonesia. *Southeast Asian Journal of Tropical Medicine and Public Health*, *36*(6), 1552–1561.

Walker, D. W., Smigaj, M., & Tani, M. (2021). The benefits and negative impacts of citizen science applications to water as experienced by participants and communities. *Wiley Interdisciplinary Reviews: Water*, *8*(1). https://doi.org/10.1002/wat2.1488

Water Governance Facility. (2014). Mainstreaming Gender in Water Governance Programmes: From Design to Results. *WGF Report*, *4*.

WHO. (2011). Guidelines for drinking-water quality. *World Health Organization*.

WHO. (2017). *Safely managed drinking water - thematic report on drinking water 2017*. https://doi.org/ISBN 978 92 4 156542 4

WHO. (2022). *Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda*.

WHO and UNICEF. (2018). Core questions on water, sanitation and hygiene for household surveys. *Joint Monitoring Programme*.

WHO, & UNICEF. (2010). *Progress on sanitation and drinking water - 2010 update*. http://whqlibdoc.who.int/publications/2010/9789241563956_eng_full_text.pdf

WHO, & UNICEF. (2017a). *Guidelines for drinking-water quality: fourth edition incorporating the first addendum* (Vol. 53, Issue 9). https://doi.org/10.1017/CBO9781107415324.004

WHO, & UNICEF. (2017b). *Guidelines for drinking-water quality: fourth edition incorporating the first addendum* (Vol. 53, Issue 9). https://doi.org/10.1017/CBO9781107415324.004

WHO, & UNICEF. (2019). *Progress on household drinking water, sanitation and hygiene 2000-2017. Special focus on inequalities.* 140.

WHO, & UNICEF. (2020). *Inequalities*. https://washdata.org/monitoring/inequalities

WHO, & UNICEF. (2021). *Five years into the SDGs - Progress on household drinking water, sanitation and hygiene*. https://www.oecd.org/dac/

Willetts, J., Halcrow, G., Carrard, N., Rowland, C., & Crawford, J. (2014). *Making the Invisible Visible : Gender and Pacific Water , Sanitation and Hygiene Initiatives*. 1–15.

World Bank. (2013). *Urban Sanitation Review: Indonesia Country Study*.

World Bank. (2020). *World Bank Country and Lending Groups*. https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-group

Wright, J., Gundry, S., & Conroy, R. (2004). Household drinking water in developing countries: A systematic review of microbiological contamination between source and point-of-use. *Tropical Medicine and International Health*, *9*(1), 1. https://doi.org/10.1046/j.1365-3156.2003.01160.x

Yang, H., Bain, R., Bartram, J., Gundry, S., Pedley, S., & Wright, J. (2013). Water safety and inequality in access to drinking-water between rich and poor households. *Environmental Science and Technology*, *47*(3), 1222–1230. https://doi.org/10.1021/es303345p

A3 Household surveys

Relevant questions from the household survey in Bekasi and Metro for **Chapter IV** and **Chapter V**

Relevant survey questions for Chapter IV:

Bekasi:

0. District (Single-select)
    - 0.1 Bantar Gebang
    - 0.2 Jatiasih
    - 0.3 Jatisampurna
1. How many people usually live in this household (Numeric: Integer)
2. Does your household own the land upon which they live? (Single select)
    - 2.1 Owned by this household
    - 2.2 Owned by other family members
    - 2.3 Renting
    - 2.4 Squatting
3. Does your household own the house in which you live? (Single select)
    - 3.1 Owned by this household
    - 3.2 Owned by other family members
    - 3.3 Renting
    - 3.4 Squatting
4. What type of fuel does your household mainly use for cooking? (Single-select)
    - 4.1 Electricity
    - 4.2 LPG
    - 4.3 Natural gas
    - 4.4 Biogas
    - 4.5 Kerosene
    - 4.6 Coal
    - 4.7 Charcoal
    - 4.8 Wood
    - 4.9 Straws/shrubs/grass
    - 4.10 Agricultural crop
    - 4.11 Animal dung
    - 4.12 No food cooked in household
    - 4.13 Other (Text)
5. How many rooms in this household are used for sleeping? (Numeric: Integer)

6. Does this household own any livestock, herds, other farm animals, or poultry? (Single-select)

 6.1 No

 6.2 Yes

7. What kind of livestock, herds, other farm animals, or poultry does this household own? (Multi-select)

 7.1 Milk cows or bulls

 7.2 Water Buffaloes

 7.3 Horses or Donkeys

 7.4 Goats/Sheep

 7.5 Pigs

 7.6 Rabbit

 7.7 Chicken or Poultry

8. What is the building area of this house? (Numeric: Decimal)

9. What is the land area of this house? (Numeric: Decimal)

10. Observe the main material of the floor of the dwelling? (Single-select)

 10.1 Zinc

 10.2 Asbestos

 10.3 Tile

 10.4 Other (Text)

11. Observe the main material of the exterior walls of the dwelling (Single-select)

 11.1 Cement blocks

 11.2 Wood/Planks

 11.3 Covered abode

 11.4 Uncovered abode

 11.5 Other (Text)

12. Does any member of this household have a bank account or an account in a cooperative? (Single-select)

 12.1 No

 12.2 Yes

13. Which of the following does your household have? (Multi-select: Yes/No)

 13.1 Watch

 13.2 Mobile Phone/Tablet

 13.3 Bicycle

 13.4 Motorcycle or motor scooter

 13.5 Animal-drawn cart

 13.6 Car or truck

 13.7 Boat with a motor

13.8 Radio

13.9 Television

13.10 Non-mobile telephone

13.11 Computer/PC/Laptop

13.12 Refrigerator

13.13 Fan

13.14 Washing machine

13.15 Air condition

14. What kind of electricity does this household's own? (Multi-select)

14.1 None

14.2 PLN Token (Prepaid)

14.3 PLN Subscription (Postpaid)

14.4 Solar Panel

14.5 Other

15. What is the main source of drinking water for members of your household? (Single-select)

15.1 Piped water

15.2 Public Tap

15.3 Private borehole

15.4 Public borehole

15.5 Private protected well

15.6 Public protected well

15.7 Private unprotected well

15.8 Public unprotected well

15.9 Refill water

15.10 Bottled water

15.11 Tanker truck

15.12 Cart with small tank

15.13 Protected spring

15.14 Unprotected spring

15.15 Rainwater

15.16 Surface water (river, stream, dam, lake, pond, canal, irrigation canal)

16. What is the main source of water used by your household for other domestic purposes? (Single-select: Linked)

17. What kind of sanitation facility do members of your household usually use? (Single-select)

17.1 Flush to piped sewer system

17.2 Flush to septic tank (with concrete base)

17.3 Flush to cubluk (bottomless tank)

17.4 Flush to septic tank (don’t know if it has concrete base)

17.5 Flush to pit latrine

17.6 Flush to open drain

17.7 Flush to don’t know where

17.8 Dry pit latrine with slab

17.9 Dry pit latrine without slab (open pit)

17.10 Composting toilet

17.11 Twin pit with slab

17.12 Twin pit without slab

17.13 Other composting toilet

17.14 Bucket

17.15 Container based sanitation

17.16 Hanging toilet/hanging latrine

17.17 Other (Text)

18. Is groundwater source a well or borehole? (Single-select)

18.1 Borehole

18.2 Dug well

18.3 Artesian well

19. Please take the GPS coordinates for the household’s well/borehole (GPS)

20. Please take a photo of the household’s well/borehole (Picture)

21. Is the water piped to your dwelling or yard? (Single-select)

21.1 No

21.2 Yes

22. Please measure/estimate the depth of borehole (Numeric: Integer)

23. Please measure/estimate the depth to groundwater (distance between ground and water level) (Numeric: Integer)

24. Is there an opening at the top of the borehole that would allow contamination to enter? (Single-select)

24.1 No

24.2 Yes

25. Is there a concrete platform/floor around the borehole?

25.1 No

25.2 Yes

26. Please measure/estimate the depth of well – from top of well wall to bottom of well (m) (Numerric: Decimal)

27. Please measure/estimate the height of well wall relative to ground (m) (Numeric: Decimal)

28. Please measure/estimate the distance between top of well wall and the water (m) (Numeric: Decimal)

29. Please take a photo of well head (Picture)

30. What type of well is it? (Single-select)

30.1 Protected well

30.2 Unprotected well

31. How is water currently lifted from well/borehole? (Multi-select)

31.1 Motorized pump

31.2 Artesian (no pump)

31.3 Handpump

31.4 Rope and bucket – windlass

31.5 Rope and bucket – pulley system

31.6 Rope and bucket (no windlass or pulley)

31.7 Other (Text)

32. How many sanitation facilities are within 20m? (Numeric: Integer)

33. Estimate the distance between the well/borehole and sanitation facility (m)? (Numeric: Integer)

34. What type sanitation facility is? (Single-select)

34.1 Septic tank

34.2 Cubluk

34.3 Pit latrine

34.4 Flush to sewer

34.5 Flush to drain

34.6 Hanging toilet

34.7 Other (Text)

34.8 Don't know

35. What is the distance between the well/borehole and the closest septic tank/cubluk (m)? (Numeric: Integer)

36. What is the source of water for the source sample? (Single-select)

36.1 Piped water (PDAM)

36.2 Public tap

36.3 Private borehole

36.4 Public borehole

36.5 Private protected well

36.6 Public protected well

36.7 Private unprotected well

36.8 Public unprotected well

36.9 Artesian well

36.10 Surface water (river, stream, dam, lake, pond, canal, irrigation canal)
36.11 Neighbour's borehole
36.12 Neighbour's protected well
36.13 Neighbour's unprotected well
36.14 Neighbour's tap
36.15 Other (Text)

