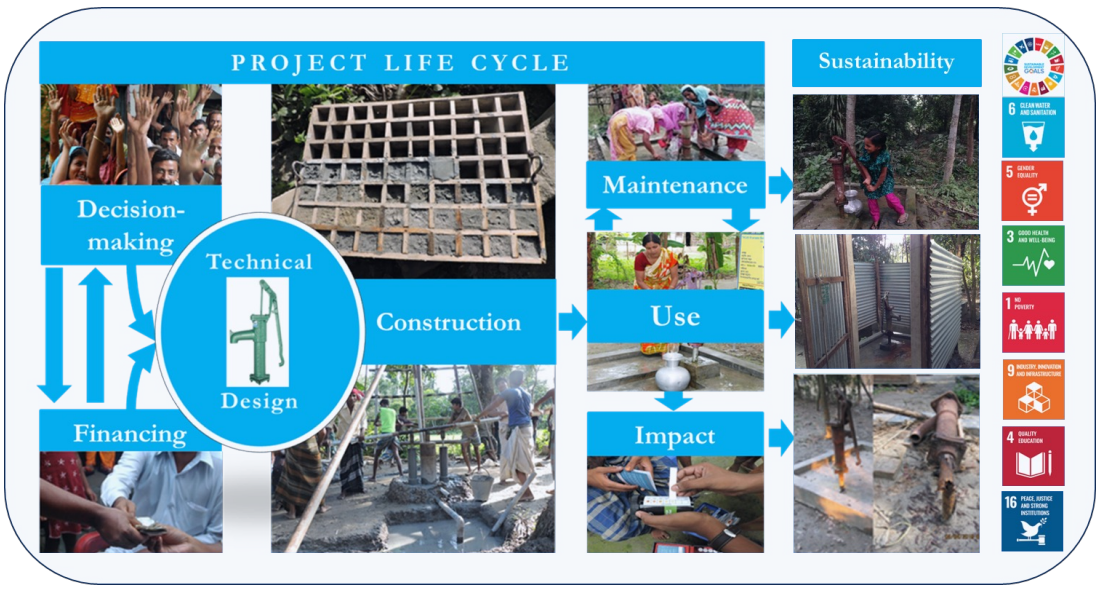
KTH ROYAL INSTITUTE
OF TECHNOLOGY

Doctoral Thesis in Land and Water Resources Engineering

Increasing the impact and sustainability of safe drinking water supply systems in rural Bangladesh

Randomized experiments with interventions in project life cycle

MD AHASAN HABIB



Stockholm, Sweden 2023

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Cover page photo and illustration:
Upper panel: Conceptualized a project life cycle; Interventions panel: Left: Communities participating in decision-making process for installing tubewell. Middle upper: Communities' contribution in labour; Middle lower: Communities' contribution in cash Right upper: After the intervention, installed tubewell for use of community; Middle lower: Tubewell users are cleaning tubewell Bottom right panel: Functional tubewells with respect to years since installation by experimental status. Right panel: Selected SDG targets relevant to the thesis.

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Participation and Sustainability (PARSU)

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DEDICATION

To
My Beloved Late Mother

SAMMANFATTNING

Tillgång till rent dricksvatten är en global utmaning, vilket återspeglas i hållbar utvecklingsmål 6. I Bangladesh är det en brådskande fråga att överbrygga klyftan mellan de som har säkert hanterat dricksvatten och de med förbättrade källor. Denna studie uppskattar orsakssamband mellan ingrepp i projektets livscykel och deras inverkan på hållbar tillgång till rent dricksvatten på landsbygden. En serie randomiserade kontrollförsök (RCT) genomfördes i olika regioner i Bangladesh under 15 år av rörbrunnskonstruktionsprogram för att tillhandahålla arsenikfritt dricksvatten. RCT:erna utvärderade förändringar av beslutsprocesser, bidragskrav och underhållspraxis. Gemenskapens deltagande i beslutsprocesser kan öka effekten och hållbarheten hos program för säkert dricksvatten. Att kräva att samhällen bidrar ekonomiskt eller genom arbetskraft ökar inte nödvändigtvis programmets genomslagskraft, och det kan leda till minskat utnyttjande och minskad kostnadseffektivitet, även om det kan öka hållbarheten. Gemenskapens vattenkällor är mindre effektiva än förväntat på grund av föroreningar som införts under kollektiv användning och problem som rör transport och lagring: de bidrar till att minska exponeringen för arsenik men tar inte upp avföringskontamination effektivt. Desinficering av brunnar med en svag klorlösning minskade fekal kontaminering. Vaktmästares standardrengöringsmetoder följer i allmänhet inte bästa praxis och kan försämra vattenkvaliteten. Utbildning av vaktmästare i bästa praxis visade sig dock vara mycket effektiv för att minska. *Escherichia coli*-kontamination, vilket avsevärt förbättrar vattenkvaliteten. Trots vissa brister i vaktmästarens återkallande och efterlevnad, belyser dessa resultat den avgörande roll som korrekta rengörings- och underhållsmetoder spelar för att minska exponeringen för fekal kontaminering på landsbygden i Bangladesh, för att säkerställa tillgång till rent dricksvatten. Studien belyser kraften hos RCT:er för att ta itu med komplexa orsaksfrågor relaterade till säker tillgång till dricksvatten. Även om värdefulla insikter har uppnåtts, understryker studien att många obesvarade frågor kvarstår, vilket understryker det pågående behovet av forskning inom detta kritiska område. Sammanfattningsvis ger denna studie viktiga bevis om hur man kan förbättra projektdesign och därmed öka tillgången till säkert dricksvatten på landsbygden i Bangladesh.

Nyckelord: Randomiserat Experiment; Säkert Dricksvatten; Deltagande; Beslutsfattande; Bidragskrav; Kostnadseffektivitet; Fekal Koliform; Arsenik; Tubewell; Rengöring; Underhåll; Påverkan; Hållbarhet; Bangladesh.

SUMMARY IN BANGLA (বাংলা সার-সংক্ষেপ)

জাতিসংঘের টেকসই উন্নয়ন লক্ষ্যমাত্রা-৬ (SDG-6) অনুসারে, নিরাপদ পানীয় জলের প্রাপ্যতা নিশ্চিতকরণ বিশ্বব্যাপী একটি অত্যাবশকীয় কর্তব্য। বাংলাদেশে, নিরাপদ পানীয় জলের ব্যবহার এবং উন্নত পানীয় জলের উৎগুলির মধ্যে ব্যবধান কমানো একটি অত্যন্ত গুরুত্বপূর্ণ বিষয়। এই গবেষণাটি প্রকল্পের বিভিন্ন পর্যায়ে ইন্টারভেনশন এর মাধ্যমে গ্রামীণ সমাজে টিউবওলের মাধ্যমে নিরাপদ পানীয় জলের ব্যবহার বৃদ্ধিকল্পে প্রনীত পদক্ষেপগুলির প্রভাব ও স্থায়িত্ব এর মধ্যে কার্যকারণসম্বন্ধীয় প্রমানভিত্তিক কারণ সনাক্ত করেছে। গত ১৫ বছর যাবত বাংলাদেশের বিভিন্ন অঞ্চলে টিউবওলে মাধ্যমে আর্সেনিক মুক্ত নিরাপদ পানির প্রকল্পে-সিদ্ধান্ত গ্রহন প্রক্রিয়া, অর্থ বা শ্রমের মাধ্যমে কন্ট্রিবিউশন, পরিচ্ছন্নতার অনুশীলন এবং প্রশিক্ষণের উপর একটি ধারাবাহিক র‍্যান্ডমাইজড কন্ট্রোল ট্রায়াল (Randomized Control Trial) গবেষণা করা হয়েছে।

সিদ্ধান্ত গ্রহণ প্রক্রিয়ায় কমিউনিটির অংশগ্রহণ নিরাপদ পানীয় জল কর্মসূচির প্রভাব ও স্থায়িত্ব বাড়াতে পারে। প্রয়োজনী অর্থ বা শ্রমের মাধ্যমে কমিউনিটির কন্ট্রিবিউশনের প্রভাব প্রকল্পের ফলাফল খুব একটা বৃদ্ধি করে তা নয়, বরং প্রকল্পের টেক-আপ হ্রাস, ব্যয়-কার্যকারিতার চ্যালেঞ্জ বৃদ্ধি এবং স্থায়িত্ব বাড়াতে পারে। কমিউনিটি ডিপ টিউবওয়েলের সমষ্টিগত ব্যবহার এবং পানি পরিবহন ও সংরক্ষন সাথে সংশ্লিষ্ট বিষয়গুলোর কারনে পানি শুরুতেই পয়ঃবর্জ্য দ্বারা দূষিত হয়ে যায়, এজন্য কমিউনিটির পানির উৎসগুলো প্রত্যাশার চেয়ে কম কার্যকর। কমিউনিটি ডিপ টিউবওয়েল আর্সেনিক সংক্রমণ প্রশমিত করতে সাহায্য করে, কিন্তু কার্যকরভাবে পয়ঃবর্জ্য দূষণের সমাধান করে না। এক্ষেত্রে একটি স্বল্পমাত্রার ক্লোরিন দ্রবণ দিয়ে জীবাণুমুক্তকরণের মতো একটি সাধারণ প্রক্রিয়া টিউবওয়েল পরিচ্ছনতা চর্চাকে উন্নত করে এবং পয়ঃবর্জ্য দূষণের প্রভাব কমাতে পারে। গবেষণায় দেখা যায়, যখন কেয়ারটেকার নিজে পরিষ্কার করে তখন তা প্রায়ই সর্বোত্তম অনুশীলন পন্থা অনুসরণ করেনা , ফলে পানির গুনগত পুনঃদূষণের কারনে মান আরো খারাপ হয়। এক্ষেত্রে, ব্যবহারিক প্রশিক্ষণ কর্মশালাগুলি উল্লেখযোগ্যভাবে পানির গুণগতমান উন্নত করেছে এবং *Escherichia coli* দূষণ কমাতে অত্যন্ত কার্যকর প্রমাণিত হয়েছে। কেয়ারটেকারদের কাজে কিছুটা অপূর্ণতা থাকা সত্ত্বেও এই ফলাফলগুলি গ্রামীণ বাংলাদেশে নিরাপদ পানীয় জলের প্রাপ্যতা নিশ্চিত করার মাধ্যমে, পয়ঃবর্জ্য দূষণ কমাতে সঠিক পরিচ্ছন্নতা এবং রক্ষণাবেক্ষণ অনুশীলনের গুরুত্বপূর্ণ ভূমিকা তুলে ধরে। এই গবেষণা নিরাপদ খাবার পানির প্রবেশাধিকার সংশ্লিষ্ট বিভিন্ন জটিল প্রশ্নের সমাধানে RCT এর সক্ষমতা তুলে ধরেছে। যদিও এ গবেষণাকর্মের মাধ্যমে মূল্যবান সম্যক ধারনা অর্জিত হয়েছে, তবুও অসংখ্য উত্তরবিহীন প্রশ্ন রয়ে গেছে, এই সংকটপূর্ণ ক্ষেত্রে গবেষণার নিরন্তর প্রয়োজনীয়তার উপর জোরারোপ করা হয়েছে। সংক্ষেপে, প্রকল্পের ডিজাইনের আরো উন্নয়ন এবং গ্রামীণ বাংলাদেশে নিরাপদ খাবার পানির প্রবেশাধিকার বাড়ানোর জন্য এই বিস্তৃত গবেষণা গুরুত্বপূর্ণ প্রমাণ সরবরাহ করে। নির্দিষ্ট ভাবে পানির গুনগতমান এবং প্রবেশাধিকার বাড়াতে এই গবেষণা কার্যকর ভাবে সম্ভাব্য কাজ এবং জড়িত বহুমুখী চ্যালেঞ্জের উপর গুরুত্বআরোপ করে।

মুলশব্দঃ র‍্যান্ডোমাইজড পরীক্ষা; নিরাপদ খাবার পানি; অংশগ্রহন; সিদ্ধান্ত-গ্রহন; কন্টিবিউশনের প্রয়োজনীয়তা; ব্যয়- কার্যকারিতা; ফিকাল কলিফরম; আর্সেনিক; টিউবওয়েল; পরিচ্ছন্নতা; রক্ষনাবেক্ষন; প্রভাব; স্থায়িত্ব; বাংলাদেশ।

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Md Ahasan Habib

Stockholm, December 2023

ABBREVIATIONS

As	Arsenic
ATT	Average Treatment Effect on the Treated
BAMWSP	Bangladesh Arsenic Mitigation Water Supply Project
BBS	Bangladesh Bureau of Statistics
C	Cash
CDF	Cumulative Distribution Functions
CFU	Colony Forming Unit
CP	Community Participation
DALY	Disability Adjusted Life Year
DHS	Demographic and Health Surveys
DPHE	Department of Public Health Engineering
DTW	Deep Tubewell
FAO	Food and Agriculture Organization
FC	Faecal Coliform
GDP	Gross domestic product
GIEWS	Global Information and Early Warning System
HH	Household
IDTW	Intermediate Deep Tubewell
JMP	Joint Monitoring Programme
L	Labour
LGRD&Co	Local Government, Rural Development and Cooperatives
M	Meter
MIN	Minute
MDG	Millennium Development Goal
MICS	Multi-Indicator Cluster Surveys
MPN	Most Probable Number
RCP	Regulated Community Participation
RCT	Randomized Control Trials
SASMIT	Sustainable Arsenic Mitigation
SDG	Sustainable Development Goal
TC	Total Coliform
TD	Top Down
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations International Children's Emergency Fund
W	Waiver
WHO	World Health Organization
WS	Water Source

List of Appended Papers and Author Contributions

I. Madajewicz, M., Tompsett, A., & **Habib, M.A**., 2021. How does delegating decisions to communities affect the provision and use of a public service? Evidence from a field experiment in Bangladesh. *Journal of Development Economics*, 150. 102609, https://doi.org/10.1016/j.jdeveco.2020.102609.

Third author. I performed as lead to manage project implementation, data collection and supervision. I contributed to M.M. and A.T. in conceptualizing, experiments setup, data compilation, results interpretation and reviewing paper.

II. **Habib, M.A**., Madajewicz, M., & Tompsett, A., 2023. When does community participation in decision-making improve outcomes? Evidence from a field experiment in Bangladesh. *ADBI Working Paper Series*, No. 1406. Asian Development Bank Institute. https://doi.org/10.56506/FEQW6636.

Equal co-author (alphabetical order). I performed as lead to manage project implementation, data collection and supervision. I contributed to M.M. and A.T. in conceptualizing, experiments setup, data compilation, results interpretation and reviewing paper.

III. Cocciolo, S., Ghisolfi, S., **Habib, M.A**., & Tompsett, A., 2023. Time is not money: A randomized experiment with community contribution requirements in cash and labour. (*Manuscript*).

Equal co-author (alphabetical order). I led the management of project implementation, data collection and supervision. I contributed to A.T. and other co-authors in conceptualizing, methodology, investigation, validation, experiments setup, data compilation, results interpretation, writing and reviewing paper.

IV. Tompsett, A., **Habib, M.A.**, Cocciolo, S., Raihan, M.M.A Bhattacharya, P., & Madajewicz, M., 2023. Participation and sustainability: Experimental evidence from safe water sources in Bangladesh. (*Manuscript*).

Second author. I co-led the development of project design, managed project implementation, data collection and supervision, as well as contributed with A.T. and other co-authors in conceptualization, methodology, result interpretation, drafting, and reviewing paper.

V. Cocciolo, S., Ghisolfi, S., **Habib, M.A**., Rashid, S.M.A., & Tompsett, A., 2021. Do community water sources provide safe drinking water? Evidence from a randomized experiment in rural Bangladesh. *The World Bank Economic Review* 35(4): 969-998. https://doi.org/10.1093/wber/lhab006

Equal co-author (alphabetical order). I led the management of project implementation, data collection and supervision. Contributed to S.C., A.T. and other co-authors in conceptualizing, methodology, investigation, validation, experiments setup, data compilation, results interpretation and reviewing paper.

VI. **Habib, M.A.**, Cocciolo, S., Haque, M.A., Raihan, M.M.A., Bhattacharya, P., & Tompsett, A., 2023. How to clean a tubewell: the effectiveness of three approaches to cleaning in reducing coliform bacteria in deep tubewell water. *Science of The Total Environment* 872: 161932. https://doi.org/10.1016/j.scitotenv.2023.161932

First (lead) author. I led the conceptualization and development of project design, managing project implementation, data collection and supervision. Contributed to data and results analysis and original draft.

VII. **Habib, M.A.**, Cocciolo, S., Haque, M.A., Raihan, M.M.M., Bhattacharya, P., & Tompsett, A., 2023. Training caretakers to clean community wells is a highly cost-effective way to reduce exposure to coliform bacteria. Manuscript submitted to *npj Clean Water-Nature* (NPJCLEANWATER - 01163-T)

First (lead) author. I led the conceptualization and development of project design, managing project implementation, data collection and supervision. Contributed to data and results analysis and original draft.

Note that ***Papers II***, ***III***, and ***V*** follow the economic science convention. All authors are considered equal and authorship is alphabetized.