37. What is the source of water for the point-of-use sample? (Single-select)

37.1 Piped water (PDAM)
37.2 Public tap
37.3 Private borehole
37.4 Public borehole
37.5 Private protected well
37.6 Public protected well
37.7 Private unprotected well
37.8 Public unprotected well
37.9 Refill water
37.10 Bottled water/gallon water (usually branded)
37.11 Artesian well
37.12 Surface water (river, stream, dam, lake, pond, canal, irrigation canal)
37.13 Neighbour's borehole
37.14 Neighbour's protected well
37.15 Neighbour's unprotected well
37.16 Neighbour's tap

38. From what storage container was point-of-use sample provided? (Single-select)

38.1 Gallon/Dispenser
38.2 Bottle
38.3 Kettle/teapot
38.4 Jug
38.5 Bucket
38.6 Thermos
38.8 Pot
38.9 Kedi/barrel
38.10 Tap (no storage container)
38.11 Other (Text)

39. Was storage container covered with a lid/cover? (Single-select)

39.1 No
39.2 Yes

40. Did household treat water that was collected for point-of-use sample? (Single-select)

40.1 No

40.2 Yes – boil

40.3 Yes – add bleach/chlorine

40.4 Yes – strain through cloth

40.5 Yes – use water filter (ceramic/sand/composite etc)

40.6 Yes – Solar disinfection

40.7 Yes – let it stand and settle

40.8 Other (Text)

Metro:

41. Village (Single-select)

41.1 Hadimulyo Barat

41.2 Rejomulyo

41.3 Iringmulyo

41.4 Ganjarasri

41.5 Karangrejo

42. How many people usually live in this household? (Numeric: Integer)

43. Does your household own the land upon which they live? (Single-select)

43.1 Owned by this household

43.2 Owned by other family members

43.3 Renting

43.4 Squatting

44. Does your household own the house in which they live? (Single-select)

44.1 Owned by this household

44.2 Owned by other family members

44.3 Renting

44.4 Squatting

45. What type of fuel does your household mainly use for cooking?

45.1 Electricity

45.2 LPG

45.3 Natural gas

45.4 Kerosene

45.5 Wood

45.6 Other (Text)

46. How many rooms in this household are used for sleeping (Numeric: Integer)

47. Does this household own any livestock, herds, other farm animals, or poultry? (If so, please specify number) (Numeric: Integer)

47.1 None

47.2 Milk cows or bulls

47.3 Horses or donkeys

47.4 Goats or sheep

47.5 Pigs

47.6 Rabbits

47.7 Chicken or poultry

47.8 Other

48. What is the approximate building area of this house? (in square meters) (Numeric: integer)

49. What is the approximate land area of this property? (in square meters) (Numeric: integer)

50. Observation: Observe the main material of the floor of the dwelling (Single-select)

50.1 Wood/planks

50.2 Ceramic/Marble

50.3 Floor tiles

50.4 Cement/red bricks

50.5 Other (Text)

51. Observation: Observe the main material of the exterior walls of the dwelling (Single-select)

51.1 Cement blocks

51.2 Wood/planks

51.3 Plastered brick

51.4 Unplastered brick

51.5 Other (Text)

52. Observation: Observe the main material of the roof of the dwelling (Single-select)

52.1 Zinc

52.2 Asbestos

52.3 Tile

52.3 Other (Text)

53. Does any member of this household have a bank account or an account in a cooperative?

53.1 Yes

53.2 No

54. Which of the following does your household have? (Single-select: yes/no)

54.1 Watch

54.2 Mobile phone/tablet

54.3 Bicycle

54.4 Motorcycle or motor scooter

54.5 Animal-drawn cart
54.6 Car or truck
54.7 Boat with motor
54.8 Radio
54.9 Television
54.10 Non-mobile telephone
54.11 Computer/PC/Laptop
54.12 Refrigerator
54.13 Fan
54.14 Washing machine
54.15 Air conditioner

55. What is the main source of drinking water for members of your household? (Single-select)

    55.1 Piped to premises
    55.2 Public tap
    55.3 Neighbour’s tap
    55.4 Private borehole
    55.5 Public borehole
    55.6 Neighour’s borehole
    55.7 Private dug well
    55.8 Public dug well
    55.9 Neighbour’s dug well
    55.10 Refill water
    55.11 Bottled/gallon water (usually branded)
    55.12 Other

56. What is the main source of water used by your household for other domestic purposes? (Single-select)

56.1 Piped to premises

    56.2 Public tap
    56.3 Neighbour’s tap
    56.4 Private borehole
    56.5 Public borehole
    56.6 Neighour’s borehole
    56.7 Private dug well
    56.8 Public dug well
    56.9 Neighbour’s dug well
    56.10 Refill water
    56.11 Bottled/gallon water (usually branded)

56.12 Other

57. How often does your household treat water from this source when using it for drinking? (Single-select)

    57.1 Always
    57.2 Usually but not always
    57.3 Only in rainy season
    57.4 Only in dry season
    57.5 Occasionally
    57.6 Never
    57.7 Other (Text)

58. What does your household usually do to make the water from this source safer to drink? (Single-select)?

    58.1 Boil
    58.2 Add bleach/chlorine
    58.3 Strain through a cloth
    58.4 Use water filter (ceramic/sand/composite etc)
    58.5 Solar disinfection
    58.6 Let it stand and settle
    58.7 Other (Text)

59. What is your definition of boiling? (Single-select)

    59.1 Until it's warm
    59.2 Until vapors starts rising on surface
    59.3 Until bubbles from base starts to rise
    59.4 Until surface boil starts (bubble collapses on surface)

60. Please confirm type(s) of private well/borehole used by household (Multi-select).

    60.1 Private borehole
    60.2 Dugwell

61. What kind of sanitation facility do members of your household usually use? (Single-select)

    61.1 Flush to piped sewer system
    61.2 Flush to septic tank or cubluk
    61.3 Flush to pit latrine
    61.4 Flush to open drain
    61.5 Flush to pond (empang)
    61.6 Flush to don't know where
    61.7 Dry pit latrine with slab
    61.8 Dry pit latrine without slab (open pit)
    61.9 Hanging toilet/hanging latrine

61.10 Other (Text)

61.11 No facility/bush field

62. Please take a photo of the private groundwater source. (Observation)

63. Is there an opening at the top of the borehole that would allow contamination to enter? (Single-select)

63.1 Yes

63.2 No

63.3 Don’t know

64. Does the well have a cover? (Single-select)

64.1 No cover

64.2 Partially covered

64.3 Fully covered

64.4 Other (Text)

65. Is there a concrete platform extending from outer edge of the private groundwater source? (Single-select)

65.1 no concrete platform

65.2 0-0.5 m

65.3 0.5-1 m

65.4 > 1m

65.5 Don’t know

66. What is the type of dug well? (Single-select)

66.1 Protected well

66.2 Unprotected well

67. How is water currently lifted from the water source? (Multi-select)

67.1 Motorized pump

67.2 Rope and bucket

67.3 Handpump

67.4 Artesian (no pump)

67.5 Other (Text)

68. How many sanitation facilities are within 20 m of the private groundwater source? (including respondent’s facility) (Text)

69. What is the distance between the closest sanitation facility and the private groundwater source? (meters) (Text)

70. Water source of source sample (Single-select)

70.1 Piped to premises

70.2 Public tap

70.3 Neighbour’s tap

70.4 Private borehole

70.5 Public borehole

70.6 Neighour’s borehole

70.7 Private dug well

70.8 Public dug well

70.9 Neighbour’s dug well

70.10 Refill water

70.11 Bottled/gallon water (usually branded)

70.12 Other (Text)

71. From what storage container was POU sample? (Single-select)

71.1 Water not stored in small containers

71.2 Gallon/Dispenser

71.3 Bottle

71.4 Kettle/teapot

71.5 Jug/pitcher – covered

71.6 Jug/pitcher – uncovered

71.7 Bucket – covered

71.8 Bucket – uncovered

71.9 Thermos

71.10 Pot – covered

71.11 Pot– uncovered

71.12 Kedi/barrel – covered

71.13 Kedi/barrel – uncovered

71.14 Other (Text)

72. Was storage container covered with a lid? (Single-select)

72.1 Yes

72.2 No

73. Was POU water treated? (Single-select)

73.1 Boil

73.2 Add bleach/chlorine

73.3 Strain through a cloth

73.4 Use water filter (ceramic/sand/composite etc)

73.5 Solar disinfection

73.6 Let it stand and settle

73.7 Other (Text)

74. Water source of POU sample (Single-select)

74.1 Piped to premises

74.2 Public tap

74.3 Neighbour’s tap

74.4 Private borehole

74.5 Public borehole

74.6 Neighour’s borehole

74.7 Private dug well

74.8 Public dug well

74.9 Neighbour’s dug well

74.10 Refill water

74.11 Bottled/gallon water (usually branded)

74.12 Other (Text)

75. Please provide the following dimensions for the private well/borehole: (Text and single-select)

75.1 Depth: ground to bottom (Respondent/Visual estimate/Measuring tape)

75.2 Depth: ground to water level (Respondent/Visual estimate/Measuring tape)

Relevant survey questions for Chapter V:

Bekasi	
1. District 1.1 Bantar Gebang 1.2 Jatiasih 1.3 Jatisampurna	[single-select]
2. Household ID	[numeric: integer]
3. How many people usually live in this household?	[numeric: integer]
4. How many adults (>18) usually live in this household?	[numeric: integer]
5. How many adults (aged 5-17) usually live in this household?	[numeric: integer]
6. How many children (<5 years) usually live in this household?	[numeric: integer]
7. Please tell me the names of all members of this household, starting with the oldest and finishing with the youngest (#names_hh_members)	[list]
8. Is #names_hh_members the respondent? 8.1 No 8.2 Yes	[single-select]
9. Sex of #names_hh_members 9.1 Female 9.2 Male	[single-select]
10. Age of #names_hh_members	[numeric: integer]
11. Relationship of #names_hh_members to head of household 11.1 Head of household	[single-select]

11.2 Wife/husband 11.3 Child 11.4 Son/daughter in law 11.5 Grandchild 11.6 Parent/In-laws 11.7 Other [text]	
12. Marriage status of #names_hh_members 12.1 Single 12.2 Married 12.3 Widower by Death 11.4 Widower by Divorce 11.5 Separate (not formally divorce)	[single-select]
13. Does anybody in this household have any permanent difficulty seeing, even if wearing glasses? 13.1 Cannot do at all 13.2 Yes, a lot of difficulty 13.3 Yes, some difficulty 13.4 No, no difficulty	[single-select]
14. Does anybody in this household have any permanent difficulty hearing, even if using hearing aid? 14.1 Cannot do at all 14.2 Yes, a lot of difficulty 14.3 Yes, some difficulty 14.4 No, no difficulty	[single-select]
15. Does anybody in the household have any permanent difficulty walking or climbing steps? 15.1 Cannot do at all 15.2 Yes, a lot of difficulty 15.3 Yes, some difficulty 15.4 No, no difficulty	[single-select]
16. Does anybody in the household have any permanent, severe difficulty concentrating or remembering 16.1 Cannot do at all 16.2 Yes, a lot of difficulty 16.3 Yes, some difficulty 16.4 No, no difficulty	[single-select]

17. Does anybody in the household have any permanent difficulty with self-care such as washing all over or dressing? 17.1 Cannot do at all 17.2 Yes, a lot of difficulty 17.3 Yes, some difficulty 17.4 No, no difficulty	[single-select]
18. Does anybody, using their usual (customary) language, have difficulty communicating, for example understanding or being understood? 18.1 Cannot do at all 18.2 Yes, a lot of difficulty 18.3 Yes, some difficulty 18.4 No, no difficulty	[single-select]
19. What type of fuel does your household mainly use for cooking? 19.1 Electricity 19.2 LPG 19.3 Natural gas 19.4 Biogas 19.5 Kerosene 19.6 Coal 19.7 Charcoal 19.8 Wood 19.9 Straws/shrubs/grass 19.10 Agricultural crop 19.11 Animal dung 19.12 No food cooked in household 19.13 Other [text]	[single-select]
20. Decision maker in 20.1 Food Expenditure 20.2 Daily Needs Expenditure 20.3 Rent/Buy House 20.4 Rent/Buy House 20.5 House Maintenance 20.6 Water consumption expenditure 20.7 Health related expenditure 20.8 Education expenditure 20.9 Buying car	[multi-select: linked]

20.10 Buying motorcycle 20.11 Buying furniture 20.12 Internet expenditure 20.13 Social activities expenditure 20.14 Family event's expenditure 20.15 Contribution for husband's family 20.16 Contribution for wife's family 20.17 Saving	
21. Attribution of different water sources (PDAM piped water/Borehole/Protected well/Unprotected well/Refill water/Bottled water/Rainwater collection) Would you rate this source as 'good' in terms of: 21.1 Safety of water for drinking 21.2 Taste of water for drinking 21.3 Appearance (e.g. colour, particles) 21.4 Reliability/available in sufficient quantities 21.5 Affordability 21.6 Convenience (ease of collecting water, convenient location) 21.7 Smell of water	[multi-select: yes/no]
22. Please describe concerns with 22.1 Safety 22.2 Taste 22.3 Appearance 22.4 Smell	[text]
23. When deciding a preferred source of water for drinking water, please rank the following attributes that influence this decision, from most important to least important 23.1 Safety of water 23.2 Taste of water 23.3 Appearance (e.g. colour, particles) 23.4 Reliability/available in sufficient quantities 23.5 Affordability 23.6 Convenient (ease of collecting water, convenient location) 23.7 Does not smell	[multi-select:ordered]

24. When deciding a preferred source of water for other domestic purposes, please rank the following attributes that influence this decision, from most important to least important 24.1 Safety of water 24.2 Taste of water 24.3 Appearance (e.g. colour, particles) 24.4 Reliability/available in sufficient quantities 24.5 Affordability 24.6 Convenient (ease of collecting water, convenient location) 24.7 Does not smell	[multi-select:ordered]
25. Which of the following sources supplies water that is safest to drink? 25.1 PDAM piped water 25.2 Borehole 25.3 Protected well 25.4 Unprotected well 25.5 Refill water 25.6 Bottled water 25.7 Rainwater collection	[single-select]
26. Which of the following sources supplies water that has the best taste? 26.1 PDAM piped water 26.2 Borehole 26.3 Protected well 26.4 Unprotected well 26.5 Refill water 26.6 Bottled water 26.7 Rainwater collection	[single-select]
27. Which of the following sources supplies water that has clearest appearance? 27.1 PDAM piped water 27.2 Borehole 27.3 Protected well 27.4 Unprotected well 27.5 Refill water 27.6 Bottled water	[single-select]

27.7 Rainwater collection	
28. Which of the following sources supplies water that is the most reliable/most available in sufficient quantities? 28.1 PDAM piped water 28.2 Borehole 28.3 Protected well 28.4 Unprotected well 28.5 Refill water 28.6 Bottled water 28.7 Rainwater collection	[single-select]
29. Which of the following sources supplies water that is the most affordable (both in terms of initial cost and ongoing cost)? 29.1 PDAM piped water 29.2 Borehole 29.3 Protected well 29.4 Unprotected well 29.5 Refill water 29.6 Bottled water 29.7 Rainwater collection	[single-select]
30. Which of the following sources is the most convenient, in terms of effort needed to collect water? 30.1 PDAM piped water 30.2 Borehole 30.3 Protected well 30.4 Unprotected well 30.5 Refill water 30.6 Bottled water 30.7 Rainwater collection	[single-select]
31. Which of the following sources supplies water for which it is the best smell (does not smelly)? 31.1 PDAM piped water 31.2 Borehole 31.3 Protected well 31.4 Unprotected well 31.5 Refill water 31.6 Bottled water 31.7 Rainwater collection	[single-select]