LIST OF OTHER RELEVANT PAPERS NOT APPENDED IN THE THESIS

I. Allakulov, U., Cocciolo, S., Das, B., **Habib, M.A.**, Rambjer, L., & Tompsett, A., 2022. Transparency, governance, and water and sanitation: experimental evidence from schools in rural Bangladesh. *Journal of Development Economics*, 163: 103082. https://doi.org/10.1016/j.jdeveco.2023.103082

II. Cocciolo, S., **Habib, M.A.**, & Tompsett, A., 2019. Understanding institutional persistence: Exposure to democratic decision-making and the value of autonomy and democracy. Institute of International Economics Studies, Stockholm University. *AEA RCT registry*. https://afosterri.org/jdepreresults/sample-page/ https://doi.org/10.1257/rct.2709-2.0

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ABSTRACT

Access to safe drinking water is a global challenge, as reflected in Sustainable Development Goal 6. In Bangladesh, bridging the gap between those with safely managed drinking water and those with improved sources is a pressing issue. This study estimates causal relationships between interventions in the project life cycle and their impact on sustainable access to safe drinking water in rural areas. A series of Randomized Control Trials (RCTs) were conducted across different regions of Bangladesh over 15 years of tubewell construction programs to provide arsenic free safe drinking water. The RCTs evaluated changes to decision-making processes, contribution requirements, and maintenance practices. Community participation in decision-making processes can enhance the impact and sustainability of safe drinking water programs. Requiring communities to contribute financially or through labour does not necessarily increase program impact, and it can lead to reduced take-up, and decreased cost-effectiveness though it may increase sustainability. Community water sources are less effective than expected due to contamination introduced during collective use and issues related to transport and storage: they help to mitigate arsenic exposure but do not effectively address faecal contamination. Disinfecting tubewells with a weak chlorine solution reduced faecal contamination. Caretakers standard cleaning practices do not generally adhere to best practices and may worsen water quality. However, training caretakers in best practices proved highly effective in reducing *Escherichia coli* contamination, significantly improving water quality. Despite some imperfections in caretakers' recall and compliance, these results highlight the crucial role of proper cleaning and maintenance practices in reducing exposure to faecal contamination in rural Bangladesh, ensuring access to safe drinking water. The study highlights the power of RCTs in addressing complex causal questions related to safe drinking water access. While valuable insights have been gained, the study emphasizes that numerous unanswered questions remain, underscoring the ongoing need for research in this critical field. In summary, this study provides important evidence about how to improve project design and thereby increase access to safe drinking water in rural Bangladesh.

***Keywords**: Randomized Experiment; Safe Drinking Water; Participation; Decision-Making; Contribution Requirements; Cost-effectiveness; Faecal Coliform; Arsenic; Tubewell; Cleaning; Maintenance; Impact; Sustainability; Bangladesh.*

1 INTRODUCTION

1.1 Global scenario on access to safe drinking water

Accessibility of using safe drinking water is not a local, state or regional issue; it is a global issue for achieving Sustainable Development Goal (SDG) 6. Globally, about 73 percent of the population uses safely managed drinking water, 57 percent of the population uses safely managed sanitation, and 75 percent has a handwashing facility with soap and water available at home (UN-Water SDG 6 data portal; SDG indicator 6.1.1, 6.2.1a, 6.2.1b, 2022). Still, around 2 billion people are without access to safely managed drinking water services (WHO, 2023). In 2022, at least 1.7 billion people use a drinking water source contaminated with faecal bacteria. Microbial contamination of drinking water as a result of contamination with faeces poses the greatest risk to drinking water safety (WHO, 2023). World Water Day 2023 reminds us of the value of a precious resource: almost one

in 10 of the world population has no access to improved sources of drinking water and one in three lacks improved sanitation. As a result, they are at risk of infectious diseases and premature death. Over the past 21 years, global access to safely managed drinking water (water from improved sources such as a pipe, borehole, or protected well that is accessible on-premises, available when needed, and free from contamination) has steadily progressed: The proportion of the global population with access to safely managed drinking water has increased from 62% in 2000 to 74% in 2020 (World Bank, 2023). Approximately 3.5 million people die yearly due to inadequate water supply, sanitation and hygiene. Clean water and sanitation is one of the UN Sustainable Development Goals. The United Nations aims to achieve universal and equitable access to safe and affordable drinking water (SDG target 6.1) by 2030 (United Nations, 2015, Box 1). This goal is not only to improve human health (*part of SDG 3*) and reduce poverty (*part of SDG 1*) but also to reduce gender inequality (*part of SDG 5*) in some parts of the world. Increased access to water can also aid in education (*part of SDG 4*) because reducing the distance to a water source from 30 to 15 minutes increases a girl's school attendance by 12 per cent, according to a study in Tanzania (United Nations, March 2022). In March 2022, WHO reported that about 829000 people in low and middle-income countries die as a result of inadequate water, sanitation, and hygiene each year, and better water, sanitation and hygiene could prevent the deaths of 297000 children aged under five years each year. There is another challenge to overcoming the naturally occurring arsenic in groundwater. Globally, an estimated 150 million people from more than 70 countries are affected by the naturally occurring arsenic in the source of drinking water (Bhattacharya *et al.*, 2004; Ravenscroft *et al.*, 2009). Arsenic has been identified as a serious public health concern (Nordstrom, 2002; Kapaj *et al.*, 2006; Nriagu *et al.*, 2007).

1.2 Present status of progress on access to safe drinking water in low and middle-income countries

However, the global scenario is not impressive for achieving safely managed drinking water and hand washing facilities, but safely managed sanitation is still under challenge to achieve SDG 6 by 2030. This challenge mainly relies on the progress of low and middle-income countries. UN Water (SDG 6.1 data 2022) indicates only 31% proportion in Sub-Saharan Africa and 68 % proportion of population in Central and Southern Asia are uses safely managed drinking water services (Fig. 1). Notably, among low and middle-income countries, which account for 84% of the global population, the share of people without access to safely managed drinking water is much higher at 42% (WHO/UNICEF JMP, 2021). A recent study result shows that access to improved water and sanitation is significantly associated with a 24.5% (ATT = − 0.245) reduction of diarrheal disease among under-five children (Merid, M.W., 2023). No consensus exists about how to improve access to services. However, agreement has emerged that economic growth is insufficient to improve service provision. Adequate access is as much a pre-condition for the growth in living standards as the outcome (Easterly, 2003). Furthermore, the resources that are required for long-term maintenance of WASH interventions are often limited in LMICs, leading to their failure (Humphrey J.H., 2019). Empirical evidence from various reports indicates that in sub-Saharan Africa (SSA), 30 to 40 per cent of handpumps, the predominant type of water infrastructure in SSA, are not functioning (RWSN 2010; Duti 2012). Failure by governments and development partners to ensure sustained access to basic water supplies in rural areas is, to a large extent, the result of inadequate investment to deliver infrastructure where needed (World Bank, 2017). Researchers hypothesize several potential reasons for the failure of WASH interventions, such as a lack of community participation in design (Abedin *et al.*, 2019 & Padawangi R., 2010), a lack of community ownership (Klug *et al.*, 2017 & Jimenez-Redal *et al.*, 2018), the abuse of funds or poor financial management (Kwangware, 2014), a lack of willingness of community members to contribute (Klug *et al.*, 2017; Jimenez-Redal *et al.*, 2018 &

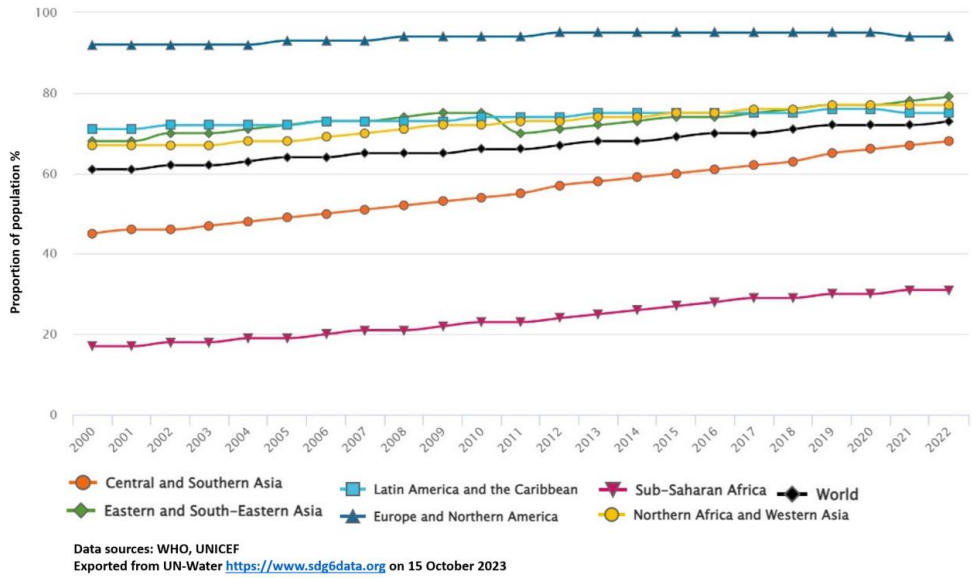

Figure 1: Global status of indicator 6.1.1 Proportion of population using safely managed drinking water services (2022).

Kwangware, 2014), a lack of communication and connectedness (Madrigal-Ballestero and Naranjo, 2015) and no ongoing support and acknowledgement of behaviour change (Russpatrick *et al.*, 2017; Ogendo et al., 2016 & Woode P.K. *et al.*, 2018).

1.3 Present progress on access to safe drinking water in Bangladesh

The major problem is to overcome the challenge of minimizing a wide-ranging gap between the proportion of population using safely managed drinking water (59%) and using improved drinking water (99%). Compared to the last two decades, UN-Water SDG 6 portal data shows that 55% and 59% achieved the proportion of population using safely managed drinking water in Bangladesh in 2000 and 2022, respectively (Fig. 2a).

Around 21 million people are exposed to naturally occurring arsenic in their primary source of drinking water, and 39 million are exposed to contamination with faecal bacteria (BBS and UNICEF, 2019). In Bangladesh, the mortality rate due to diarrhoea is 7.5 deaths per 100,000 in Bangladesh (WHO, 2021). A forthcoming assessment of the health impacts of pollution finds that over 275,000 people died in 2019 from four environmental health risks, including inadequate drinking water, hygiene, and scarce sanitation (World Bank, October 2022). Though Bangladesh is the world's seventh most climate-risk-affected country, it has been among the fastest-growing economies in the world, facing the challenge of vulnerability to climate change. A major challenge to attaining safely managed water is that water sources in the country have poor climate resilience, with water quality fluctuating throughout the year based on rainfall, temperature and other climate phenomena that are expected to get more frequent and intense with climate change (BBS and UNICEF, 2019). Challenges remain in terms of accountability and capacity to carry out some functions, particularly for long-term support and monitoring of service delivery and standards (World Bank, 2017). Along with the government, development partners are supporting a range of projects to overcome this challenge and improve the use on access to safe drinking water. Bangladesh has received a total of USD 1692 million during MGD era and USD 1723 million between 2016 and 2021 in SDG period as international official development assistance to support the target SDG 6.a.1 Water and sanitation-related official development assistance

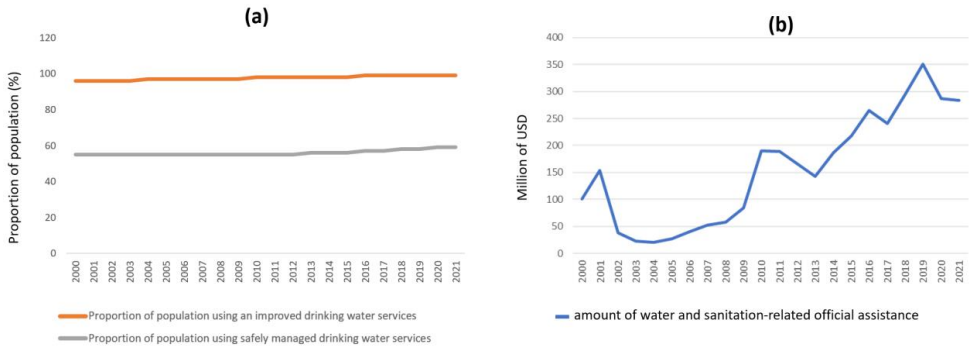

Figure 2: a) Proportion of population using safely managed and improved drinking water services in Bangladesh progress and b) amount (USD) of international cooperation and capacity-building assistance received by Bangladesh for water and sanitation related official development. (Data source: WHO, OECD https://www.sdg6data.org/en/country-or-area/Bangladesh#anchor_6.a.1)

including water sector policy and governance, water supply, sanitation, water sector policy, water resources conservation, river basins development, waste management/disposal, education and training, agricultural water resources and hydroelectric power (Fig. 2b, Source: UN SDG 6 Country data).

2 RESEARCH CONTEXT

The need for safe water in Bangladesh arises from the problem that one-third or more of the wells which draw bacteria-free groundwater have concentrations of arsenic above the Bangladeshi safety standard of 50 micrograms per litre. Since tubewells supply drinking water for about 90% of the population, at least 37 million people are consuming unsafe water (BGS and DPHE, 2001). According to the WHO-UNICEF- JMP, (2023), about 70 million people in Bangladesh (41 per cent of the population) don't have access to safely managed drinking water. Most households obtain water for drinking and cooking from shallow, hand-pumped tubewells (Human Rights Watch, 2016). In many rural areas, the primary technology used to improve access to safe drinking water is the deep tubewell. Deep tubewells draw groundwater from deep aquifers isolated from source of faecal and arsenic contamination. Though, deep tubewells are expensive and must typically be provided at the community level. However, in practice, how effectively deep-tubewell construction programs improve access to safe drinking water is unclear. Take-up rates are uncertain, leading to a range of estimates for cost-effectiveness that vary by a factor of 16 (Jamil *et al.*, 2019). Additionally, providing deep tubewells may not solve the problem of faecal contamination in drinking water if contamination also occurs during transport and storage (Wright *et al.*, 2004). Still, 40.4 % (N=6065) of the population of Bangladesh remains at risk level (>=1 *E. coli* CFU/100 ml) in drinking water at the point of collection (Bain. *et al.*, 2021).

To enhance this situation, the government, NGOs and international aid agencies are providing technical support and subsidies to improve this situation by installing and constructing different safe water options, mainly deep tubewells. Very few studies evaluate the impact of these interventions on access to safe drinking water and sustainability. Recently, the Policy Support Branch of Local Government Division, Ministry of LGRD&Co, Bangladesh has published an updated "Operation and Maintenance Guideline for Water Supply and Sanitation for Rural Areas" in June 2022, where they highlighted some successes and "lessons learned" from projects operated by DPHE, UNICEF and some other NGOs. No result-based or causal evidence-based outcomes are reported in these guidelines. Our study will contribute to this gap by providing causal evidence

on how to enhance the impact and sustainability of safe drinking water access programs in rural Bangladesh. Many studies and reports have pointed out the reasons for despair of water technologies. Such studies primarily describe maintenance levels in projects which are all implemented under the same conditions. Other studies document correlations between community participation and sustainability (e.g., Sara and Katz, 1997). None of these studies can distinguish the causal effect of participation from other factors correlated with the choice to adopt a participatory approach, which may also influence outcomes. The problem is to establish the causality when different projects take different approaches in different communities. Research to date suggests that access to safe drinking water is a challenge to achieve SDG 6.

2.1 Challenges of elite capture and maintenance on access to safe drinking water programs in rural areas

Practitioners assume that access to safe drinking water at the community level remains inadequate due to a lack of community participation, proper maintenance, adequate cleaning and local elite capture. The rich and elite are used to use collect water from their own private sources and poor families are forced to dedicate more time to collecting water from the public or other outside sources. Community development may also be inherently subject to elite capture because of the entrenched influence of local elites (Platteau and Abraham, 2004). It also appears, however, that the poor often benefit less from participatory processes than do the better off because resource allocation processes typically reflect the preferences of elite groups. Studies from a variety of countries show that communities in which inequality is high have worse outcomes, especially where political, economic, and social power are concentrated in the hands of a few. "Capture" tends to be greater in communities that are remote from centers of power, low literacy, poor or have significant caste, race, or gender disparities (Mansuri and Rao, 2004). Local social structures and levels of elite control can play a strong role in its functioning (Mansuri and Rao, 2004).

SDG 9 sets out the challenge of providing "affordable and equitable access for all" to "sustainable and resilient infrastructure". However, infrastructure is woefully under-provided in much of the developing world and often falls rapidly into disrepair (Ahuja *et al.*, 2010). This type of problem is common in rural areas, particularly for "hard-to-reach" areas, where responsibility for repair and maintenance lies with local communities.

The effect of new community water sources on faecal contamination in household drinking water is theoretically ambiguous. Improvements in source water quality may be offset by increased recontamination during transport and storage (Kremer *et al.*, 2011). Goel *et al.*, 2019 reported that there is not a significant difference in microbial contamination between shallow and deep tubewells at source. In this perspective, involving the community in decision-making and ensuring their contributions can help mitigate the dominance of the elite and enhance the sustainability aspects essential for delivering local public services, such as rural drinking water systems, through innovative project cycle interventions.