32. In the last month, has there been any time when your household did not have sufficient quantities of drinking water when needed? 32.1 Yes – at least once 32.2 No – always sufficient 32.3 Don't know	[single-select]
33. What was the main reason your household was unable to access sufficient quantities of water when needed? 33.1 Water was not available from source 33.2 Water was too expensive 33.3 Source was not accessible 33.4 Other [text]	[single-select]
34. Please select all water sources your household has used in the past 12 months (#all_water_Sources) 34.1 Piped water 34.2 Public Tap 34.3 Private borehole 34.4 Public borehole 34.5 Private protected well 34.6 Public protected well 34.7 Private unprotected well 34.8 Public unprotected well 34.9 Refill water 34.10 Bottled water 34.11 Tanker truck 34.12 Cart with small tank 34.13 Protected spring 34.14 Unprotected spring 34.15 Rainwater 34.16 Surface water (river, stream, dam, lake, pond, canal, irrigation canal)	[multi-select]
35. What is the main source of drinking water for members of your household? 35.1 Piped water 35.2 Public Tap 35.3 Private borehole 35.4 Public borehole	[single-select]

35.5 Private protected well 35.6 Public protected well 35.7 Private unprotected well 35.8 Public unprotected well 35.9 Refill water 35.10 Bottled water 35.11 Tanker truck 35.12 Cart with small tank 35.13 Protected spring 35.14 Unprotected spring 35.15 Rainwater 35.16 Surface water (river, stream, dam, lake, pond, canal, irrigation canal)	
36. What is the main source of water used by your household for other domestic purposes? 36.1 Piped water 36.2 Public Tap 36.3 Private borehole 36.4 Public borehole 36.5 Private protected well 36.6 Public protected well 36.7 Private unprotected well 36.8 Public unprotected well 36.9 Refill water 36.10 Bottled water 36.11 Tanker truck 36.12 Cart with small tank 36.13 Protected spring 36.14 Unprotected spring 36.15 Rainwater 36.16 Surface water (river, stream, dam, lake, pond, canal, irrigation canal)	[single-select]
37. Is this source (#all_water_sources) used for drinking water in the RAINY season? (#drink_rainy) 37.1 Main source 37.2 Alternative source 37.3 Not used for drinking at all	[single-select]

38. For what other purposes does your household use this water source (#all_water_sources) in RAINY season? 38.1 Cooking 38.2 Making tea 38.3 Washing fruit and vegetables 38.4 Washing the dishes 38.5 Handwashing 38.6 Bathing 38.7 Laundry 38.8 Cleaning the house 38.9 Flushing the toilet 38.10 Watering garden 38.11 Watering animals 38.12 Other productive uses [text]	[multi-select]
39. When used as an alternative drinking water source in WET season, please explain why your household switches from the MAIN drinking source to this source? (drink_rainy==2) 39.1 Supply from main source is disrupted/unavailable/dry 39.2 Supply from main source becomes too expensive 39.3 Quality of main source deteriorates 39.4 Other [text]	[single-select]
40. Is this source (#all_water_sources) used for drinking water in the DRY season? (#drink_dry) 40.1 Main source 40.2 Alternative source 40.3 Not used for drinking at all	[single-select]
41. For what other purposes does your household use this water source (#all_water_sources) in DRY season? 41.1 Cooking 41.2 Making tea 41.3 Washing fruit and vegetables 41.4 Washing the dishes 41.5 Handwashing 41.6 Bathing 41.7 Laundry 41.8 Cleaning the house 41.9 Flushing the toilet	[multi-select]

41.10 Watering garden 41.11 Watering animals 41.12 Other productive uses [text]	
42. When used as an alternative drinking water source in WET season, please explain why your household switches from the MAIN drinking source to this source? (drink_wet==2) 42.1 Supply from main source is disrupted/unavailable/dry 42.2 Supply from main source becomes too expensive 42.3 Quality of main source deteriorates 42.4 Other [text]	[single-select]
43. For this source (#all_water_sources), where is the water supplied to? 43.1 In dwelling 43.2 In yard/plot 43.3 Neighbour's dwelling/yard/plot 43.4 Elsewhere (e.g. rom public water point, shop) 43.5 Delivered to household	[single-select]
44. Does your household used this water source all throughout the year? (#year_round_use) 44.1 No 44.2 Yes 44.3 Don't know	[single-select]
45. In which months of the year would your household NOT use this water source? (#year_round_use==1) 45.1 January 45.2 February 45.3 March 45.4 April 45.5 May 45.6 June 45.7 July 45.8 August 45.9 September 45.10 October 45.11 November 45.12 December	[multi-select]

46. In the past two weeks, was water from this source unavailable for (at least one full day) (!all_water_sources.containsAny(9,10)) 46.1 Yes, unavailable for at least one full day 46.2 No	[singe-select]
47. In the past two weeks, for how many full days was water from this source unavailable?	[numeric:integer]
48. Do you think the water from this source (#all_water_sources) is acceptable for drinking in terms of 48.1 Taste 48.2 Colour/appearance 48.3 Safety 48.4 Odour	[multi-select:yes/no]
49. When drinking water from this source, is anything done to the water to make it safe to drink? (drink_dry==1, drink_dry==2, drink_rainy==1, drink_rainy==2) (#treat_water) 49.1 Yes 49.2 No	[single-select]
50. How often does your household treat water from this source when using it for drinking? (treat_water==1) 50.1 Always 50.2 Usually but not always 50.3 Only in rainy season 50.4 Only in dry season 50.5 Occasionally 50.6 Never 50.7 Other [text]	[single-select]
51. What does your household usually do to make the water from this source safer to drink? (treat_water==1) 51.1 Boil 51.2 Add bleach/chlorine 51.3 Strain through a cloth 51.4 Use water filter (ceramic/sand/composite etc.) 51.5 Solar disinfection 51.6 Let it stand and settle 51.7 Other [text]	[single-select]
52. What is the primary reason for not having a PDAM piped connection?	[single-select]

52.1 PDAM water has a poor taste 52.2 PDAM water has a poor appearance 52.3 PDAM water is unsafe to drink 52.4 PDAM water is unreliable/insufficient in quantity 52.5 Cost of PDAM connection fee is too much 52.6 PDAM water bills are too much 52.7 PDAM does not supply water to this area 52.8 PDAM water smelly 52.0 Other [text]	
53. If PDAM were to expand infrastructure to this area, how likely is it that your household would connect? (assuming a connection fee of xx) 53.1 Definitely yes 53.2 Very likely 53.3 Somewhat likely 53.4 Unlikely 53.5 Definitely not 53.6 Don't know	[single-select]
54. What is the primary reason for not having a private borehole/well? 54.1 Water from a well/borehole has a poor taste 54.2 Water from a well/borehole has a poor appearance 54.3 Water from a well/borehole is unsafe to drink 54.4 Water from a well/borehole is unreliable/insufficient in quantity 54.5 High cost of constructing a well/borehole 54.6 Difficult to locate groundwater in this area 54.7 Physical constraints make drilling/excavation difficult 54.8 Well/borehole water is smelly 54.9 Other [text]	[single-select]
55. What is the primary reason for not using refill water? 55.1 Refill water has a poor taste 55.2 Refill water has a poor appearance 55.3 Refill water is unsafe to drink 55.4 Refill water is not always available/insufficient in quantity 55.5 Refill water is too expensive	[single-select]

55.6 Other [text]	
56. What is the primary reason for not using bottled water? 56.1 Bottled water has a poor taste 56.2 Bottled water has a poor appearance 56.3 Bottled water is unsafe to drink 56.4 Bottled water is not always available/insufficient in quantity 56.5 Bottled water is too expensive 56.6 Other [text]	[single-select]
57. Who in the household decide to invest in the construction of well/borehole?	[multi:select:linked]
58. What was the reasons(s) for investigating in a private well/borehole; please select up to 3 reasons, in order of importance (select most important reason first) 58.1 Wanted a safer water source 58.2 Wanted a water source with better taste 58.3 Wanted a clearer water source 58.4 Wanted a more affordable water source 58.5 Wanted a source that is more reliable/supplies greater quantities 58.6 Wanted a more convenient source 58.7 Wanted a source that does not smell 58.8 Other [text]	[multi-select:ordered)
59. Which household member has primary responsibility for managing drinking water in the home on a day-today basis (e.g. storage and/or treatment)?	[single-select:linked]
60. Which household member has primary responsibility for maintaining the cleanliness/sanitary conditions of the well/borehole?	[single-select:linked]
61. Which household member has primary responsibility for maintaining the well/borehole and the pump and arranging repairs when needed?	[single-select:linked]
62. Which household member has primary responsibility for managing the money to pay for water services (e.g. water bill, purchasing water, pay for maintenance and repairs)	[single-select:linked]
63. Has the household ever had to deepen the well/borehole, or deepen the pump setting due to a change in groundwater depth?	[multi-select]

63.1 Deepen the well/borehole 63.2 Deepen the pump setting 63.3 Neither 63.4 Don't know	
64. Has well/borehole ever gone dry such that water cannot be obtained? 64.1 No 64.2 Yes 64.3 Don't know	[single-select]
65. Has well/borehole gone dry at any point in the last 12 months such that water cannot be obtained? 65.1 No 65.2 Yes 65.3 Don't know	[single-select]
66. In which months has borehole/well gone dry in last 12 months? 66.1 January 66.2 February 66.3 March 66.4 April 66.5 May 66.6 June 66.7 July 66.8 August 66.9 September 66.10 Oktober 66.11 November 66.12 December	[multi-select]

Metro	
1. Village 1.1 Hadimulyo Barat 1.2 Rejomulyo 1.3 Irinigmulyo 1.4 Ganjarasri 1.5 Karangrejo	[single-select]
2. Household ID	[numeric: integer]

3. How many people usually live in this household?	[numeric: integer]
4. How many adults (>18) usually live in this household?	[numeric: integer]
5. How many adults (aged 5-17) usually live in this household?	[numeric: integer]
6. Please tell me the names of all members of this household, starting with the oldest and finishing with the youngest	[list]
7. Please specify age, sex, and marital status of each household member	[list]
8. Who is the respondent? 8.1 Name 1 8.2 Name 2 …	[single-select]
9. Who is the head of household? 9.1 Name 1 9.2 Name 2 …	[single-select]
10. Age of #names_hh_members	[numeric: integer]
11. Does anybody in this household have any permanent difficulty seeing, even if wearing glasses? 11.1 Cannot do at all 11.2 Yes, a lot of difficulty 11.3 Yes, some difficulty 11.4 No, no difficulty	[single-select]
12. Does anybody in this household have any permanent difficulty hearing, even if using hearing aid? 12.1 Cannot do at all 12.2 Yes, a lot of difficulty 12.3 Yes, some difficulty 12.4 No, no difficulty	[single-select]
13. Does anybody in the household have any permanent difficulty walking or climbing steps? 13.1 Cannot do at all 13.2 Yes, a lot of difficulty 13.3 Yes, some difficulty 13.4 No, no difficulty	[single-select]
14. Does anybody in the household have any permanent, severe difficulty concentrating or remembering 14.1 Cannot do at all	[single-select]

14.2 Yes, a lot of difficulty 14.3 Yes, some difficulty 14.4 No, no difficulty	
15. Does anybody in the household have any permanent difficulty with self-care such as washing all over or dressing? 15.1 Cannot do at all 15.2 Yes, a lot of difficulty 15.3 Yes, some difficulty 15.4 No, no difficulty	[single-select]
16. Does anybody, using their usual (customary) language, have difficulty communicating, for example understanding or being understood? 16.1 Cannot do at all 16.2 Yes, a lot of difficulty 16.3 Yes, some difficulty 16.4 No, no difficulty	[single-select]
17. What type of fuel does your household mainly use for cooking? 17.1 Electricity 17.2 LPG 17.3 Natural gas 17.4 Kerosene 17.5 Wood 17.6 Other [text]	[single-select]
18. Please select all water sources your household has used in the past 12 months (#all_water_Sources) 18.1 Piped to premises 18.2 Public Tap 18.3 Neighbour's Tap 18.4 Private borehole 18.5 Public borehole 18.6 Neighbour's borehole 18.7 Private dug well 18.8 Public dug well 18.9 Neighbour's dug well 18.10 Refill water 18.11 Bottled water 18.12 Other	[multi-select]

19. What is the main source of drinking water for members of your household? (#all_water_sources) 19.1 Piped to premises 19.2 Public Tap 19.3 Neighbour's Tap 19.4 Private borehole 19.5 Public borehole 19.6 Neighbour's borehole 19.7 Private dug well 19.8 Public dug well 19.9 Neighbour's dug well 19.10 Refill water 19.11 Bottled water 19.12 Other	[single-select]
20. What is the main source of water used by your household for other domestic purposes? 20.1 Piped to premises 20.2 Public Tap 20.3 Neighbour's Tap 20.4 Private borehole 20.5 Public borehole 20.6 Neighbour's borehole 20.7 Private dug well 20.8 Public dug well 20.9 Neighbour's dug well 20.10 Refill water 20.11 Bottled water 20.12 Other	[single-select]
21. In the last month, has there been any time when your household did not have sufficient quantities of drinking water when needed? 21.1 Yes – at least once 21.2 No – always sufficient 21.3 Don't know	[single-select]
22. What was the main reason your household was unable to access sufficient quantities of water when needed? 22.1 Water was not available from source 22.2 Water was too expensive	[single-select]

22.3 Source was not accessible 22.4 Other [text]	
23. Is this source (#all_water_sources) used for drinking water in RAINY/DRY season? 23.1 Main source 23.2 Alternative source [text] 23.3 Not used for drinking at all	[single-select]
24. For what other purposes does your household use this water source (#all_water_sources) in RAINY/DRY season: 24.1 Cooking 24.2 Making tea 24.3 Washing fruit and vegetables 24.4 Washing the dishes 24.5 Handwashing 24.6 Wudhu or other religious ritual purification 24.7 Menstrual hygiene 24.8 Bathing 24.9 Laundry 24.10 Cleaning the house 24.11 Flushing the toilet 24.12 Flushing the toilet 24.13 Watering garden 24.14 Watering animals 24.15 Other productive uses [text]	[multi-select]
25. In the past two weeks, was water from this source unavailable for (at least one full day) (#all_water_sources) 25.1 Yes, unavailable for at least one full day 25.2 No	[singe-select]
26. In the past two weeks, for how many full days was water from this source unavailable?	[numeric:integer]
27. Do you think the water from this source (#all_water_sources) is acceptable for drinking in terms of 48.1 Safety 48.2 Taste 48.3 Colour/appearance 48.4 Odour 48.5 Quantity available	[single-select: acceptable/ unacceptable/ don’t know]

48.6 Reliability	
28. When drinking water from this source, is anything done to the water to make it safe to drink? (#all_water_sources) 28.1 Yes 28.2 No 28.3 Don't know	[single-select]
29. How often does your household treat water from this source when using it for drinking? 29.1 Always 29.2 Usually but not always 29.3 Only in rainy season 29.4 Only in dry season 29.5 Occasionally 29.6 Never 29.7 Other [text]	[single-select]
30. What does your household usually do to make the water from this source safer to drink? 30.1 Boil 30.2 Add bleach/chlorine 30.3 Strain through a cloth 30.4 Use water filter (ceramic/sand/composite etc.) 30.5 Solar disinfection 30.6 Let it stand and settle 30.7 Other [text]	[single-select]
31. What fuel do you use to cook/boil the water? 31.1 Electricity 31.2 LPG 31.3 Natural gas 31.4 Kerosene 31.5 Wood 31.6 Other [text]	[single-select]
32. Who owns the water source (#all_water_sources)? 32.1 Respondent's household 32.2 Landlord 32.3 Neighbour 32.4 Local government 32.5 Other [text]	[single-select]

33. Has well/borehole ever gone dry? 33.1 Yes 33.2 No 33.3 Don’t know	[single-select]
34. Has well/borehole gone dry in the last 12 months? 34.1 Yes 34.2 No 34.3 Don’t know	[single-select]
35. In which months has borehole/well gone dry in last 12 months? 35.1 January 35.2 February 35.3 March 35.4 April 35.5 May 35.6 June 35.7 July 35.8 August 35.9 September 35.10 Oktober 35.11 November 35.12 December	[multi-select]
36. Who in the household decide to invest in the construction of well/borehole? 36.1 Name 1 36.2 Name 2 36.3 …	[multi-select]
37. What was the reasons(s) for investigating in a private well/borehole? Of these reasons, please rank them in order of importance. 37.1 Wanted a safer water source 37.2 Wanted a water source with better taste 37.3 Wanted a clearer water source 37.4 Wanted a more affordable water source 37.5 Wanted a source that is more reliable/supplies greater quantities 37.6 Wanted a more convenient source 37.7 Wanted a source that does not smell 37.8 Other [text]	[multi-select]

38. Which household member has primary responsibility for managing drinking water in the home on a day-today basis (e.g. storage and/or treatment)? 38.1 Name 1 38.2 Name 2 38.3 …	[single-select]
39. Which household member has primary responsibility for maintaining the cleanliness/sanitary conditions of the well/borehole? 39.1 Name 1 39.2 Name 2 39.3 …	[single-select]
40. Which household member has primary responsibility for maintaining the well/borehole and the pump and arranging repairs when needed? 40.1 Name 1 40.2 Name 2 40.3 …	[single-select]
41. Which household member has primary responsibility for managing the money to pay for water services (e.g. water bill, purchasing water, pay for maintenance and repairs) 41.1 Name 1 41.2 Name 2 41.3 …	[single-select]
42. What is the primary reason for not having a PDAM piped connection? 42.1 PDAM water is unsafe to drink 42.2 PDAM water has a poor taste 42.3 PDAM water is smelly 42.4 PDAM water has a poor appearance 42.5 PDAM water is unreliable/insufficient in quantity 42.6 Cost of PDAM connection fee is too much 42.7 PDAM water bills are too much 42.8 PDAM does not supply water to this area 42.9 Other [text]	[single-select]
43. If PDAM were to expand infrastructure to this area, how likely is it that your household would connect? (assuming a connection fee of xx) 43.1 Definitely yes 43.2 Very likely	[single-select]