2.2 Limited causal evidence about the causal effect of interventions to increase access to safe drinking water in rural areas

Limited evidence-based experience exists for evaluating and identifying the causal effects of different interventions on the impact and sustainability of the rural water supply. Community engagement is thought to play a crucial role in ensuring the success and sustainability of rural water supply initiatives. In rural areas, community participation involves the active engagement of users in water service management (Jiménez. *et al.*, 2019 and Kelly. *et al.*, 2017). Community participation also refers to enabling communities to initiate project ideas and to take decisions about technology

type and facility location that best suits their needs (Kwangware *et al.*, 2014).) Community contribution requirements are ubiquitous in participatory development projects (White *et al.*, 2018). Lack of community participation is often seen as a hindrance in collaborative action (Naiga R. & Penker M., 2014). People have suggested many ways to improve project design that might increase impact. There is little causal evidence about their effects. So, we need to examine and consider the type of community participation required to enhance access to safe drinking water programs and ensure their long-term sustainability. Our measures the causal effects of interventions in the project life cycle on impacts on safe drinking water access and the sustainability of infrastructure via four different experiments and over time scales of up to 15 years after installation.

2.3 Research objectives and rationale

The overall objective of this study is to understand how strategic interventions in project design can increase the impact and sustainability of WASH projects in rural Bangladesh and, in particular, how participatory approaches affect sustainability.

The specific objectives of this thesis are as follows.

1) Understanding the effects of participation in decision-making on the impact of projects to provide safe drinking water sources and examine how differences in impacts depend on the characteristics of the targeted beneficiary community. This will give a clear idea to whom decision-making authority should be assigned to maximize impact. (***Papers I, II & IV*).**
2) Understand the effects of community contributions requirements in cash or labour in projects that aim to provide safe drinking water tubewells in rural Bangladesh. **(*Papers III & IV*)**
3) Understand the effects of technology choice-specifically, community water sources. (***Paper V***).
4) Understand whether and how changes in cleaning practices could improve water quality in community water sources. (***Papers VI & VII***)

2.4 Research questions

The specific objectives were achieved through the following research questions;

I. How does allocation of decision-making authority affect the impact of a project to provide a local public good? (***Paper I***)
II. How does heterogeneity in the effects of decision-making processes affect the program's impact? (***Paper II***)
III. Does requiring beneficiary communities to contribute in cash or labour towards project costs affect the impact of projects to provide safe sources of drinking water? (***Paper III***)
IV. How does the extent and type of community participation in decision-making, design, financing and construction improve the sustainability of safe drinking water supply programs in Bangladesh? (***Paper IV***)
V. How successfully do community drinking water sources provide safe drinking water in rural areas of Bangladesh? (***Paper V***)
VI. Can we improve water quality through improved cleaning practices? (***Paper VI***)
VII. Can we improve community tubewell water quality by training caretakers in improved cleaning practices?(***Paper VII***)

Box 1: Overview of the selected SDG targets that are relevant to the thesis. (United Nations, 2015).

Goal 6. Ensure availability and sustainable management of water and sanitation for all.

6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all.

6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations.

6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.

Goal 3. Ensure healthy lives and promote well-being for all at all ages.

3.1 By 2030, reduce the global maternal mortality ratio to less than 70 per 100,000 live births.

3.2 By 2030, end preventable deaths of newborns and children under 5 years of age, with all countries aiming to reduce neonatal mortality to at least as low as 12 per 1,000 live births and under-5 mortality to at least as low as 25 per 1,000 live births.

Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.

9.1 Develop quality, reliable, sustainable and resilient infrastructure, including regional and transboundary infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all.

9.5 Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending.

9.a Facilitate sustainable and resilient infrastructure development in developing countries through enhanced financial, technological and technical support to African countries, least developed countries, landlocked developing countries and small island developing States.

Goal 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.

16.7 Ensure responsive, inclusive, participatory and representative decision-making at all levels.

Goal 5. Achieve gender equality and empower all women and girls.

5.4 Recognize and value unpaid care and domestic work through the provision of public services, infrastructure and social protection policies and the promotion of shared responsibility within the household and the family as nationally appropriate.

5.5 Ensure women's full and effective participation and equal opportunities for leadership at all levels of decision-making in political, economic and public life.

Goal 1. End poverty in all its forms everywhere.

1.2 By 2030, reduce at least by half the proportion of men, women and children of all ages living in poverty in all its dimensions according to national definitions.

1.b Create sound policy frameworks at the national, regional and international levels, based on pro-poor and gender-sensitive development strategies, to support accelerated investment in poverty eradication actions.

Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.

4.7 By 2023, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and of culture's contribution to sustainable development.

3 RESEARCH DESIGN AND METHODS

The research described in this thesis is consistent of experiments with different interventions in the project life cycle through four Randomized Control Trial experiments, which address the objectives in section 2.3.

3.1 Project life cycle

In this study, I conceptualize the project life cycle as having several different stages, namely, *A. Decision-making*, *B. Financing*, *C. Technical design*, *D. Construction* *E. Use* and *F. Maintenance*. The following flow diagram (Fig. 3) sketches out this project cycle to show different the project stages, from decision-making to the impact and sustainability of project.

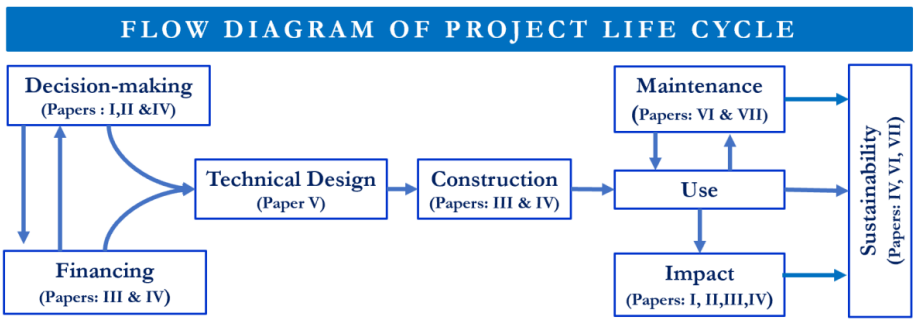

Figure 3: Flow diagram of project life cycle with outcomes of Papers or results.

3.2 Overview of project life cycle and significance of experimenting with interventions

In our study, we conduct experiments with interventions at different stages of the project cycle, from decision-making to maintenance, to generate evidence-based results that can help policy makers, development practitioners and academics to plan and design programs that maximize impact and sustainability. The first intervention, "decision-making," involves evaluating the impact of decision-making approaches on safe drinking water usage through **Experiment I** (Section 3.4.2.1). **Experiment II** evaluates effects of requiring community contributions on average program impact, and the distribution of cost and benefits as well as the program design efficiency by studying different types of contribution requirements within a consensus-based decision-making approach (Section 3.4.2.2). **Experiments III** and **IV** are designed to identify causal effects on sustainability through interventions related to cleaning practice (Sections 3.4.2.3 and 3.4.2.4).

3.3 Study area

We implement the study in six Upazilas, namely: Matlab North and Matlab South Upazilas (Subdistricts) in Chandpur District in Southeastern Bangladesh; Gopalganj Sadar Upazila in Gopalganj District in Southwestern Bangladesh; Shibganj and Sonatala Upazilas in Bogura District in Northwestern Bangladesh; and Gobindaganj Upazila in Gaibandha District also in Northwestern Bangladesh (Fig. 4). Gopalganj and Chandpur Districts are the country's arsenic hot spots, and previous arsenic mitigation efforts had not been enough. Shibganj and Sonatala Upazilas in Bogura and Gobindaganj Upazila in Gaibandha Districts lie outside the epicenter of the arsenic contamination problem, but government officials and national media reported high levels of arsenic contamination in scattered pockets (Fig. 4). Before our program, these areas had received limited interventions to address the problem of arsenic. In Matlab and Gopalganj Upazilas, we ran

Experiment I, and the results are described in ***Papers I, II*** and ***IV***. The Upazilas of the Northwestern part is selected to run **Experiments II, III** and **IV**. The results of these experiments are described in ***Papers III, IV, V, VI*** and ***VII***. Demographic information about the study areas is shown in Table 1.

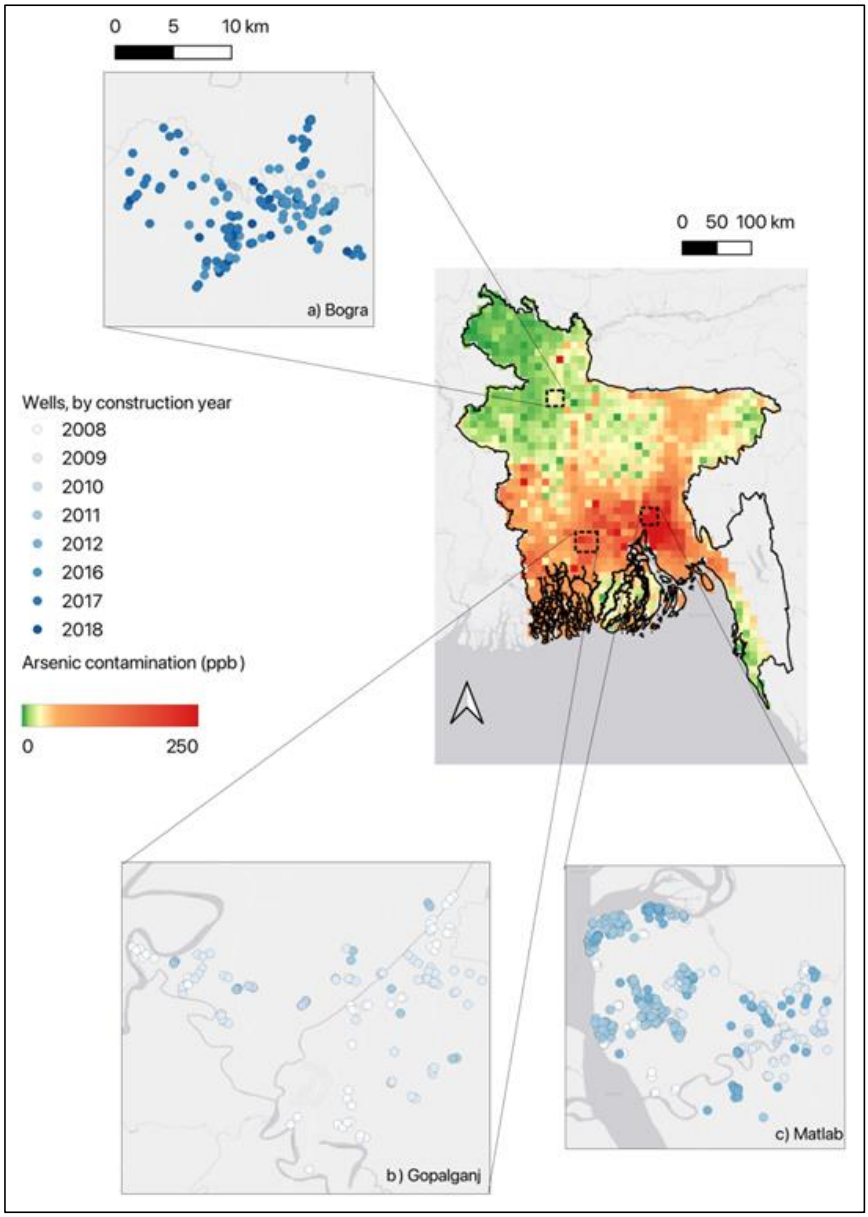

Figure 4: Study regions and tubewells sampling locations. The three study regions were all exposed to relatively high levels of arsenic contamination before the interventions, based on interpolated arsenic contamination in 1998-9 British Geological Survey 2001). Tubewells in Bogra constructed between 2016 and 2018; in Gopalganj, between 2008 and 2011; and in Matlab between 2008 and 2012.

Table 1: Demographic information of the study areas.

Item of description	Gopalganj		Chandpur				Bogura				Gaibandha	
	Gopalganj Sadar		Matlab North		Matlab South		Shibganj		Sonatala		Gobindaganj	
Year	2001	2011	2001	2011	2001	2011	2001	2011	2001	2011	2001	2011
Population	321934	344008	299935	292053	207611	210050	352415	378700	167547	186778	461428	514696
Area (sq. km)	391.35	389.61	277.53	260.29	131.92	129.32	315.92	314.92	156.73	156.75	481.66	460.42
No of HHs	60292	73126	58394	63784	41068	45569	83120	99242	38364	48569	107878	132572
No of Union	21	21	13	14	6	6	12	12	7	7	17	17
Avg size HH		4.67		4.6		4.6		3.81		3.84		3.88
Population Density (per sq. km)		883		1122		1624		1203		1191		1118
*Percentage of household population with *E. coli* in PoC water (>1 per 100mL) by division	52.1% (N=6349) Dhaka		51.3 % (N=5094) Chattogram				28.8% (N=3288) Rajshahi				24.2% (N=2904) Rangpur	
*Percentage of sampled household population under different contamination levels of Arsenic and Districts	44.9%(<=10ppb) 10.2%(>10-50ppb) 21.3%(>50-<=200ppb) 23.6%(>200ppb) N=445		53.8% (<=10ppb) 4.1% (>10-50ppb) 3.4% (>50-<=200ppb) 38.6% (>200ppb) N=812				94.2% (<=10ppb) 3.9% (>10-50ppb) 1.9% (>50-<=200ppb) N=1251				84.4% (<=10ppb) 9.3% (>10-50ppb) 4.8% (>50-<=200ppb) 1.0 % (>200ppb) N=905	

Source: BBS 2001 and 2011; *Source: MICS 2019.

3.4 Methods

This section provides a brief background to the methods applied in this thesis. Table 2 shows which papers use which methods. An overview of methods used in the research is provided here in sections 3.4.1 to 3.14 but the details are elaborated in the appended Papers.

Table 2: Overview of the methods applied to each experiment and appended Papers.

Methods	Exp. I		Exp. II				Exp.III	Exp.IV
	Papers		*Papers*				*Paper*	*Paper*
	I	*II*	*IV*	*III*	*IV*	*V*	*VI*	*VII*
Randomized field experiments	X	X	X	X	X	X	X	X
Households surveys	X	X	X	X	X	X		
Engineering assessment			X		X			
Focus Group Discussions	X	X						
Qualitative data	X	X		X				
Water Quality Testing	X	X	X	X	X	X	X	X
Economic Modelling	X	X						
Modelling: Mathematical and Statistical	X	X		X		X		
Cost-effectiveness analysis	X			X		X		X
Statistical analysis	X	X	X	X	X	X	X	X

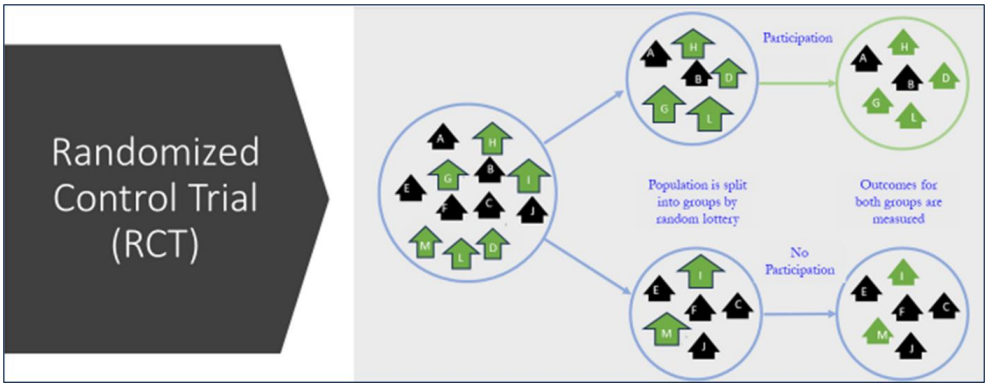

Figure 5: An overview of the Randomized Control Trial (RCT).

3.4.1 Randomized field experiments or randomized controlled trials (RCT)

We used randomized field experiments to identify the causal effect of interventions in the different stages in the project life cycle on the impact and sustainability of the water supply projects we study. Assigning communities randomly to treatment ensures that the assignment is unrelated to any observed or unobserved characteristics of the community or household (Fig. 5). As a result, the communities treated under each different treatment arm will be comparable to communities in the control group. Randomization removes problems with selection bias. In this study, we implement experiments at different stages in the project life cycle from decision-making to maintenance.

3.4.2 Experimental design

The experiment is structured with interventions from decision-making to training throughout the various stages in the project life cycle (Fig. 6). The research described in this thesis is conducted during the period from 2007 to 2023.

3.4.2.1 Experiment I: Decision-making process

This first experiment intervenes in the decision-making stage of the project cycle (***Paper I***). The experiment is implemented in 191 villages selected from a broader population of villages where a minimum of 65% of tubewells exhibited unsafe levels of arsenic in Matlab North and Matlab South

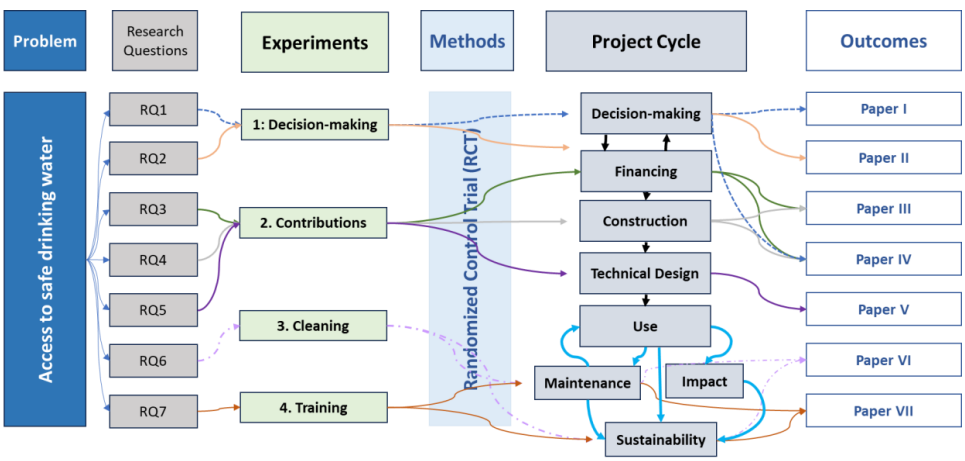

Figure 6: The generalized conceptual methodology used in this study.