43.3 Somewhat likely 43.4 Unlikely 43.5 Definitely not 43.6 Don’t know	
44. What is the primary reason for not having a private borehole/well? 44.1 Water from a well/borehole is unsafe to drink 44.2 Water from a well/borehole has a poor taste 44.3 Water from a well/borehole has a poor appearance 44.4 Well/borehole water is smelly 44.5 Water from a well/borehole is unreliable/insufficient in quantity 44.6 High cost of constructing a well/borehole 44.7 Difficult to locate groundwater in this area 44.8 Physical constraints make drilling/excavation difficult 44.9 Other [text]	[single-select]
45. What is the primary reason for not using refill water? 45.1 Refill water is unsafe to drink 45.2 Refill water has a poor taste 45.3 Refill water has a poor appearance 45.4 Refill water is smelly 45.5 Refill water is not always available/insufficient in quantity 45.6 Refill water is too expensive 45.7 Other [text]	[single-select]
46. What is the primary reason for not using bottled water? 46.1 Bottled water is unsafe to drink 46.2 Bottled water has a poor taste 46.3 Bottled water has a poor appearance 46.4 Bottled water is smelly 46.5 Bottled water is not always available/insufficient in quantity 46.6 Bottled water is too expensive 46.7 Other [text]	[single-select]
47. When deciding a preferred source of water for drinking water, please rank the following attributes that influence this decision, from most important to least important 47.1 Safety of water 47.2 Taste of water 47.3 Appearance (e.g. colour, particles)	[multi-select:ordered]

47.4 Reliability/available in sufficient quantities 47.5 Affordability 47.6 Convenient (ease of collecting water, convenient location) 47.7 Does not smell	
48. When deciding a preferred source of water for other domestic purposes, please rank the following attributes that influence this decision, from most important to least important 48.1 Safety of water 48.2 Taste of water 48.3 Appearance (e.g. colour, particles) 48.4 Reliability/available in sufficient quantities 48.5 Affordability 48.6 Convenient (ease of collecting water, convenient location) 48.7 Does not smell	[multi-select:ordered]
49. Which of the following sources supplies water that is safest to drink? 49.1 PDAM piped water 49.2 Borehole 49.3 Protected well 49.4 Unprotected well 49.5 Refill water 49.6 Bottled water 49.7 Rainwater collection	[single-select]
50. Which of the following sources supplies water that has the best taste? 50.1 PDAM piped water 50.2 Borehole 50.3 Protected well 50.4 Unprotected well 50.5 Refill water 50.6 Bottled water 50.7 Rainwater collection	[single-select]
51. Which of the following sources supplies water that has clearest appearance? 51.1 PDAM piped water 51.2 Borehole 51.3 Protected well 51.4 Unprotected well	[single-select]

51.5 Refill water 51.6 Bottled water 51.7 Rainwater collection	
52. Which of the following sources supplies water that is the most reliable/most available in sufficient quantities? 52.1 PDAM piped water 52.2 Borehole 52.3 Protected well 52.4 Unprotected well 52.5 Refill water 52.6 Bottled water 52.7 Rainwater collection	[single-select]
53. Which of the following sources supplies water that is the most affordable (both in terms of initial cost and ongoing cost)? 53.1 PDAM piped water 53.2 Borehole 53.3 Protected well 53.4 Unprotected well 53.5 Refill water 53.6 Bottled water 53.7 Rainwater collection	[single-select]
54. Which of the following sources is the most convenient, in terms of effort needed to collect water? 54.1 PDAM piped water 54.2 Borehole 54.3 Protected well 54.4 Unprotected well 54.5 Refill water 54.6 Bottled water 54.7 Rainwater collection	[single-select]
55. Which of the following sources supplies water for which it is the best smell (does not smelly)? 55.1 PDAM piped water 55.2 Borehole 55.3 Protected well 55.4 Unprotected well 55.5 Refill water	[single-select]

55.6 Bottled water 55.7 Rainwater collection	

A4 In-depth interviews

This appendix includes the in-depth interview guide with sample questions, and a protocol example used to gather background information from household survey findings on the target households for in-depth interviews. This appendix is relevant to **Chapter V**.

In-depth interview guide

Sampling approach

- 8-12 interviews, with 6-8 women, and 2-4 men.
- Aim to include 1-2 people with a disability if that is possible.
- Focus on households that use self-supply for drinking and domestic purposes
- Using the household survey results, ensure that the interviewer already knows some information about the household's primary and secondary water sources, practices etc. So that way we can probe about reasons (why and how) rather than ask the same questions we have already covered in the household survey.

Introductory brief:

- Project purpose and interview scope
- Informed consent, privacy, confidentiality, expected duration
- Provide 1-page project information sheet with key contacts

Background information:

- Name and age
- Male/Female/Other
- Educational background

Drinking and domestic water supply:

- How has your access to safe water supply in this city changed over the last 10-20 years? Probe: types of supplies (piped, non-piped/self-supply etc.), sufficient quantity, reliability, quality etc.
- Do you feel satisfied with your current situation in relation to drinking water and water for other household purposes? Why? Why not?
- To what extent does your water supply meet all of your personal needs (e.g. washing, bathing, menstrual hygiene etc.)
- What do you expect the future to look like? Why? Do you feel your household will be able to ensure operation maintenance of your system into the future?

Gendered perceptions and drivers of safety and risk regarding water-supply

- Who makes household decisions on water source choice and investment in water supply? Is there household discussion on this issue? Why? Why not? If the system had to be replaced, who would make decisions about that?
- Who do you see as the owner of your self-supply system? Do you feel like you are an owner of the system?
- If it were you, what choices would you make and why? Probe: which factors/drivers are taken into account: perceived water quality, reliability, quantity, taste, smell other, cost, convenience etc.
- Which source do you see as safest for drinking? Why? Do other household members agree? Or do they have a different opinion? Why?
- Has there ever been any conflict or tension in the household in relation to drinking water access? Or drinking water management (e.g. household-related tasks)?
- What do you do if there are any troubles with water quality?
- What do you do if there are any troubles with the water availability?

Gendered roles related to water:

- How are water-related household tasks divided up between different members of your household? (e.g. collecting water, household water purification practices, hygiene/cleaning tasks, repair tasks etc.) Who does what?
- Are you satisfied with how these roles are shared between household members? Why? Why not? What would you change?
- How do you feel about any workload associated with providing safe water to the household? If you feel the workload is too high (e.g. relating to water treatment/boiling) what do you do? (e.g. not boiling, change water source, ask sb. else to boil,…)

Gender follow-up questions:

Water boiling:

- Who boils the water in the house?
- Is this a tiring task?
- What do you do when you are too tired to boil water?
- Are there any disputes relating to this task?

Water perception and preferences:

- Is there disparity in water perceptions and preferences among household members?
- Who prefers which source and why?

- Are there any disputes in choosing/deciding the water source among household members?

Water disturbances

- Who solves the problems related to water disturbances (e.g. broken pump)?
- Is this an overwhelming task?
- Are there any disputes relating to this task?

Protocol with information on household representative

Background information

Household ID:	103011014
Interview Key:	88-14-78-23
Gender respondent:	female
Head of Household:	yes
Phone Respondent:	yes
District:	2
Household members:	3
Wealth:	poor

Drinking and domestic water supply

Main drinking water source:	Private borehole
Main source for domestic purposes:	Private borehole
Source acceptability, Taste/Appearance/Safety/Odour:	yes/yes/yes/yes
Year around use:	yes
Water treatment: How and how often:	Always boil

Gendered perceptions and drivers of safety and risk regarding water-supply

Why no PDAM:	Water bills are too much
Why no refill:	Other: not sure about refilled water, it is more suitable for self-cooking
Why no bottled:	too expensive
Reason for investing in private borehole:	Wanted a more convenient source
Most important attributes on decision for preferred source of water for drinking:	Taste, Safety, Appearance
Most important attributes on decision for preferred source of water for domestic purpose:	Appearance, does not smell, safety
Concerns with safety/taste/appearance/smell:	No
Water source safest for drinking:	Borehole
Water source with the best taste:	Borehole
Water source with the clearest appearance:	Borehole
Water source with best reliability/availability:	Borehole
Water source most affordable:	Borehole
Water source most convenient:	Borehole
Water source with best smell:	Borehole

Gendered roles related to water

Who is responsible for:

- Managing water in home: female head of household
- Cleanliness of source: female head of household
- Maintenance and repairs: female head of household
- Finance: female head of household