Figure 7: Participation in decision-making process meeting at the community level.

Upazilas, and in Gopalganj sadar Upazila, a minimum of 75% of tubewells exhibited unsafe levels of arsenic. These Upazilas had severe arsenic contamination in shallow tubewells, which are the most popular source of drinking water and no other major interventions underway to mitigate the problem. All treated villages were randomly assigned to one of three decision-making processes: one centralized, top-down process and two participatory processes (Fig. 11a). Under the top-down process, project staff took all decisions, using information from the community. Under one participatory process, the community took all decisions using their own internal decision-making processes. Under the other, the community took all decisions by consensus at a meeting with representation of women and the poor (Fig. 7).

Project staff offered the same safe water technologies (mostly deep tubewells) in all treatment villages. They also provided all technical information identified feasible safe water technologies, tested the water after installation, and replaced problematic water sources. Each village had to contribute between 10% and 20% of the cost of each source and could install at most 2 or 3 sources of safe water, depending on the type of tubewell. The required contribution varied by type of technology and number of sources chosen because of the installation costs. Only those sources for which the community raised the contribution within 12 weeks were installed. The funding rule necessarily implies that communities decide how many safe water sources they will install, up to the maximum number of offered sources, under each approach to decision-making. The project held community meetings in all treatment villages and explained that the project would offer sources of safe drinking water and outlined the conditions. The conditions depended on the approach to which the village was assigned. Project staff publicized the meetings in each village. Village residents decided whether or not to attend.

Matlab and Gopalganj Upazilas differ in important respects hypothesized to affect the success of participatory approaches and, more generally, collective action, including pre-intervention access to safe drinking water, cohesiveness, community size, religious fractionalization, and inequality. ***Paper II*** investigates heterogeneity in how the decision-making processes affected the program's impact.

3.4.2.2 Experiment II: Requiring community contributions

The program was implemented in geographically adjacent communities, ranging from 50 to 250 households, defined by natural boundaries (Fig. 8). Prior research had indicated that assessing the impacts of similar interventions in larger communities would pose challenges (Madajewicz *et al.*, 2021). In larger communities, we provided the option for two Deep Tubewells (DTWs), while in smaller communities, we offered one DTW. In total, we conducted screening for 200 communities. Among them, 29 communities were excluded due to low arsenic contamination, and we recruited 171 communities (Fig. 4 in ***Paper III***).

Community participation was essential, with communities deciding during meetings how many of the offered tubewells to install and where to construct any DTW. Our field staff oversaw and facilitated this decision-making process, and community members arrived at unanimous decisions.

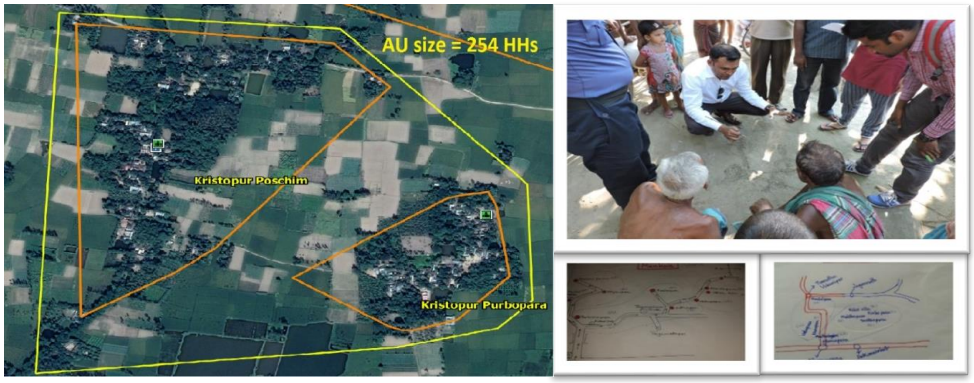

Figure 8: A sample map of construction of treatment unit/community (HHs 50-250) by defining natural boundaries of geographically contiguous communities.

The study villages were randomly assigned to one of three participatory contribution approaches within the treatment group, or to a control group. In total, 129 communities received the intervention. Among the treated villages, 43 were randomly assigned to a requirement of raising a cash contribution for the installation cost, while another 43 were assigned to a waiver of this contribution requirement. By comparing these two groups, we aimed to estimate the impact of participation in financing. Furthermore, 43 of the treated villages were randomly assigned to a requirement to contribute manual labor during tubewell construction (Fig. 11b). This participation in construction is considered approximately equal in value to the cash contribution and was also a part of ***Paper III***. The remaining 42 communities to a control group that did not receive any intervention.

We allocated communities to these groups through public lottery meetings, where representatives from eligible communities were invited to participate. These public lottery meetings played a crucial role in providing field staff with a means of establishing legitimacy in case communities raised questions about why certain villages received the intervention while others did not, or why contribution requirements varied among communities. The resultant distribution of communities across treatment arms is geographically well balanced (Fig. 8). Communities assigned to different treatment arms are statistically indistinguishable at baseline.

In **Experiment II**, communities were responsible for deciding how many of the offered tubewells they wanted to install and determining the locations for these tubewells. These decisions were made during full community meetings by unanimous consensus (as in **Experiment I**). If a community reached an agreement on a location, obtained consent from the landowner, and fulfilled any required contribution obligations, we then instructed contractors to proceed with the installation of a safe tubewell.

The installation process involved drilling down to a safe aquifer, which is an underground layer through which water flows and is separated from the arsenic-contaminated aquifers near the surface by an impermeable layer that prevents the passage of contaminated water. The drilling process primarily relied on local technologies and human labor. It typically took approximately 72 hours, with laborers working in shifts around the clock. Contractors utilized the rotary reverse-circulation drilling method, locally known as the Donkey method, for installing tubewells (Fig. 9) (Hossain *et al.*, 2014).

We collected data on all installed tubewells within the treated communities for several years after the intervention to assess the impact of participation on sustainability, as described in ***Paper IV***. **Experiment II** also contributed significantly in evaluating the program's impact on access to

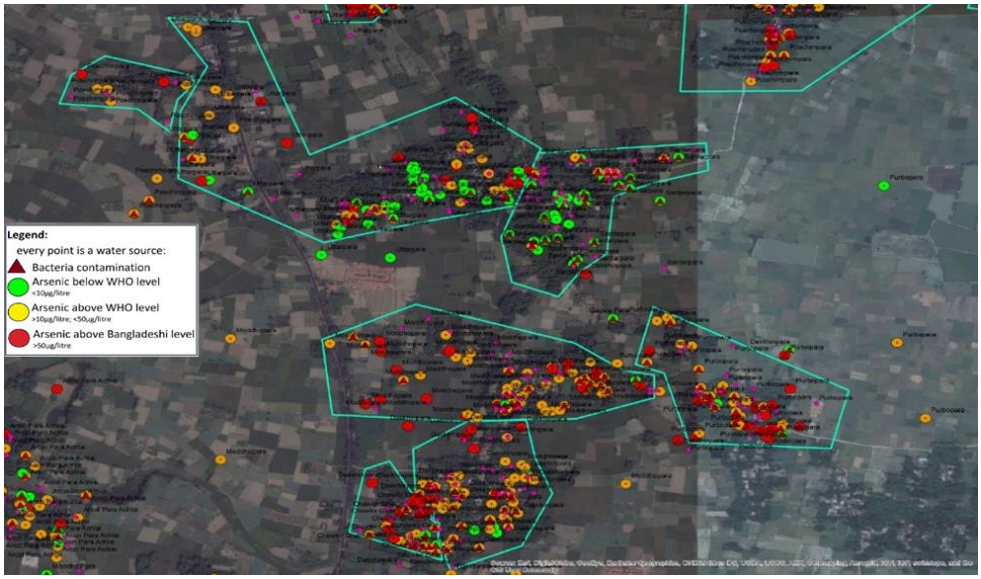

Figure 9: Showing arsenic concentration and E.coli presence in drinking water sources in some treatment units of Deuli union under Shibganj upazila, Bogura District.

safe drinking water by introducing new, secure sources of drinking water to communities, as outlined in ***Paper V***.

It is worth noting that while the introduction of new community safe water sources theoretically encourages households to adopt safer drinking water sources, its effect on water quality is not straightforward. This is because it may also prompt households to change their practices related to the transportation and storage of drinking water. These alterations in transportation and storage methods could, in turn, influence the quality of the drinking water available.

3.4.2.3 Experiment III: Cleaning of tubewells

The sustainability of tubewells depends on proper maintenance and cleaning, as indicated by our prior findings in **Experiment II** (***Paper V***). In that study, our project's Deep Tubewells (DTWs) mostly had arsenic contamination levels below the WHO threshold. However, they were only 13 percentage points (28 percent) less likely to test positive for faecal contamination compared to other tubewells within the same communities (Cocciolo *et al.*, 2021). We designed **Experiment III** to evaluate the impact of three different cleaning approaches on reducing faecal contamination in DTWs, as illustrated in Figure 10. We randomly assigned the 126 DTWs that were installed during **Experiment II** to these three different cleaning protocols and also included a control group (Fig. 11c), as outlined in section 2.3 of ***Paper VI***. To ensure a balanced distribution, we utilized pseudo-random number generators in STATA to assig tubewells to their respective treatment groups, with stratification based on communities that were subject to different rules regarding contribution requirements and decision-making processes during the project implementation (Fig. 2, ***Paper VI***). The final sample for this study consisted of 94 DTWs that were operational at the time of data collection, which took place between June and July 2021, as detailed in Table 1 of ***Paper VI.***

3.4.2.4 Experiment IV: Training of caretakers

An effective and cost-efficient tubewell cleaning protocol has the potential to significantly reduce or completely eliminate faecal contamination at the point of water collection, as outlined in ***Paper VI***. To further explore this, we developed **Experiment IV** based on this low-cost effective cleaning

Caretaker | Flame | Weak chlorine

Figure 10: Three different cleaning experiments Caretaker's usual standard of cleaning, Flame disinfection and Disinfection with weak chlorine.

protocol to assess whether training caretakers in more effective tubewell cleaning practices can lead to improved water quality. The intervention we are assessing involves a single two-and-a-half-hour-training workshop conducted in December 2021 for the caretakers responsible for community tubewells. These workshops were led by trained facilitators.

In this experiment, we utilized the original sample of 94 DTWs from **Experiment III** (as illustrated in Figure 3 of ***Paper VII***). The DTWs were allocated to one of three study arms: 32 were assigned to a control group that did not receive any intervention, while the remaining 62 were divided into two treatment arms that received the training intervention (Fig. 11d). Among the caretakers responsible for tubewells in the training intervention group, half of them were additionally provided with a year's supply of essential materials necessary to implement the cleaning protocols taught during the workshop. These supplies included a stiff brush and a twelve-month supply of bleach powder, packaged as twelve 4g doses in separate Ziploc bags.

Each workshop commenced with an introduction to best practices in water, sanitation, and hygiene (WASH). Following this, a practical demonstration was provided on how to effectively clean a tubewell. This demonstration included instructions on how to disassemble the tubewell, clean the external and accessible internal surfaces of the pump, and rinse all surfaces with a weak chlorine solution. The facilitators emphasized the importance of removing all deposits that could potentially harbor bacteria and emphasized the need to pump the tubewell for ten minutes after reinstallation to eliminate residual chlorine from the tubewell body.

During the workshop, facilitators also presented findings from a pilot study, which demonstrated that local cleaning practices did not lead to improved water quality. In contrast, the approach taught during the workshop was found to be effective in improving water quality.

To incentivize participation, caretakers received a packed lunch and were reimbursed for their travel expenses after the workshop, although they were not informed of these benefits in advance. Subsequently, caretakers evaluated the training workshop positively, listing similar strengths regardless of whether they were assigned to receive training alone or training along with supplies.

3.4.3 Non- Experimental Data

We collected data from the Sustainable Arsenic Mitigation (SASMIT) project to gain a better understanding of the average duration for which tubewells provide safe drinking water. The SASMIT project was implemented in 99 villages, located in the same area (Matlab) as **Experiment I**. Under the SASMIT project, these 99 villages received a program for safe drinking water, specifically Intermediate Deep Tubewells (IDTWs), which included participatory features (Bhattacharya *et al.*, 2014). Our dataset includes information on 245 IDTWs that were installed as part of the SASMIT program. We conducted surveys of these SASMIT tubewells in the years 2012, 2015, 2021, and 2023 to gather comprehensive data on their performance and the sustainability of safe drinking water provision.

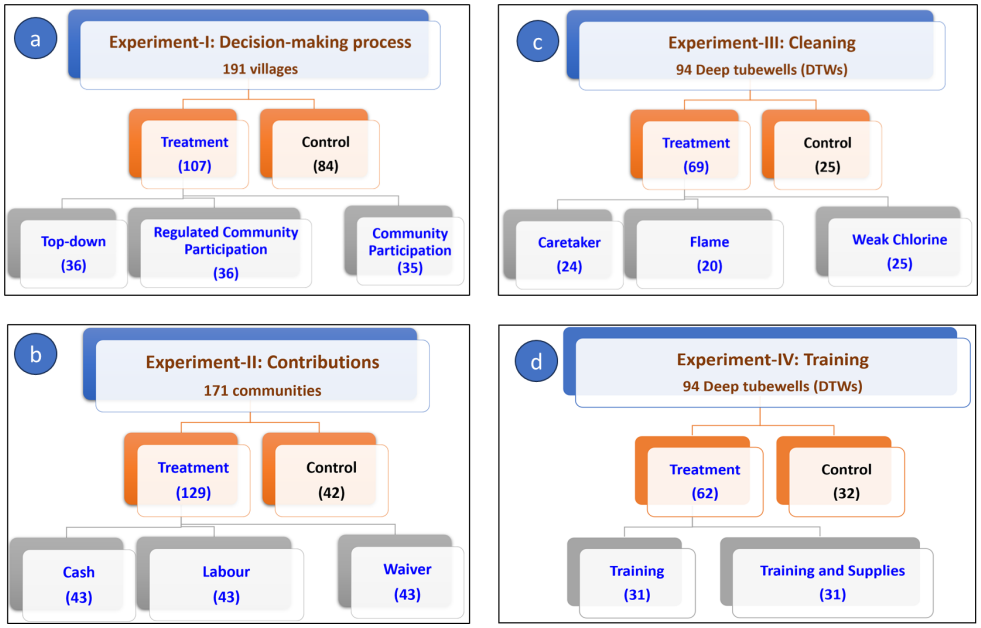

Figure 11: Randomized Control Trial (RCT) used in the experiments (I-IV).

3.4.4 Tubewell engineering assessment

For engineering assessment of tubewells, DTWs under **Experiments I & II** and 245 IDTWs under no-experiment of SASMIT project are considered to assess the condition. A total of 272 DTWs were installed under **Experiment I** are listed in Table 3. Under **Experiment II**, a total of 107 DTWs tubewells were feasible for engineering assessment where 10 (9.35%) DTWs installed under cash treatment, 48 (44.86%) under labour treatment and 49 (45.79%) installed under waiver treatment between 2016 and 2018 following by the *Consensus-based* decision and contributions rules (section 3, ***Paper III***). All DTWs were installed by Rotary reverse-circulation drilling method (Fig. 12).

Table 3: Installed arsenic safe tubewells under decision-making process (Experiment I).

Upazilas Name	Decision-making approaches	DTWs	IDTWs	Total
North Matlab	TD	27	-	27
	CP	34	-	34
	RCP	26	-	26
South Matlab	TD	-	14	14
	CP	-	12	12
	RCP	-	16	16
Gopalganj sadar	TD	39	-	40
	CP	45	-	47
	RCP	38	-	41
Total		209	42	257

Figure 12: Tubewells installation followed by Rotary reverse-circulation drilling (locally called the Donkey method).

3.5 Key outcome variables: Impact and Sustainability

The study combines randomized **Experiments (I-IV)** to evaluate the impact and sustainability of safe drinking water access programs. Here impact and sustainability are key outcome variables. ***Papers I*** and ***II*** rely on self-reported use of safe drinking water. ***Papers III*** and ***V*** use data from water quality testing to obtain a more objective measure of impact. In ***Paper III***, we focus on arsenic, aggregating information from water quality tests and tests of household drinking water into an arsenic exposure index. In ***Paper V***, we focus on both exposure to arsenic and to faecal bacteria, and we separately report results for contamination in sources used by households and in household drinking water.