Shared responsibility of water related tasks? No

Who decide to invest in well/borehole: Female head of household

Household characteristics of purposely selected households

Bekasi

#	District	Income (non-poor, middle, poor)*	Head (f, m)	Respondent (f, m)	Martial status (Married, widow, separated)	Head = Respondent (yes, no)	Household members (n)	Disability (yes, no)	Main drinking and domestic water source (Borehole (BH), dug well (DW))	Responsibility water tasks (sole female/male, shared)**	Decision-making (sole female/male, shared)
1	Jatiluhur	non-poor	female	female	Widow	yes	6	no	BH	sole female	sole female
2	Sumur Batu	poor	male	male	Widow	yes	4	yes	BH	sole male	sole male
3	Jatirangga	non-poor	male	male	Married	yes	6	yes	BH	shared	sole male
4	Sumur Batu	non-poor	female	female	Widow	yes	4	no	BH	shared	sole female
5	Sumur Batu	middle	female	female	Widow	yes	4	yes	BH	shared	sole female
6	Sumur Batu	poor	male	female	Married	no	5	no	BH	shared	sole male
7	Jatiluhur	middle	male	female	Married	no	5	yes	BH	sole male	sole male
8	Sumur Batu	poor	male	male	Married	yes	9	no	BH	sole male	sole male
9	Sumur Batu	middle	male	male	Married	yes	4	no	DW	shared	sole male
10	Sumur Batu	middle	male	female	Married	no	6	no	BH	sole female	sole male
11	Jatirangga	middle	male	male	Separated	yes	2	yes	DW	sole female	shared
12	Jatirangga	poor	female	female	Widow	yes	1	yes	BH	sole female	sole female

Metro

#	District	Income (non-poor, middle, poor)*	Head (f, m)	Respondent (f, m)	Martial status (Married, widow, separated, single)	Head = Respondent (yes, no)	Household members (n)	Disability (yes, no)	Main drinking and domestic water source (Borehole (BH), dug well (DW))	Responsibility water tasks (sole female/male, shared)**	Decision-making (sole female/male, shared)
1	Ganjarasri	middle	female	female	Widow	yes	2	yes	DW	sole female	sole female
2	Iringmulyo	middle	male	female	Widow	no	7	no	DW	sole female	sole female
3	Iringmulyo	non-poor	male	male	Married	yes	5	no	DW	sole male	sole male
4	Rejomulyo	poor	male	female	Married	no	2	no	DW	shared	shared
5	Iringmulyo	middle	female	female	Widow	yes	8	no	BH	shared	sole male
6	Iringmulyo	middle	male	female	Married	no	2	no	DW	sole female	sole male
7	Iringmulyo	middle	female	female	Widow	yes	3	yes	DW	sole female	sole female
8	Iringmulyo	non-poor	male	female	Married	no	5	no	DW	shared	shared
9	Iringmulyo	middle	male	male	Married	yes	4	no	BH	shared	sole male
10	Ganjarasri	middle	female	female	Widow	yes	3	no	DW	sole female	sole female
11	Ganjarasri	middle	female	female	Widow	yes	6	no	BH	shared	shared
12	Karangrejo	middle	male	male	Single	yes	1	no	DW	sole male	sole male

*Categorisation based on tertiles of wealth index of all surveyed households **Based on analysis of survey questions on responsibilities of water tasks

A5 Pre- and post-monitoring surveys

This appendix includes pre- and post-monitoring survey questions relevant to Chapter VI.

Pre-Monitoring Survey

General: Water source

Q1: For which purposes do you use your self-supply water source? [multiple selection]

1) Drinking
2) Cooking
3) Showering
4) Washing cars
5) Watering plants
6) Others [please specify]

Q2: Which water sources do you use for drinking? [multiple selection]

1) Private borehole
2) Private unprotected dug well
3) Private protected dug well
4) Public piped water
5) Artesian well
6) Refill water
7) Bottled water
8) Others [please specify]

Q3: If used for drinking, how often do you treat the following water sources before consumption? [single selection]

	Every time	Sometimes	Never	Not used for drinking
1) Private borehole				
2) Private unprotected dug well				
3) Private protected dug well				
4) Public piped water				
5) Artesian well				
6) Refill water				
7) Bottled water				

Feasibility (willingness and difficulties)

Q4: Who in the household has the main responsibility for doing the testing? [single selection]

1) Woman
2) Man
3) Child (<18 years)
4) More than one person [please specify]

Q5: Why are you interested to participate in the water quality testing? [multiple selection]

1) Learning about drinking water quality
2) Caring about personal and family's health
3) Recognition or respect from others
4) Felt compelled to participate
5) Because of the remuneration
6) Other reason [please specify]

Q6: What's your preferred frequency of testing the water? [single selection]

1) Once per week
2) Once every two weeks
3) Once each month
4) No time
5) Other [please specify]

Q7: In which steps do you have difficulties in testing the water quality with Aquagenx? [multiple selection]

1) No difficulties
2) Collecting the water sample
3) Adding the growth medium
4) Incubating the sample
5) Score and send the results
6) Other difficulties [please specify]

Q8: How difficult was the training to understand how to test the water quality? [single selection]

1) Very easy
2) Easy
3) Neutral
4) Difficult
5) Very difficult

Q9: How difficult is the test to use? [single selection]

1) Very easy
2) Easy
3) Neutral
4) Difficult [please specify]
5) Very difficult [please specify]

Awareness

Q10: How would you rate the safety of your tested self-supply drinking water at the source before treatment? [single selection]

1) Excellent
2) Very good
3) Good
4) Fair
5) Poor

Q11: How would you rate the safety of your tested drinking water at home after treatment? [single selection]

1) Excellent
2) Very good
3) Good
4) Fair
5) Poor

Q12: Which of the following factors do you think are important indicators of whether water is safe to drink? [Multiple selection]

1) Taste – Yes/No
2) Appearance (particles)
3) Appearance (colour)
4) Odour
5) Recent flooding/rain
6) Proximity of sanitation facilities
7) Previous experience (e.g. have/have not previously been sick)
8) Health
9) Whether water has been treated
10) How water is stored
11) Other [please specify]

Q13: Please select the following statements which you think are TRUE. [Multiple selection]

1) Microbial contamination in drinking water can cause diarrheal diseases. [TRUE/FALSE]
2) Boiling water is an effective method of removing pathogens in drinking water. [TRUE/FALSE]
3) Groundwater is always safe to drink. [TRUE/FALSE]

Q14: What will you do in response to a ‘contaminated’ water test result? [Multiple selection]

1) Do nothing
2) Choose an alternative water source for drinking
3) Boil the water before consumption
4) Clean the storage containers
5) Running my tap water before using it each day
6) Other [please specify]

Q15: How often do you talk to the following groups of people about drinking water quality? [Single selection]

	Never	Rarely	Sometimes	Often	Every time
1) Family					
2) Friends					
3) Neighbours					
4) Colleagues					
5) Strangers					
6) Others [please specify]					

Post-monitoring Survey

General: Water source

Q16: For which purposes do you use your self-supply water source? [multiple selection]

1) Drinking
2) Cooking
3) Showering
4) Washing cars
5) Watering plants
6) Others [please specify]

Q17: Which water sources do you use for drinking? [multiple selection]

1) Private borehole
2) Private unprotected dug well
3) Private protected dug well
4) Public piped water
5) Artesian well
6) Refill water
7) Bottled water
8) Others [please speficy]

Q18: If used for drinking, how often do you treat the following water sources before consumption? [single selection]

	Every time	Sometimes	Never	Not used for drinking
1) Private borehole				
2) Private unprotected dug well				
3) Private protected dug well				
4) Public piped water				
5) Artesian well				
6) Refill water				
7) Bottled water				

Feasibility (willingness and difficulties)

Q19: Who in the household had the main responsibility for doing the testing? [single selection]

1) Woman
2) Man
3) Child (<18 years)
4) More than one person [please specify]

Q20: Did you change the responsibility for doing the testing? [single selection]

1) Yes [please specify]
2) No

Q21: To whom did you explain how to test the water quality? [multiple selection]

1) No one
2) Family
3) Friends
4) Neighbours
5) Other [Please specify]

Q22: After participating in the water quality monitoring, what's your preferred frequency of testing the water? [single selection]

1) Once per week
2) Once all two weeks
3) Once each month
4) No time
5) Other [please specify]

Q23: In which steps did you have difficulties in testing the water quality with Aquagenx? [multiple selection]

1) No difficulties
2) Collecting the water sample
3) Adding the growth medium
4) Incubating the sample
5) Score and send the results
6) Other difficulties [please specify]

Q24: After participating in the water quality monitoring, how difficult was the test to use? [single selection]

1) Very easy
2) Easy
3) Neutral
4) Difficult [please specify]
5) Very difficult [please specify]

Awareness

Q25: Did participating in the monitoring improve your understanding about the quality of your drinking water? [single selection]

1) Yes
2) No

Q26: Would you be willing to continue monitoring the water quality if given the opportunity? [single selection]

1) Yes
2) No [please specify]

Q27: How likely would you be willing to pay anything to continue monitoring the water quality?