In ***Paper IV***, we measure the sustainability of the installed tubewells under **Experiments I & II** and SASMIT tubewells. We have compiled comprehensive data on the tubewells to analyze the factors influencing tubewell sustainability in **Experiment II**. This analysis aims to determine the extent to which tubewell functionality is influenced by factors that communities can control. For our analysis, functionality is defined based on whether or not a tubewell still provides water. In ***Paper VI***, we examine into a specific aspect of sustainability by examining the impact of cleaning and maintenance on water quality, particularly contamination levels with total coliforms and *E. coli* in the water sourced from the tubewells. This paper aims to assess how cleaning and maintenance practices influence the provision of safe drinking water from these tubewells.

Specifically, we assess functionality by evaluating whether an enumerator can collect 7 liters of water from the tubewell, which corresponds to the volume of a commonly used local vessel known as a "kolci" for collecting and storing drinking water.

In ***Papers VI*** and ***VII***, our focus is on the sustainability of water quality provided by project tubewells. These tubewells were constructed during the period from 2015 to 2018. The assessment

of tubewell's water quality and functionality was conducted at the time of data collection, which occurred in 2021 for ***Paper VI*** and in May 2023 for ***Paper VII***.

In ***Paper VII***, we continue to assess sustainability, but the focus shifts to evaluating the effects of caretaker training on ensuring the availability of safe drinking water. The measurement of sustainability in this context aligns with the same criteria used in ***Paper VI***. This paper examines whether training caretakers can contribute to the provision of safe and reliable drinking water from the project tubewells.

3.6 Verifying random assignment

We conducted statistical tests to assess whether the experiments effectively generated statistically comparable treatment and control groups, as elaborated in detail in the Methodology Chapter of ***Paper I*** (with references to Tables 2 and 3). The experiments were executed according to their designated plans, with one notable exception. In **Experiment I** in Matlab, the project director at the time did not adhere to the study protocol. Instead, he assigned all the villages in a particular area of Matlab to the treatment group.

However, in Gopalganj, the random assignment to treatment and the random allocation of decision-making processes for all treated villages took place as initially intended. We have elaborated on how we address this situation empirically in ***Paper I*** to account for the deviation from the planned random assignment in Matlab.

3.7 Data collection

3.7.1 Households survey

In **Experiments I** and **II** we conducted households surveys in a random sample of households, before and after the interventions. The household surveys were conducted in Bengali with the household head, their spouse, or another adult household member, who provided informed oral consent before participating. We collected data on various aspects, including awareness of the arsenic problem, household water sources, household characteristics (such as ownership of assets, house construction materials, access to electricity, ownership of sanitary latrines), household social networks, and the household's relationship with the village community. In both studies, attrition was very low, because it is rare for entire households to migrate in these contexts. In both analyses, we applied survey weights to ensure that each village had an equal weight in sample statistics, in line with the original study design.

In **Experiment I**, our main sample initially included 7,557 study households. However, due to a data entry error involving 130 households at baseline, the final dataset consisted of 7,427 households at baseline and 7,341 households at follow-up.

For **Experiment II**, we targeted 40 households per community at baseline and surveyed a total of 6,529 households at baseline, averaging 38 households per community (Fig. 11b). We successfully completed the endline survey with over 99% of the targeted households, with a low attrition rate of 0.12%. During the baseline survey, we conducted a water source census and tested water quality in drinking water for 6,051 study households, including all the water sources they reported using. We matched households to the water sources they reported using. Households identified the water source(s) used for drinking or cooking purposes from a predefined list established during a baseline water source census.

Furthermore, we collected technical information about the tubewell installation process and tubewell-specific installation costs, tracking staff time used in each community. This allowed us to provide a detailed description of implementation costs under each approach in **Experiment II**.

3.7.2 Qualitative data

In the period following the interventions of **Experiment I** and preceding the follow-up survey, we conducted focus group discussions (FGDs) to gain insights into how the decision-making processes unfolded under each approach. These FGDs were carried out in a total of 12 treatment villages, with 4 FGDs conducted for each decision-making process. This involved 6 FGDs in Gopalganj and 6 FGDs in Matlab, with separate FGDs held for men and women in each location.

Furthermore, our field staff recorded audio during all community meetings, which were later transcribed, translated, and coded for analysis. This data collection process was implemented for **Experiment I**.

Additionally, field staff provided narrative reports detailing their experiences in each community, and they shared their qualitative insights with the research team during a program retreat in **Experiment II**. This comprehensive approach to data collection allowed for a thorough examination of the decision-making processes and community dynamics in both experiments (Fig. 8).

3.8 Economic modelling on decision-making and heterogeneity

In Experiment I, we employed two highly simplified models to help interpret the effects of the decision-making processes. Both models consider a specific community layout and make reasonable assumptions about land ownership and preferences. The models primarily focus on the decision of where to place a new, safe community tubewell. The models illustrate various mechanisms that lead to different patterns of safe drinking water usage and welfare outcomes under the approaches to decision-making.

In the model in ***Paper I***, we envision a triangular layout with sides of length "d." At one vertex, there is an elite household, and at another vertex, there are two non-elite households. The third vertex represents a piece of public land, as shown in (Fig. 13). Each household owns a plot of land, and every plot of land, including the public land, has the capacity to accommodate a community tubewell. A household has the authority to control access to a tubewell located on their own land, while no one can restrict access to a tubewell on public land. In the initial scenario, referred to as the "status quo," each of the three households relies on a private, unsafe tubewell that is situated on their respective land. The model serves two primary purposes: first, it determines which households would opt to use a community tubewell at a given location, and second, it investigates how the decision-making approach influences the placement of the community tubewell, as elaborated in ***Paper I***.

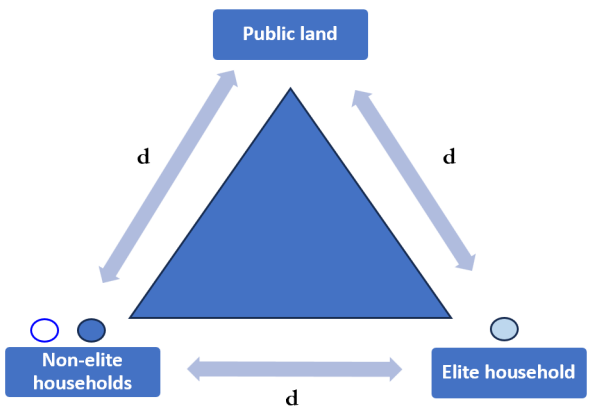

Figure 13: Idealized community geography.

We further adapted this model in ***Paper II*** to emphasize the conditions under which the consensus-based decision-making process can lead to improved outcomes compared to unrestricted decision-making by communities. We focus on these two decision-making processes since we observed the strongest evidence for heterogeneity in their effects. This modified version of the model sheds light on why the potential gains households stand to achieve from gaining access to safe drinking water might explain the heterogeneity in the impacts of consensus-based decision-making, thereby providing a rationale for our results.

3.9 Measurement of water quality (arsenic and faecal bacteria)

In **Experiment II**, we conducted arsenic and faecal contamination tests for all households and surveyed all water sources that any interviewed household reported using for drinking and/or cooking. The vast majority of households and tubewell caretakers agreed to having their water tested. For the assessment of arsenic contamination, we utilized the Hach EZ Arsenic High Range Test Kit, capable of measuring arsenic levels within the range of 0–500 ppb. This low-cost test kit is commonly used in Bangladesh (Fig. 14a). Hach reports that the EZ test can detect 90 percent of arsenic present as arsenate (As(V)) and 100 percent of arsenic present as arsenite (As(III)). However, it's important to note that field performance may be somewhat lower (Steinmaus *et al.*, 2006; Van Geen *et al.*, 2005).

Faecal contamination was detected in **Experiment II** using hydrogen sulphide vials produced by NGO Forum (Fig. 14b). These tests detect hydrogen-producing bacteria, which are almost exclusively organisms that live in the gut of warm blooded animals and therefore indicate human or animal faecal contamination. Gupta *et al.*, (2008) report 88 percent sensitivity and 80 percent specificity to detect *E. coli* contamination in samples from water sources, while Islam *et al.*, (2017) report 83 percent sensitivity and 49 percent specificity in samples of stored drinking water.

We used barcodes to track the samples and sent respondents their test results via automated SMS notifications, ensuring efficient communication of results to participants.

For **Experiments III** and **IV**, we utilized IDEXX Colilert kits to measure both total coliforms and *E. coli* contamination in water samples. The testing process involved the following steps:

- Field staff added Colilert-18 reagent to each sample vessel.
- The sample was then decanted into a Quanti-Tray/2000 testing tray. Each testing tray contained 96 wells, comprising 48 large wells and 48 small wells.
- Field staff made sure not to observe a blue flash when adding reagent to the samples, as this would indicate excessive chlorine in the samples, potentially invalidating the test results (Gregorio, 2010).
- The testing trays were sealed and incubated at 35°C for 18 hours.
- After incubation, field staff counted the number of large and small wells that had turned yellow, as well as the number of wells that were both yellow and fluorescent.
- These counts were then entered into the IDEXX MPN generator software to calculate the Most Probable Number (MPN) of Colony Forming Units (CFU) per ml for both total coliform and E. *coli*, respectively.

When analyzing contamination levels with both total coliforms and E. coli. It's worth noting that a small percentage of observations (5 out of 280, or 1.8%) had total coliform concentrations above the detection limit of 2419.6 CFU/100 ml. In these cases, these observations were coded at the detection limit for analysis purposes.

3.9.1 Measuring arsenic exposure index

To optimize the utilization of arsenic contamination data for ***Paper III*** in Experiment II, we employed an inverse-covariance weighted index approach (Anderson, 2008). This index serves to aggregate information from four distinct variables: i) indicator variables for contamination in

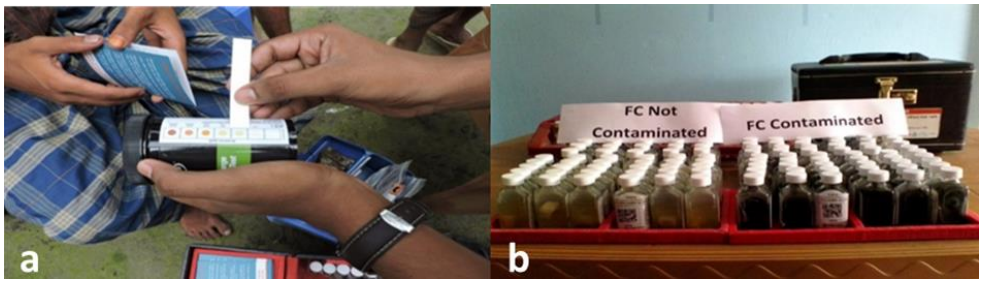

Figure 14: (a) Arsenic test by using the Hach EZ Test Kit, (b) Faecal contamination was detected using hydrogen sulphide vials.

household drinking water at both the WHO and Bangladeshi thresholds and ii) volume-weighted mean contamination at the same thresholds across all water sources from which households collect water for drinking or cooking.

3.9.2 Water quality maps development for visualizing drinking water quality scenario

In **Experiment II**, we created comprehensive community-based water quality maps for each community to visually represent the results of arsenic concentration levels and faecal contamination status (Fig. 15).

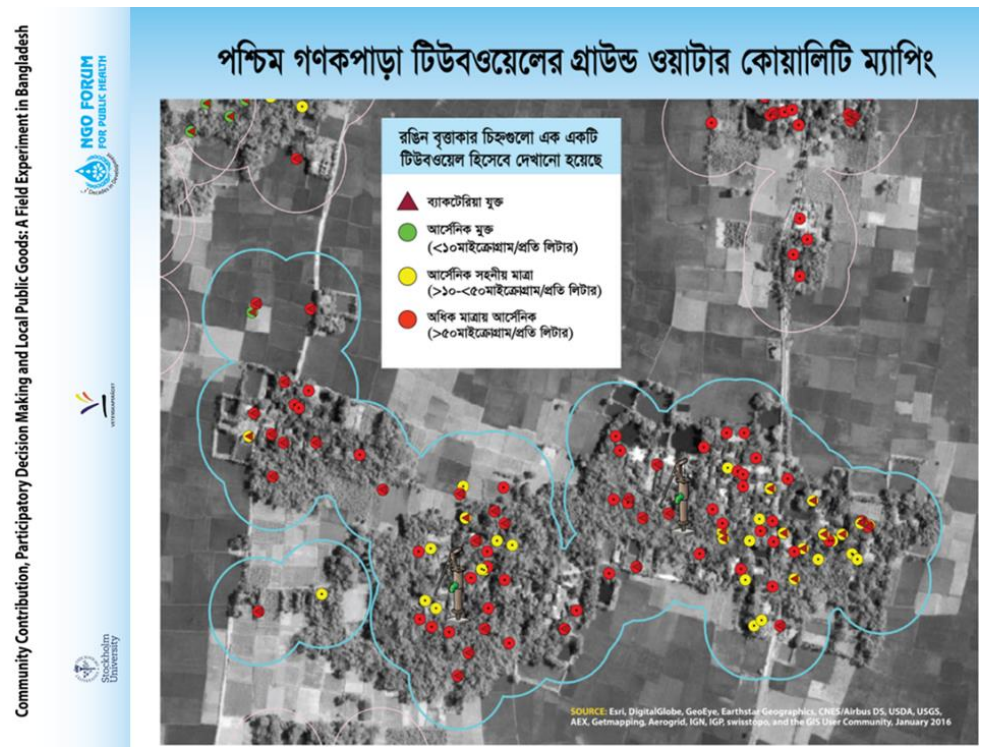

Figure 15: Map of water quality status of all drinking water sources at Paschim Gonakpara, Shibganj, Bogura with arsenic concentration and faecal contamination. As concentration tubewells labelled by < 10 ppb (green circle), >10 to 50 ppb (yellow circle) and >50 ppb (red circle) and faecal contamination labelled by red triangle.

Field staff utilized these maps during community meetings to present the collective information about the community's drinking water sources (Fig. 15). Anecdotal evidence suggested that offering extensive information regarding arsenic contamination may have played a role in limiting elite capture. The provision of information could have acted as a transparency mechanism, making it evident when decisions were unfair and thus helping to prevent capture by ensuring fairness in the decision-making process (Cocciolo *et al.*, 2023).

3.10 Cost-effectiveness analysis

This section outlines how we compile cost data at the community level for ***Papers I*** and ***III*** of the research. In ***Paper I***, we integrate data from various sources, including installation costs, community contributions, project staff travel costs, and utility costs. This comprehensive dataset allows us to estimate potential cost-effectiveness by comparing the effects of three different decision-making approaches. For ***Paper III***, we aggregate data from multiple sources to provide a comprehensive overview of implementation costs in **Experiment II**. These data sources include records of tubewell installation costs, refunds for cash contributions, field staff time allocation for tasks such as community meeting preparation, tubewell installation, pre-and post-installation monitoring, and other NGO project expenses (including overhead costs, office expenses, wages, survey costs, water quality testing, tubewell installation expenses, post-tubewell installation costs, and local travel). To calculate the total implementation costs per community, we follow these principles:

- Costs paid to the contractor for tubewells installed in a specific community are allocated to that community. Implementation costs that are uniform across communities are evenly distributed among them.
- Additional installation costs that vary with the number of attempted tubewells are allocated proportionally to the number of attempted installations in each community.
- Additional installation costs that depend on the number of successfully installed tubewells are distributed proportionally to the number of successfully installed tubewells in each community.
- Staff costs, overheads, and local travel expenses are allocated proportionally based on the share of time spent in each community, as recorded in the activity reports.

Community costs are estimated by utilizing project records and self-reported data to assess the costs incurred at the community level.

3.11 Statistical analysis

3.11.1 Effect of different decision-making process on access to safe drinking water

In ***Paper I***, we determined the treatment effect by using the following equation (Eqn. 1), where treatment is defined as a village being offered access to safe sources of drinking water under one of the three approaches to decision-making. This equation allowed us to quantify the impact of treatment, which involved providing villages with access to safe drinking water sources, while considering the specific decision-making approach that was used to allocate these resources.

$$Y_{it} = \theta_v + \beta_0 POST_t + \sum_{p \epsilon P} \beta_p (I_{p,v} \times POST_t) + Z_{vu}\gamma + \varepsilon_{ivt} \quad \text{(Eqn. 1)}$$

where Y_i is a characteristic measured at time t (baseline or endline) in household i; $I_{treated,v}$ is an indicator which is one if village v received treatment and zero, otherwise; and Z_{vu} is a vector of controls for stratification by upazila u, which consists of a demeaned upazila dummy variable and the interaction term between this variable and the treatment dummy. We construct the vector of controls Z_{vu} to ensure that βt consistently estimates the average difference between treated and control villages. For the indicator variable $I_{p,v}$, which is one if village v received treatment under decision-making process p, and zero otherwise. The subscript t, which denotes the time period,

either baseline or follow-up; $POST_t$ which is a dummy variable that is zero at baseline and one at follow-up; and θ_v, which is a village fixed effect that absorbs baseline differences across villages. We construct controls for upazila-level stratification of assignment to treatment so that each β_p estimates the average treatment effect in the regression sample.

3.11.2 Effects of community participation in decision-making processes in two different contexts

The statistical model in ***Paper II*** diverges from the model in ***Paper I***. We use a simpler model in ***Paper II*** to describe which households use a tubewell in a given location and to investigate how restrictions on elite capture affect the location. Thus, the overall outcome of the consensus-based decision-making process improves outcomes relative to unrestricted decision-making by communities.