1) Extremely likely
2) Likely
3) Neutral
4) Unlikely
5) Extremely unlikely

Q28: Were the water quality test results as you expected? [multiple selection]

1) Yes
2) No, the results were better than expected
3) No, the results were worse than expected

Q29: After participating in the water quality monitoring, how would you rate the quality of your tested self-supply source water? [single selection]

1) Excellent
2) Very good
3) Good
4) Fair
5) Poor

Q30: After participating in the water quality monitoring, how would you rate the quality of your tested drinking water at home after treatment? [single selection]

1) Excellent
2) Very good
3) Good
4) Fair
5) Poor

Q31: After participating in the water quality monitoring, which of the following factors do you think are important indicators of whether water is safe to drink? [Multiple selection]

1) Taste – Yes/No
2) Appearance (particles)
3) Appearance (colour)
4) Odour

5) Recent flooding/rain
6) Proximity of sanitation facilities
7) Previous experience (e.g. have/have not previously been sick)
8) Health
9) Whether water has been treated
10) How water is stored
11) Other [please specify]

Q32: Please select the following statements which you think are TRUE. [Multiple selection]

1) Microbial contamination in drinking water can cause diarrheal diseases. [TRUE/FALSE]
2) Boiling water is an effective method of removing pathogens in drinking water. [TRUE/FALSE]
3) Groundwater is always safe to drink. [TRUE/FALSE]

Q33: What did you do in response to a 'contaminated' water test result? [Multiple selection]

1) Did nothing
2) Chose an alternative water source for drinking
3) Boiled the water before consumption
4) Cleaned the storage containers
5) Running my tap water before using it each day
6) Other [please specify]

Q34: How has knowing the results changed your behaviour in relation to drinking water? [Multiple selection]

1) No change
2) Change in treatment practice [please specify]
3) Change in water storage practice [please specify]
4) Change in hygiene practice (e.g. washing hands) [please specify]
5) Change in water source choice [please specify]
6) Other [please specify]

Q35: After the participation in the water quality monitoring, how likely are you to talk to the following groups of people about drinking water quality? [Single selection]

	Never	Rarely	Sometimes	Often	Every time
1) Family					
2) Friends					
3) Neighbours					
4) Colleagues					
5) Others [please specify]					

Q36: Where do you see benefits from testing your water quality? [Multiple selection]

1) No benefits
2) Better understanding of drinking water quality
3) More trust in water quality

4) Different perception of water quality
5) Supports water source choice
6) Improvement of health
7) Other [please specify]

A6 Protocol household-led water quality testing

This appendix contains the sampling and testing procedure for household-led water quality testing using Aquagenx. This appendix is relevant to **Chapter VI**.

DETECTION OF E. COLI USING AQUAGENX

Description

This protocol describes the testing of self-supply water for the presence of *E. coli* using the Aquagenx P/A test kit. Household members will collect and proceed the samples bi-weekly at the self-supply source and the point-of-use (POU); and share the results with the research team. Aquagenx uses a powder growth medium with a glucose substrate called X-Gluc. When *E. coli* metabolize this substrate in Aquagenx's growth medium, the color of the water turns blue, indicating the presence of *E. coli*.

Required Instruments & Consumables

- Whirl Pak Thio-Bags (100 mL)
- Aquagenx test kit
- Hand sanitizer
- Waterproof marker

Method

1. Label the 100 mL Whirl-Pak Thio-Bag using a permanent marker with your initials, source type / POU type and date
    - Source type code:
        - BH = borehole
        - PW= protected well
        - UW= unprotected well
    - POU type code:
        - BH-POU = borehole
        - PW-POU = protected well
        - UW-POU = unprotected well
        - AW = artesian well
        - BW = bottled water
        - RF = refill water

2. Disinfect your hands with hand sanitizer immediately before taking sample.
3. Tear off the top of the Whirl-Pak Thio-Bag along perforation and use the pull tabs on each side of the bag to open, without touching the inside or the opening of the bag.
    - Do not remove the white tablet in Whirl-Pak Thio-Bag. It is sodium thiosulfate, which neutralizes residual chlorine if present in sample.
4. Collect a water sample from your groundwater self-supply source / POU source using the Whirl-Pak Thio-Bag.
    - Collect water in a way you usually would

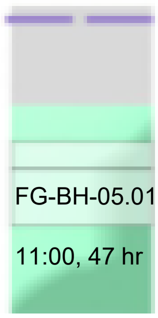
   Source sample:

- ➢ Well with rope and bucket: scoop water from well as you normally would, and pour water from the bucket into sampling bag
- ➢ Motorized pump: Take sample from a tap in the house

POU sample:

- ➢ Collect water in a way you usually would when drinking from stored container (e.g. pour water into a glass or cup, or direct from storage container)

5. Fill in your water sample up to the upper black fill mark line
6. Add Aquagenx growth medium to water sample in Whirl-Pak Thio-Bag
   - ➢ Open growth medium packet and pour powder growth medium into Whirl-Pak Thio-Bag
   - ➢ Do not touch growth medium with bare fingers or hands
7. Close Whirl-Pak bag by pulling the ends of the wire, whirl shut, and lock bags by bending the wire ends over onto the bag.
8. Dissolve medium in sample. Gently swirl the bag and squeeze clumps of powder until medium is dissolved.
9. Place the sample immediately afterwards at a warm place near a heat source, ideally > 30°C, and record the start time with your marker on the bag. Incubate it for 48 hours.
10. After 48 hours (2 days), view color in Whirl-Pak Thio-Bag. Record incubation time with your marker on the bag and take a picture.
    - ➢ Blue/blue green is positive for *E. coli* (presence). Positive results include any trace of blue/blue-green, such as one or more specks of blue/blue-green, or blue/blue-green sediment at bottom of Thio-Bag.
    - ➢ Yellow/yellow'brown is negative for *E. coli* (absence).



11. Share the pictures with the research team using whats app.
12. Empty the Whirl-Pak Thio-Bag by pouring the contents into the toilet. Dispose the empty Thio-Bag safely.
13. Repeat the steps all two weeks

Collect 100 mL sample | Add Aquagenx growth medium | Incubate at ambient temp. 20-48 hours | Score *E. coli* results in ambient light

A7 Conference materials

Conference materials such as abstracts, presentations and posters can be accessed online from the corresponding repository.

Conference presentations

Genter, F., Putri, G. L., Suleeman, E., Darmalanti, L., Priadi, C., Foster, T., Willetts, J. (2023). Understanding household self-supply use and management in urban Indonesia. Indonesian Water, Sanitation and Hygiene Symposium 2023, 20-21 March. Virtual Meeting.

Genter, F., Putri, G. L., Suleeman, E., Darmalanti, L., Priadi, C., Foster, T., Willetts, J. (2022). Understanding household self-supply use and management in urban Indonesia. SIWI World Water Week. Virtual Meeting. URL: https://www.youtube.com/watch?v=IgQ44R1x_OQ&list=PLI3myanJ6_jSTtXzJtL3ZRMwIZ4GIVMvx&index=1

Genter, F., Putri, G. L., Pratama, M. A., Priadi, C., Willetts, J., Foster, T. (2022). Faecal contamination of groundwater self-supply in urban Indonesia: Assessment of sanitary and socio-economic risk factors. 1st Water-WISER Early Career Researcher Conference. In person Conference at Loughborough University, 21-23 June. URL: https://repository.lboro.ac.uk/articles/conference_contribution/Faecal_contamination_of_groundwater_self-supply_in_urban_Indonesia_Assessment_of_sanitary_and_socio-economic_risk_factors/20122877

Genter, F., Putri, G. L., Pratama, M. A., Priadi, C., Willetts, J., Foster, T. (2021). Groundwater self-supply safety and associated risk factors for faecal contamination in urban Indonesia. UNC Water and Health Conference. Virtual Meeting. URL: https://www.youtube.com/watch?v=dj8dw7VNQTU&t=611s

Conference posters

Genter, F., Willetts, J., Foster, T. (2021). Faecal contamination of groundwater self-supply in low- and middle income countries. 42nd WEDC International Conference. Equitable and Sustainable WASH Services: Future challenges in a rapidly changing world. Virtual Conference: 13-15 September 2021. URL: https://repository.lboro.ac.uk/articles/`poster/Faecal_contamination_of_groundwater_self-supply_in_low-_and_middle_income_countries/16831588