In our analysis, we assess outcomes by comparing the results across the three treatment arms, and we also compare each treatment arm individually to the control group. This approach allows us to examine the effects of the different decision-making approaches on various outcomes and to understand how each treatment arm performs in relation to the control group (***Paper III***). The estimating equation (Eqn. 2) is:

$$Y_{ijt} = \alpha_j + \sum_{m \epsilon M} \beta_m (\mathbb{1}_{mj} \times POST_t) + f(Z_j, POST_t) + \epsilon_{ijt} \quad \text{(Eqn. 2)}$$

where Y_{ijt} is an outcome variable in household i in community j at time t, either baseline or endline, and aj is a fixed effect that absorbs mean time-invariant differences across communities. Each indicator variable $\mathbb{1}_{mj}$ takes the value one if community j is assigned to treatment under contribution requirement m from the set $M = \{cash, labour, waiver\}$ and zero otherwise. The indicator $POST_t$ takes the value one at endline and zero at baseline. The function f(Z_j, $POST$) includes the $POST_t$ indicator and stratification controls, centered and interacted with the treatment dummies and the POST indicator (following Gibbons *et al.*, 2019; Imbens and Rubin, 2015; Lin, 2013).

We assessed the average program impacts on changes in household behavior related to obtaining drinking water, the quality of water sources used, the distance households walk to collect water, and whether they store water in the household before consumption. Additionally, we evaluated the impact on the quality of drinking water at the point of use within the household. This analysis is detailed in ***Paper V***. We conducted this assessment using the following equation:

$$\Delta y_{ic} = \alpha + \beta_T T_c + Z_c \gamma + \epsilon_c \quad \text{(Eqn. 3)}$$

Equation 3 allowed us to measure and quantify the program's impact on various aspects of household behavior and water quality, providing insights into the effectiveness of the intervention. Where Δy_{ic} is the change in outcome variable y between baseline and follow-up in household i in community c, T_c is an indicator that takes the value 1 if community c is assigned to treatment and 0 otherwise, and the vector Zc contains stratification controls. The parameter of interest is β_T, which measures the mean difference-in-differences between treatment and control groups. Because T_c is randomly assigned to communities, it is independent of any other determinants of the outcomes of interest, meaning that β_T has a causal interpretation. We cluster standard errors by community to account for correlated changes in outcome variables within communities (Bertrand, Duflo, and Mullainathan 2004).

In ***Paper V***, we utilized the following equation to estimate how changes in source water quality, walking distance, and water storage practices influence the quality of drinking water within households. This estimation was carried out using a difference-in-difference approach (Eqn. 4):

$$\Delta FC_i^h = b_0 + b_1 \Delta FC_i^w + b_2 \Delta DIST_i^w + b_3 \Delta STORAGE_i + \eta_c + \epsilon_i \quad \text{(Eqn. 4)}$$

This equation allowed us to examine how alterations in the quality of source water, changes in the distance households traveled to collect water, and modifications in water storage practices impacted the quality of drinking water within households. The difference-in-difference

methodology helps assess the causal relationship between these variables and the quality of household drinking water. This analysis is elaborated upon in ***Paper V***.

Where, all variables are changes, denoted Δ, between baseline and follow-up. The variable FC^h is faecal contamination in household drinking water and FC^w is mean faecal contamination in water sources used by the household, weighted by volume obtained from each source. The variable $DIST^w$ is the weighted mean distance travelled by the household to collect water from its water source or sources. The variable STORAGE is an indicator variable for whether or not household *i* stores drinking water, as opposed to collecting drinking water on demand. The term η_c denotes a community-level dummy variable that absorbs community mean changes in both the outcome variable and the right-hand-side variables. The coefficients of interest are b_1, b_2 and b_3.

3.11.3 Program's sustainability

In ***Paper IV***, we use locally-linear regression to trace out the probability of survival over time for tubewells installed under a given treatment arm in a given region. The locally-linear regression

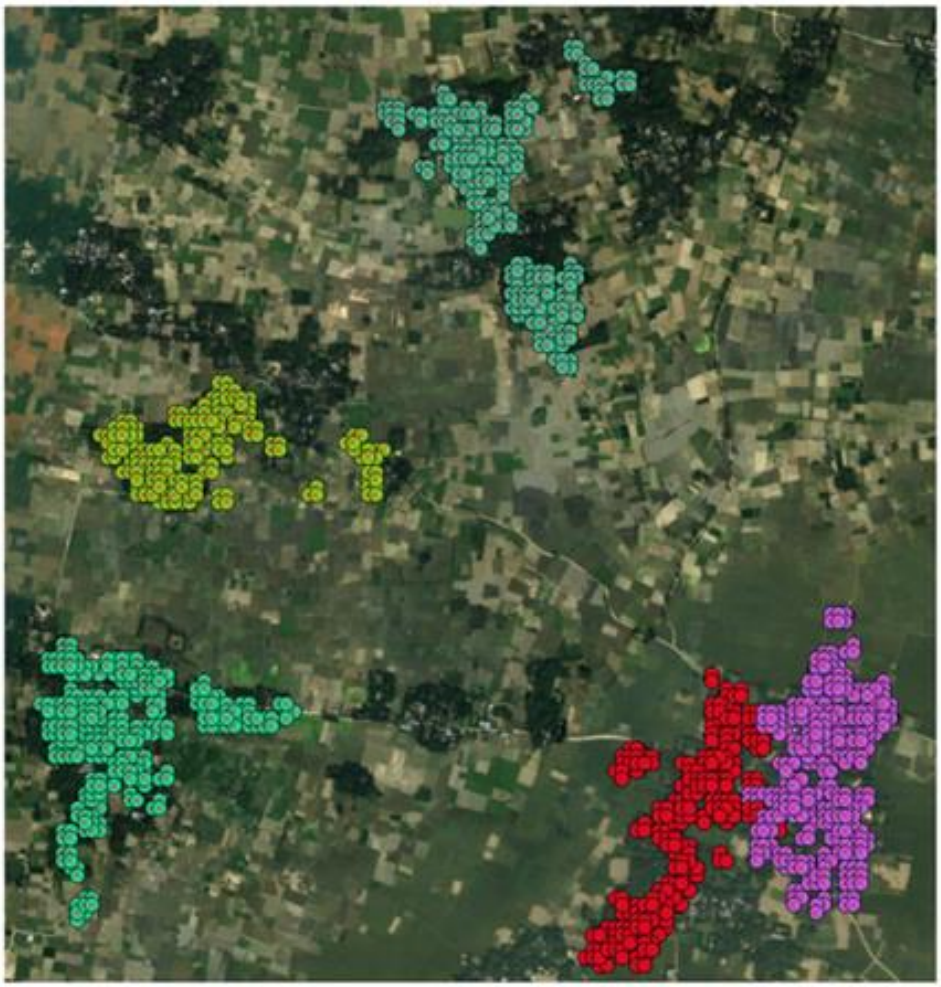

Figure 16: Example of grids for measuring the tubewell location quality.

uses a bandwidth of 1.5 years and the Epanechnikov kernel. We conduct inference using Bayesian bootstrapping with Dirichlet (4,...,4) weights, 1000 replications.

3.11.4 Measuring the faecal contamination effects of cleaning and training

In ***Paper VI***, we conducted a comparison of contamination with total coliforms and *E. coli* for **Experiment III** using regression analysis. In total, there were five observations (N = 280, accounting for 1.8%) with total coliform concentrations exceeding the detection limit of 2419.6 CFU/100 ml. These observations were coded at the detection limit.

For **Experiment IV**, we estimated two statistical models in ***Paper VII***. In the first model, outcome variables were regressed to a dummy variable for each training treatment arm, while in the second model, a dummy variable for receiving any training treatment was used. When dealing with binary outcome variables, such as the presence of contaminants, we utilized linear probability models, which are consistent for fully saturated regression models. In cases where concentration data was analyzed, we employed an arcsinh transformation to mitigate the influence of outliers without excluding zero values. For caretaker survey data analysis, observations were weighted by the inverse of the number of observations per tubewell to ensure that each tubewell had equal weight in the analysis, consistent with tubewell-level analyses. Standard errors were robust (Long *et al.*, 2000) or clustered by tubewell when caretaker survey data was used.

3.12 Mathematical modelling for location quality

In the evaluation of location quality in ***Paper III***, we assess the likelihood of tubewell utilization at various points within a community by employing predictive models. Subsequently, we create metrics for location quality by contrasting the anticipated tubewell utilization at a specific location with the projected utilization across all potential points within the community (Fig. 16). The grid we use to identify potential locations is characterized by a 20-meter resolution. We define a "potentially feasible location" as a point on the grid that falls within a 20-meter radius of a household, a community water source, or a project tubewell.

3.13 Modelling: Simulation on program effect

In ***Paper V***, we used simulations to assess the impact of various take-up patterns on a program designed to provide access to safe drinking water. These simulations aim to explore how an increase in take-up rates could potentially alter the program's effectiveness. Our primary focus is on a straightforward scenario. We start with the observed patterns of take-up and systematically increase the proportion of water that households obtain from project-installed tubewells. It's important to note that we always adhere to a feasibility constraint, ensuring that households do not collect more than 100 percent of their water from a project tubewell. We continue this process until the percentage of a community's water sourced from project tubewells reaches a specified increase factor. This approach is designed to honor the existing adoption patterns evident in the data. Specifically, households located closer to the tubewell and those with higher baseline arsenic contamination tend to collect a greater share of their water from the project-installed tubewell. Subsequently, we simulate the effects of these changes on the use of contaminated water sources and travel distances. Drawing on the estimated effects of the program, we then create models to predict how these changes translate into alterations in the levels of faecal contamination in household drinking water.

3.14 Machine learning

We used machine learning in ***Papers II*** and ***III*** to evaluate heterogeneous treatment effects (***Paper II***) and to study selection: into successfully installing tubewells at the community level and into contributing towards a tubewell and using a tubewell at the household level (***Paper III***).

For ***Paper II***, we adapt the generic machine learning framework of Chernozhukov *et al.* (2020) to evaluate which community-level characteristics most strongly correlate with a higher predicted

impact. We execute the approach through the following steps, applicable to any two groups that we label as the reference group (R) and the comparison group (C). Our primary goal is to make comparisons between the effects of the intervention in two treatment arms that underwent the intervention under different decision-making processes. In this context, we assign one of the treatment arms arbitrarily as R and the other as C. Additionally, we conduct a second analysis where we examine the correlations between the variables related to the decision-making mechanisms and the changes in the use of safe drinking water.

In ***Paper III***, we use machine learning approaches designed to evaluate heterogeneous treatment effects to study selection: into successfully installing tubewells at the community level and into contributing towards a tubewell and using a tubewell at the household level. We follow the same algorithm as Chernozhukov *et al.* (2020). As in Chernozhukov *et al.* (2020), the inputs are data from units of observation $i \in [N] = \{1, ..., N\}$. Units of observation may be communities or households. The vector Z_i contains variables that are either measured at baseline or predetermined, so cannot plausibly be affected by the intervention.

4 Results and Discussion

The results and discussion session are presented in this section according to the specific objectives outlined in section 2.3.

4.1 Effects of participation in decision-making on the impact of access to safe drinking water and program sustainability (Exp. I)

This section presents the comprehensive impact of decision-making on the utilization, outcomes, and long-term sustainability of the drinking water supply program. Here, we present the findings that illustrate how decision-making influences access to safe drinking water and explore how the effects of different decision-making processes vary between the two study regions. Additionally, we aim to provide causal evidence regarding whether participation has an impact on the sustainability of the program.

4.1.1 Impacts of the decision-making approaches on the use of safe drinking water

Paper I focuses on understanding how decision-making affects the usage of safe drinking water, evaluating the impacts of the intervention, and assessing the program's sustainability. To estimate treatment effects, the study employs Ordinary Least Squares (OLS) analysis based on data collected from households at both baseline and follow-up. The study's findings reveal a substantial increase in the proportion of households using safe drinking water between baseline and follow-up in villages that follow the RCP process compared to the other two decision-making approaches. Specifically, the proportion increases by 27 percentage points in RCP villages, by 15 percentage points in CP villages, and by 14 percentage points in TD villages as indicated in Column 1 of Table 4. It's noteworthy that the difference between the RCP approach and the combined effects of the other two decision-making processes, as well as the pairwise differences between RCP and each of the other approaches, are statistically significant at the 5% level. When excluding the treated sample from South Matlab and focusing solely on the group of villages that were randomly assigned to both treatment and a specific approach to decision-making, Column 2 of the table illustrates that the comparisons between decision-making processes remain consistent and similar in terms of outcomes. The control group's use of safe drinking water shows minimal change on average, indicating that the reported treatment effects in columns 3 and 4 closely resemble the changes observed over time in safe drinking water usage, as presented in columns 1 and 2. When excluding South Matlab from the analysis, the comparisons of decision-making processes exhibit remarkable similarity, although the pairwise comparison between the RCP and CP approaches does not reach statistical significance at the 10% level ($p = 0.103$) when South Matlab is excluded and control villages are included.

Table 4: Impact on use of safe drinking water by approach to decision-making.

	Reported use of safe drinking water			
	(1)	**(2)**	**(3)**	**(4)**
TD	0.14***	0.12***	0.12**	0.15***
	(0.04)	(0.05)	(0.05)	(0.04)
CP	0.15***	0.14***	0.15***	0.15***
	(0.04)	(0.04)	(0.04)	(0.04)
RCP	0.27***	0.27***	0.25***	0.27***
	(0.04)	(0.05)	(0.05)	(0.05)
Average change in control group			-0.01	-0.01
			(0.02)	(0.02)
RCP vs CP	0.032**	0.039**	0.103	0.038**
CP vs TD	0.941	0.743	0.583	0.926
TD vs RCP	0.028**	0.026**	0.041**	0.032**
TD vs pooled	0.179	0.136	0.136	0.185
CP vs pooled	0.216	0.297	0.519	0.239
RCP vs pooled	0.014**	0.016**	0.037**	0.017**
N	8206	6022	12551	14735
Includes South Matlab	Yes	No	No	Yes
Includes control group	No	No	Yes	Yes

Note: Table shows estimated change in reported use of safe drinking water. Data are at household level with two periods, weighted so that each village counts equally in summary statistics. All estimates absorb village fixed effects and control for upazila-level stratification. Standard errors, clustered by village, are shown in parentheses. Reported p values test: i) significance of the difference between the estimated effects in each decision-making process pair; and ii) significance of the difference between the estimated effect under one decision-making process and the remainder of the treated villages. ***p <0.01, **p <0.05, *p < 0.1.

The similarity between the estimates in columns 3 and 4 implies that the assumptions necessary for obtaining unbiased estimates using Ordinary Least Squares (OLS) in the sample including South Matlab and control villages are met. The RCP approach outperforms the other two decision-making approaches in a stochastic sense. The cumulative density function (CDF) of the mean change in the use of safe water sources in each village under the RCP approach consistently lies to the right of the CDF for the TD and CP approaches across the entire distribution (Fig. 17). The RCP approach exhibits a clear stochastic dominance over the other two decision-making approaches. In the CDF representing the mean change in the use of safe water sources in each village under the RCP approach, it consistently occupies a position to the right of the CDF for both the TD and CP approaches across the entire range of the distribution (Fig. 17).

The RCP approach leads to an increase in the use of safe water compared to the other two approaches, even though communities install a similar number of tubewells under all three decision-making processes, as indicated in Table 5, Panel A. Households that already have their own tubewells at both baseline and follow-up report an increase in the number of users under the RCP approach, while they experience a decline in the number of users under the TD and CP approaches, as shown in the last row of Panel E in Table 5. Additionally, households that do not utilize tubewells installed by the project tend to switch to other safe tubewells at higher rates in

RCP villages compared to TD and CP villages, as demonstrated in Table 5, the fifth row of Panel E. It's worth noting that the top-down process installed a significantly higher percentage of tubewells on public land than either of the participatory approaches, as presented in Table 5, the first row of Panel B.

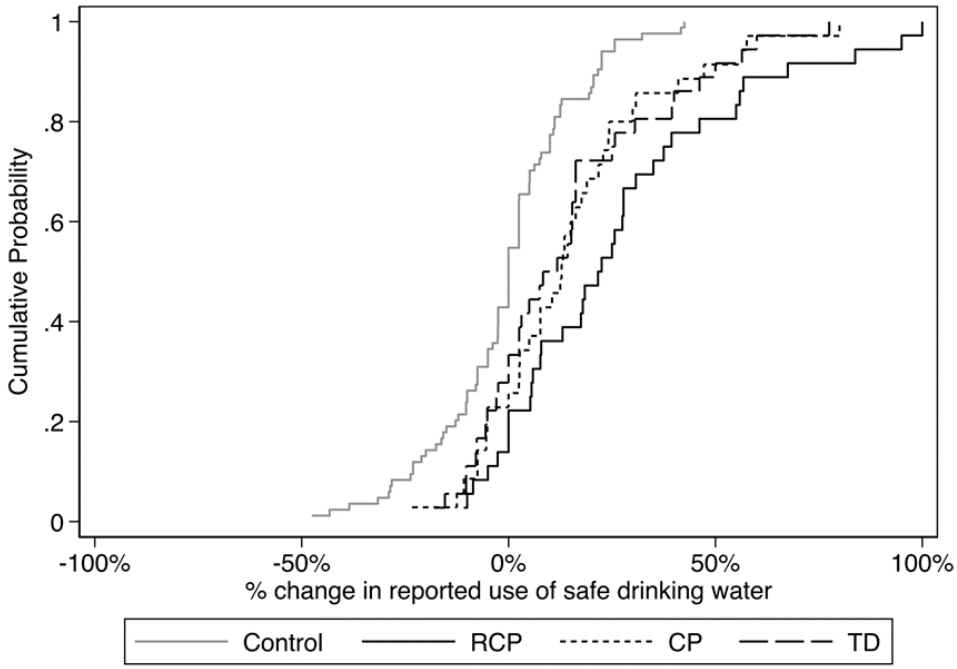

Figure 17: Empirical cumulative distribution functions (CDF) Change in reported use of safe drinking water. (CDF Corresponds to mean change in reported use of safe drinking water in each village in the main sample).

Simultaneously, communities, under the RCP process, selected more convenient tubewell locations, placing them approximately 25% closer to households on average, as shown in Table 5, the second row of Panel B. They also reduced the distance to the nearest safe tubewell by twice as much, as indicated in the third row of Panel B.

One notable distinction between the RCP and CP approaches seems to be that community elites may have a reduced role in determining tubewell locations under the RCP approach compared to the CP approach. Alternatively, as suggested by our model, the RCP process might encourage self-interested elites to make more altruistic decisions. An indication of a smaller group of individuals controlling the location and access to tubewells in CP villages is that, on average, the mean number of contributors per tubewell installed by the project is the lowest in CP villages. Insights from Focus Group Discussions (FGDs) reveal that participants in CP villages reported that a select few influential individuals, often men or village leaders, were responsible for deciding on tubewell installations and financial contributions. In contrast, FGDs conducted in RCP villages indicate that participants engaged in active negotiations during large meetings to reach agreements necessary to meet the unanimity rule. FGDs in CP villages reported that influential individuals installed tubewells on their own land and restricted access to others. In contrast, FGDs in RCP villages did not report restrictions on access to installed tubewells, and participants mentioned that they were careful to place tubewells on land owned by individuals who were trusted to allow broad access.

The increase in the use of private tubewells in RCP villages suggests that households in RCP villages transition to safe water sources not only due to the convenience and accessibility of project tubewells but also because communities in RCP villages may renegotiate access to both existing and new private safe tubewells to facilitate agreements regarding the new project tubewells.

Table 5: Explaining differences between impacts of the three approaches to decision-making.

	TD	CP	RCP		*p* values
Panel A: Safe water sources installed					
Number of water sources installed per village	2.36	2.53	2.47	RCP = CP	0.769
	(0.16)	(0.14)	(0.12)	CP = TD	0.432
		N=108		TD = RCP	0.581
Proportion of offered water sources installed per village	0.81	0.87	0.85	RCP = CP	0.765
	(0.05)	(0.05)	(0.04)	CP = TD	0.432
		N=108		TD = RCP	0.575
Panel B: Location of installed water sources					
Fraction of sources built in public places per village	0.58	0.29	0.39	RCP = CP	0.174
	(0.06)	(0.05)	(0.06)	CP = TD	<0.001***
		N=96		TD = RCP	0.032**
Distance between household and nearest project source (minutes)	8.62	10.12	6.54	RCP = CP	<0.001***
	(1.12)	(0.92)	(0.48)	CP = TD	0.305
		N=3832		TD = RCP	0.091*
Change in distance to household's nearest safe source (minutes)	-3.35	-5.48	-6.79	RCP = CP	0.389
	(0.78)	(1-01)	(1.14)	CP = TD	0.098*
		N=3630		TD = RCP	0.014**
Change in distance to household's main source (minutes)	-0.33	-0.25	-0.08	RCP = CP	0-610
	(0.20)	(0.26)	(0.19)	CP = TD	0.793
		N=3972		TD = RCP	0.366
Panel C: Contributions					
Number of contributing households per village	10.31	6.10	10.85	RCP = CP	0.023**
	(1.80)	(1.02)	(1.78)	CP = TD	0.045**
		N=107		TD = RCP	0.833
Fraction of villages with one household paying contribution per tubewell	0.45	0.52	0.33	RCP = CP	0.088*
	(0.07)	(0.08)	(0.08)	CF = TD	0.491
		N=102		TD = RCP	0.258
Relative log total assets (contributing households)	0.09	0.08	0.20	RCP = CP	0.276
	(0.08)	(0.06)	(0.09)	CP = TD	0.973
		N=305		TD = RCP	0.349
Relative connectedness to local leaders (contributing households)	-0.04	0.10	0.05	RCP = CP	0.495
	(0.04)	(0.06)	(0.05)	CP = TD	0.049**
		N=308		TD = HCP	0.184
Relative kin connectedness to local leaders (contributing households)	-0.04	0.09	0.01	RCP = CP	0.288
	(0.04)	(0.06)	(0.04)	CP = TD	0.080*
		N=308		TD = RCP	0.405
Panel D: Self-reported project evaluation					
Household agreed with decisions taken	0.78	0.70	0.75	RCP = CP	0.221
	(0.03)	(0.03)	(0.02)	CP = TD	0.079*
		N=3815		TD = RCP	0.493
Household felt that decision-making process was fair	0.89	0.84	0.86	RCP = CP	0.329
	(0.01)	(0.02)	(0.01)	CP = TD	0.013**
		N=3775		TD = RCP	0.108
Household reported that decision-making process favored influential individuals	0.07	0.14	0.12	RCP = CP	0.272
	(0.01)	(0.02)	(0.01)	CP = TD	<0.001***
		N=3830		TD = RCP	0.004***
Household reported safe sources to be hard to access due to installation on private land	0.08	0.09	0.08	RCP = CP	0.794
	(0.01)	(0.01)	(0.01)	CP = TD	0.496
		N=4098		TD = RCP	0.645
Household reported access to project sources to be restricted by landowner	0.01	0.02	0.02	RCP = CP	0.846
	(0.003)	(0.008)	(0.005)	CP = TD	0.268
		N=4092		TD = RCP	0.170
Household reported safe sources too far from house	0.60	0.61	0.53	RCP = CP	0.127
	(0.04)	(0.04)	(0.04)	CP = TD	0.823
		N=4075		TD = RCP	0.203

Table 5 (Contd.)

	TD	CP	RCP		*p* values
Panel E: Use of tubewells installed by the project and other sources					
Fraction of households using project source	0.27	0.24	0.29	RCP = CP	0.306
	(0.04)	(0.04)	(0.04)	CP = TD	0.591
		N=4057		TD = RCP	0.654
Change in reported use of safe drinking water, households using project source	0.49	0.54	0.58	RCP = CP	0.735
	(0.07)	(0.07)	(0.06)	CP = TD	0.613
		N=1041		TD = RCP	0.360
Change in reported use of safe drinking water, households not using project source	0.03	0.03	0.10	RCP = CP	0.104
	(0.03)	(0.02)	(0.04)	CP = TD	0.927
		N=2900		TD = RCP	0.117
Change in no, of households using tubewell owned by reporting household (tubewell owners only)	-0.74	-1.11	0.64	RCP = CP	0.038**
	(0.54)	(0.75)	(0.35)	CP = TD	0.691
		N=439		TD = RCP	0.035**

Note: Outcome variables listed as. Reported coefficients reflect regression-estimated mean values in villages treated under the listed decision-making process. Data are from project records (Panel A; row 1 of Panel B; and Panel C) or household surveys. When the household is the unit of analysis, weights are applied so that each village counts equally in the analysis. Regressions control for upazila-level stratification. The number of observations enumerates non-missing observations in each analysis. Standard errors, robust or clustered by village, are shown in parentheses. In Panel C, "relative" means that variables are constructed by first demeaning with respect to village-level averages. Reported p values test significance of the pairwise difference between mean outcomes in each decision-making process pair. $***p < 0.01$ $**p < 0.05$, $* p < 0.1$.

4.1.2 Heterogeneity of RCP effects on programs

This section evaluates whether the absolute and relative effects of the decision-making processes vary in the two study regions. These analyses in ***Paper II*** underscore the significant heterogeneity in the program's impact, particularly under the RCP process. The RCP process notably increases the proportion of households using safe water to a much greater extent compared to the other two processes, particularly in Gopalganj. Specifically, in Column 1 of Table 6, it is reported that in Gopalganj, treatment under the RCP process raises the proportion of households using safe water by a substantial 42 percentage points. In contrast, treatment under the CP process increases this proportion by 19 percentage points, and treatment under the TD process increases it by 21 percentage points. In Gopalganj, the difference between the RCP process and the combined effects of the other two processes, as well as the pairwise differences between the RCP process and the other two processes, are statistically significant. However, the difference between the effects of the CP and TD processes is not statistically significant. The empirical cumulative distribution functions for the three processes in each region further confirm that the RCP process clearly outperforms the others in Gopalganj (Fig. 18).

In Matlab, as shown in column 2 of Table 6, the three processes yield more similar results. While treatment under the RCP process still has the most significant impact on the use of safe water in Matlab, the increase in the proportion of households using safe water is very comparable across all three processes. Specifically, under the RCP process, this proportion increases by 14 percentage points, under the CP process it increases by 12 percentage points, and under the TD process, it increases by 10 percentage points (as reported in column 2 of Table 6). Notably, none of the differences between these processes are statistically significant in Matlab.

These findings contribute to a better understanding of why studies examining participation in decision-making often reveal such substantial variations in their effects. However, it's worth noting that there are statistically significant differences when comparing the treatment effects between the RCP process and the other two processes combined in Gopalganj compared to Matlab. Similarly, the null hypothesis is rejected when comparing the pairwise difference between the RCP and CP processes in Gopalganj and Matlab. The *p*-value for the comparison of the differences between the RCP and TD processes in the two regions falls just outside the range of statistical significance (p=0.147).

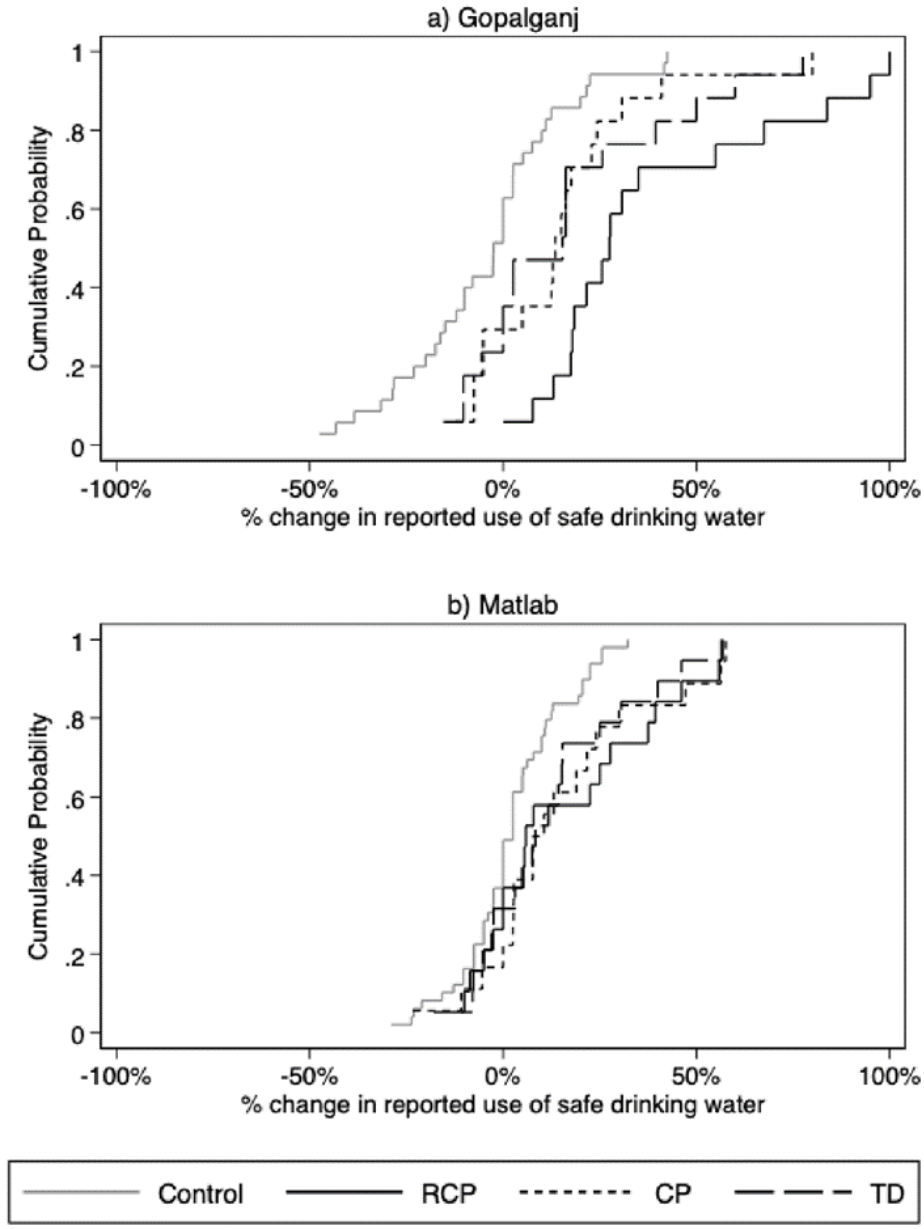

Figure 18: Change in reported use of safe drinking water in Gopalganj and Matlab Upazilas. Empirical cumulative distribution functions of the village mean change in the reported use of safe drinking water for villages in which tubewells were feasible and matched control villages in each study region as indicated.

Table 6: Heterogenicity of program impacts by Upazilas.

	Gopalganj (1)	**Matlab (2)**		***p* value**
TD	0.21***	0.10**	$TD_G = TD_M$	0.238
	(0.08)	(0.05)		
CP	0.19***	0.12**	$CP_G = CP_M$	0.433
	(0.07)	(0.06)		
RCP	0.42***	0.14**	$RCP_G = RCP_M$	0.005***
	(0.09)	(0.06)		
Average change in control group	-0.04	0.02		
	(0.04)	(0.02)		
RCP vs CP	0.017**	0.886	$RC_G - RCP_M = CP_G - CP_M$	0.073*
CP vs TD	0.858	0.748	$CP_G - CP_M = TD_G - TD_M$	0.732
TD vs RCP	0.037**	0.634	$TD_G - TD_M = RCP_G - RCP_M$	0.147
TD vs pooled	0.235	0.632	$TD_G - pooled_G = TD_M - pooled_M$	0.489
CP vs pooled	0.113	0.925	$CP_G - pooled_G = CP_M - pooled_M$	0.199
RCP vs pooled	0.012**	0.722	$RCP_G - pooled_G = RCP_M - pooled_M$	0.067*

Note: This table shows the estimated impact on the use of safe drinking water under each of the three decision-making processes in each upazila. Data are collapsed to village-level means, and robust standard errors are in parentheses. Reported values are derived from a fully saturated regression on indicators of treatment under each decision-making process and their interactions with an indicator for Gopalganj. Regressions include 107 villages in which tubewells are feasible and 84 matched control villages. In columns 1 and 2, p values for the following tests are reported: i) the significance of the pairwise difference between the means in each decision-making process pair; and ii) the significance of the difference between means under one decision-making process and for the remainder of the treated villages. *** p <0.01, ** p <0.05, * p <0.1.

Additionally, the performance of the CP process is better than the TD process in Matlab but worse than the TD process in Gopalganj. These differences are small and not statistically significant. All p values are given in Table 6.

4.1.3 Heterogeneity in effects of decision-making processes

Machine learning is used to identify the baseline characteristics and mechanisms that correlate most strongly with impact. In order to address these questions, machine learning techniques are utilized to explore the variability in effects within a randomized field experiment. Figure 19 shows the predicted changes in the use of safe drinking water in quartiles defined by the heterogeneity score. We estimate significant heterogeneity under the RCP process, a modest amount of heterogeneity under the TD process, and very little heterogeneity under the CP process (***Paper II***). Statistically, we reject the null hypothesis that there is no heterogeneity with respect to the mechanism variables we consider only for the RCP process. Again, detecting little heterogeneity can mean that there is limited heterogeneity but it can also mean that the variables we use to describe mechanisms are not good predictors of impact or that we have limited statistical power to detect heterogeneity.

For the differences between the RCP and CP processes, we can identify the characteristics that most strongly differ between the least affected quartile the group for which outcomes are most similar between the two decision-making processes and the most affected quartile the group for which the RCP process results in the greatest increase in impact (Table 7). For the RCP process, the use of safe drinking water in the most impacted quartile increases by 50 percentage points but

by only 6 percentage points in the least impacted quartile. The mechanisms that are most strongly associated with the magnitude of the change in the use of safe drinking water fall into two categories (Table 8). First, larger changes in use are associated with greater reductions in the distance to the nearest safe well and greater changes in the use of safe drinking water among well adopters. One potential interpretation of these differences is that the RCP process results in better targeting when it is most effective. Second, larger changes in the use of safe drinking water are associated with better decisions and lower levels of elite capture: households report that they agree with decisions and that decision-making was fair at higher rates in higher-impact quartiles, and they are less likely to report that decisions favored influential people or that wells on private land were hard to access. This latter group of differences suggests that, when the RCP process works well, it yields decisions that are fair and equitable, and vice versa.

For the TD process, greater changes in the use of safe drinking water among tubewell adopters are also associated with greater changes in the use of safe drinking water in the community more generally (Table 9). As for the RCP process, this pattern has several potential interpretations. One interpretation that is consistent with other results is that this pattern reflects the problems with information under the TD process. When the TD process works poorly, it does not apparently successfully target those most in need, possibly as a consequence of the inefficient strategies to which field staff resort in the absence of other effective ways to reduce elite capture, such as locating the well on public land even when this results in the well being inconvenient to access or distant from those most in need of access to safe drinking water.

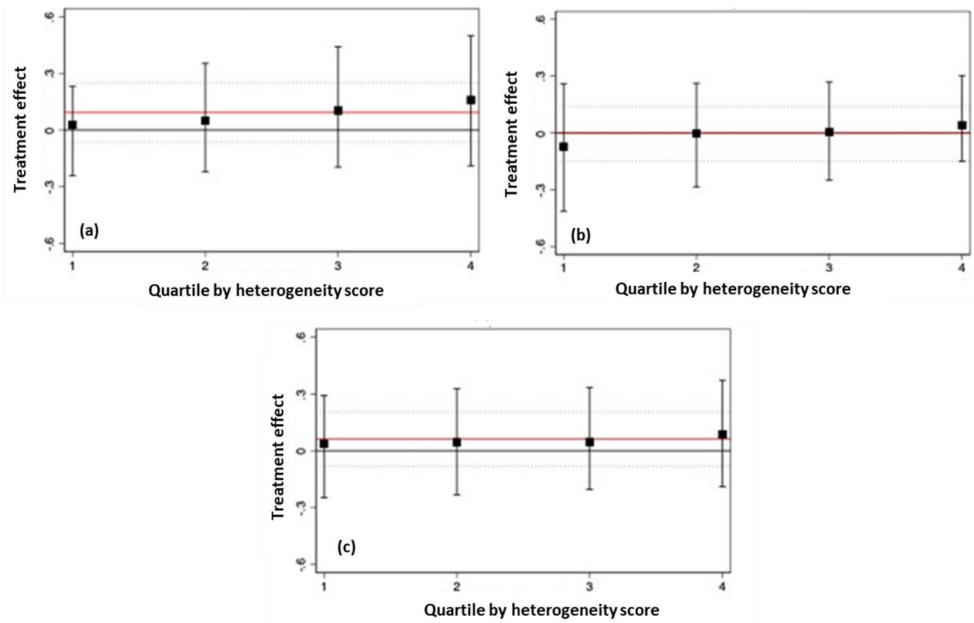

Figure 19: Heterogeneity in impacts of decision-making processes. a) RCP vs CP; b) CP vs TD and c) RCP vs TD. The estimated Group Average Differential Treatment Effect for quartiles defined by the heterogeneity score. The x-axis shows quartiles defined by the predicted heterogeneity score. The y-axis shows the estimated differential effect of treatment under the decision-making process listed first compared to the decision-making process listed second. The average differential treatment effect is shown in red.

Table 7 : Characteristics that correlate with a greater impact of the RCP process vs the CP process.

	25% Least	**25% Most**	**Difference**
Baseline reported use of safe drinking water	0.65 (0.42, 0.87)	0.20 (0.06, 0.36)	−0.46 (-0.71, -0.19) [0.002]
Share switching from As-contaminated wells, last 5 years	0.58 (0.36, 0.81)	0.18 (0.04, 0.35)	−0.41 (-0.67, -0.14) [0.007]
Distance to safe drinking water (minutes)	6.99 (3.99, 10.14)	20.32 (12.22, 27.77)	12.92 (5.03, 21.08) [0.006]
Distance to market (hours)	18.22 (11.63, 25.74)	38.67 (21.07, 56.20)	19.44 (0.94, 38.78) [0.079]
Average share of village related	0.05 (0.03, 0.07)	0.14 (0.07, 0.21)	0.09 (0.01, 0.17) [0.050]
Mean no. of community associations participated in	1.17 (1.03, 1.32)	0.91 (0.69, 1.09)	−0.28 (-0.53, -0.03) [0.051]
Mean no. of collective actions, total	1.41 (0.93, 1.83)	0.47 (-0.00, 1.05)	−0.98 (-1.63, -0.30) [0.012]
Mean no. of collective actions participated in	0.69 (0.41, 0.96)	0.23 (-0.01, 0.51)	−0.43 (-0.86, -0.02) [0.040]
Share participating in community decision-making	0.74 (0.62, 0.87)	0.50 (0.35, 0.64)	−0.26 (-0.45, -0.06) [0.018]
Any conflicts	0.22 (-0.08, 0.52)	0.67 (0.33, 1.01)	0.56 (0.14, 0.91) [0.021]
Leader selection is wealth-based	0.89 (0.66, 1.12)	0.44 (0.09, 0.80)	−0.44 (-0.80, -0.02) [0.080]
Mean share of leaders seeking input from many	0.65 (0.59, 0.70)	0.76 (0.69, 0.82)	0.11 (0.01, 0.20) [0.061]
Share poor or very poor (self-reported)	0.31 (0.21, 0.43)	0.44 (0.33, 0.55)	0.14 (-0.01, 0.28) [0.081]

Note: This table shows the mean value of the listed characteristic for the quartiles with i) the smallest (or most negative) differential treatment effect of the decision-making process listed first compared to the decision-making process listed second and ii) the greatest (or most positive) differential treatment effect of the decision-making process listed first compared to the decision-making process listed second, and the difference in mean values between the two quartiles. Only characteristics for which the least and most affected quartiles differ significantly ($p < 0.1$) are shown.

Table 8: Mechanism characteristics that correlate with a greater impact of the RCP process.

	25% Least	25% Most	Difference
Mean change in distance to nearest safe tubewell	-1.06 (-2.75, 0.57)	-22.05 (-36.14, -6.21)	-21.06 (-35.79, -5.04) [0.025]
Share agreeing with project decisions	0.66 (0.50, 0.80)	0.88 (0.71, 1.01)	0.22 (0.00, 0.44) [0.093]
Share viewing project decision-making as fair	0.74 (0.52, 0.93)	0.98 (0.95, 1.01)	0.21 (0.03, 0.46) [0.051]
Share reporting decisions favored influential people	0.22 (0.06, 0.41)	0.03 (-0.01, 0.08)	-0.19 (-0.39, -0.02) [0.059]
Share reporting tubewells hard to access, as they are on private land	0.13 (0.05, 0.21)	0.03 (-0.00. 0.07)	-0.09 (-0.19, -0.01) [0.072]
Change in use of safe drinking water, users	0.25 (-0.03, 0.59)	0.91 (0.67, 1.03)	0.66 (0.30, 1.00) [0.002]

Note: These tables show the mean value of the listed characteristic for the quartiles with i) the smallest (or most negative) predicted change in the use of safe drinking water and ii) the greatest (or most positive) predicted change in the use of safe drinking water, and the difference in the mean values between the two quartiles. Only characteristics for which the least and most affected quartiles differ significantly ($p< 0.1$) are shown.

For the CP process, for which we detected little heterogeneity, the classification analysis does not identify any mechanisms that are associated with predicted changes in use.

The results confirm that significant heterogeneity under the RCP process, a modest amount of heterogeneity under the TD process, and very little heterogeneity under the CP process.

4.1.4 Effect of decision-making on program sustainability

In this section, the impact of decision-making on the long-term sustainability of the program is summarized using data from the assessment of tubewells installed over fifteen years under two decision-making processes: Top-down and Regulated Community Participation or Consensus processes (***Paper IV***). The proportion of functional tubewells after this period drops to just over half, at 53% (Fig. 20), as we do not yet know the final lifetime of the remaining functional tubewells. This average also conceals significant variability, with a substantial portion of tubewells (about one

Table 9: Mechanism characteristics that correlate with a greater impact of the TD process.

	25% Least	25% Most	Difference
Change in use of safe drinking water, users	0.27 (-0.03, 0.59)	0.80 (0.55, 1.02)	0.54 (0.13, 0.91) [0.029]

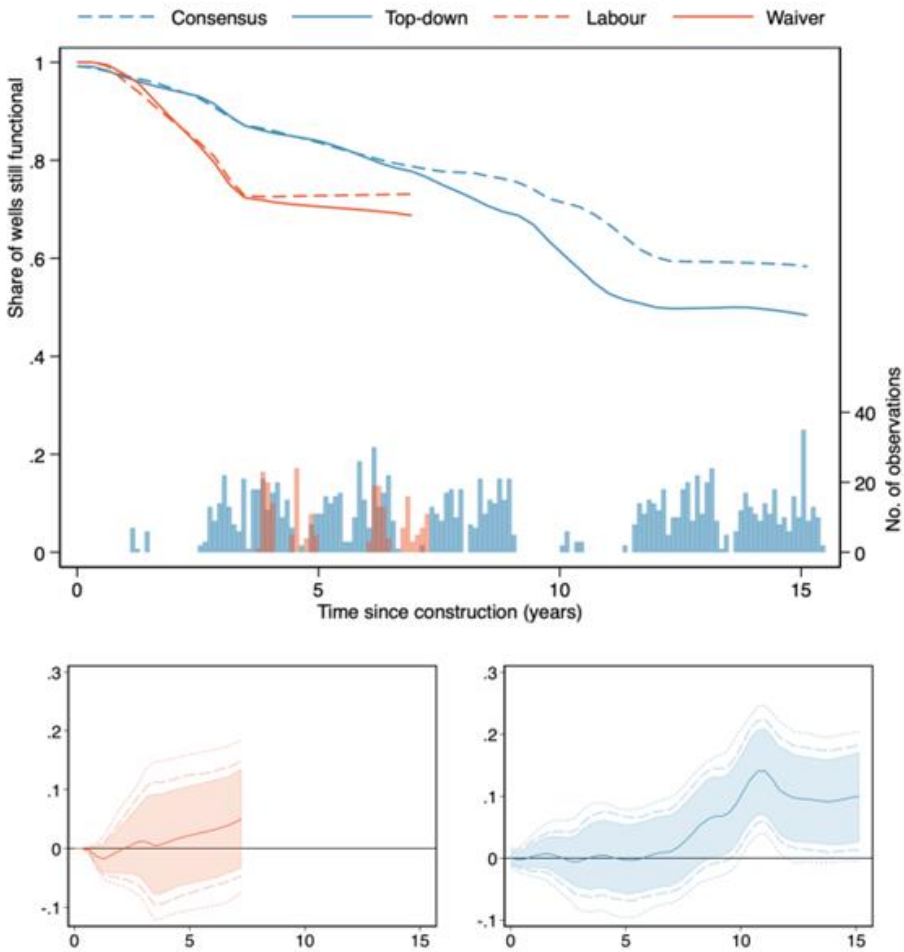

***Figure 20**: Main panel showing estimated share of tubewells which are functional with respect to years since installation by experimental status. Decision-making experiment is shown in orange, contributions experiment is shown in blue. More participatory approaches are shown with dashed lines. Estimates obtained from a locally-linear regression (bandwidth 1.5 years). Histogram plots timing of tubewell condition observations relative to construction date. Subpanels show estimated treatment effects of increased community participation obtained from difference between regression-fit lines in main panel. Bayesian-bootstrapped confidence intervals using Dirichlet weights shown: 90% interval shaded, 95% and 99% intervals shown in dashed lines.*

in five) failing quickly, within five years of installation. Although there are some regional differences, they are relatively small when compared to the overall trend over time. In ***Paper IV***, it becomes evident that the consensus-based approach outperforms the top-down approach to decision-making, with the two curves clearly diverging after approximately nine to ten years from installation. The area under the curve indicates an additional 0.7 years of functional life for each tubewell installed under the consensus-based approach compared to the top-down approach, representing roughly a 6% increase in the lifespan of tubewells up to that point.

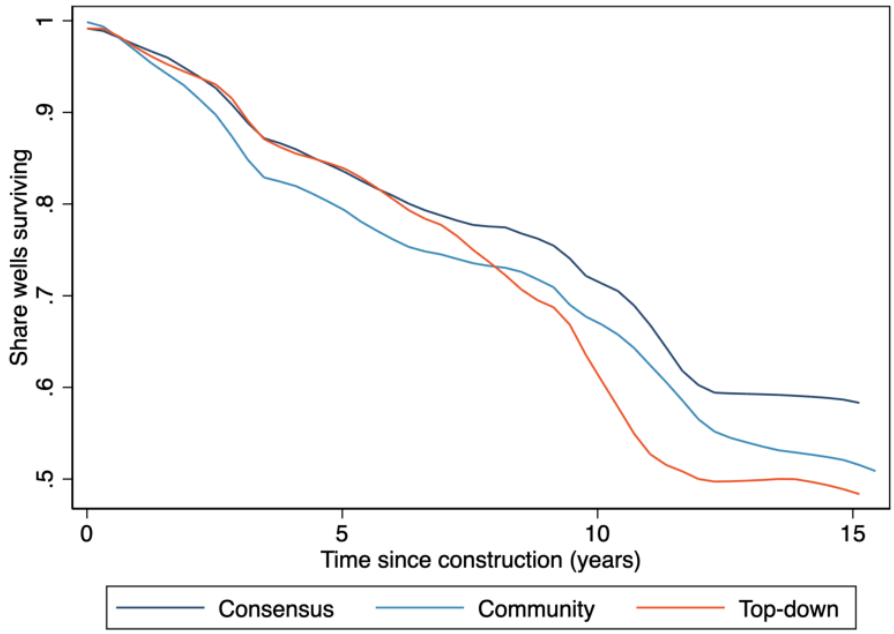

Figure 21: Graph shows the estimated share of tubewells still functional with respect to years since installation by treatment arm under the decision-making experiment.

Consequently, when considering all these results together, it suggests that the net impact of consensus-based decision-making can increase the sustainability. The decision-making approach that involves more participation tends to result in higher sustainability compared to the less participatory approach. Additionally, sustainability is also higher when communities make decisions without imposed rules compared to the top-down approach after a period of ten to fifteen years. However, the differences in sustainability between these two approaches become less pronounced over time (Fig. 21).

4.2 Effects of community contributions in cash or labour to provide safe drinking water (Exp. II)

In this section, the results are presented regarding the effects of various contributions on the program when implemented under a consensus-based decision-making approach, which is designed based on the Regulated Community Participation (RCP) process in **Experiment I**. The results and discussions primarily center around the impact of contributions on the average effects on program costs and benefits, as well as the distribution of costs and benefits, to gain a better understanding of who benefits from the intervention and who bears the costs. The analysis includes comparisons between communities that successfully install tubewells and those that do not, and between households that use a project tubewell and those who do not, and finally, the effect of contributions on program sustainability.

4.2.1 Effects on average program impact under different contributions

In the contributions experiment, a total of 107 arsenic-free tubewells were installed. The average impact of the program on exposure to arsenic contamination under each of the three treatment arms is presented in Table 10 (panel a). Compared to the control group, exposure to arsenic only decreases in the labor and waiver treatment arms.

Table 10: Impact on access to safe drinking water.

	Control Mean (1)	Estimated impact Cash (2)	Labour (3)	Waiver (4)	C=W (6)	L=W (7)	C=L (7)	N (8)
a. Changes in exposure to arsenic contamination								
Arsenic exposure index	-0.10	0.02	-0.10*	-0.11**	0.016	>0.999	0.022	13617
	(0.02)	(0.03)	(0.04)	(0.04)				
Household drinking water (WHO)	-0.10	0.01	-0.05	-0.03	0.094	0.432	0.076	13560
	(0.02)	(0.02)	(0.03)	(0.02)				
Household drinking water (BGD)	-0.02	0.02	-0.01	-0.04	0.052	0.460	0.114	13560
	(0.01)	(0.02)	(0.02)	(0.02)				
Water source (WHO)	-0.07	-0.02	-0.10**	-0.06**	0.240	0.278	0.070	13476
	(0.02)	(0.03)	(0.03)	(0.02)				
Water source (BGD)	-0.01	0.00	-0.02	-0.07**	0.012	0.184	0.340	13474
	(0.02)	(0.02)	(0.02)	(0.02)				
b. Use of project tubewells								
Share of households	0.00	0.07**	0.20***	0.22***	<0.001	0.598	<0.001	7094
	()	(0.02)	(0.20)	(0.03)				
Share of water	0.00	0.03**	0.08***	0.09***	<0.001	0.624	<0.001	7094
	(-)	(0.01)	(0.01)	(0.01)				

Notes: Table reports program impact relative to control group in panel a) and mean values in panel b). Clustered standard errors are in parentheses. In panel a), regression includes baseline and follow-up data, all randomly-sampled households, and community fixed effects. In panel b), regression includes follow-up data only. Significance levels obtained from randomization-based inference with stratification controls. Asterisks reflect significance of impacts with respect to the control group: *** p <0.01, p <0.05, * p <0.1.

Exposure to arsenic contamination shows a decrease of 0.11 standard deviations (s.d.s) when the program is implemented under the contribution waiver, with a 90% confidence interval ranging from -0.18 to -0.04. Similarly, under the labor contribution requirement, exposure to arsenic falls by a statistically indistinguishable 0.10 s.d.s, with a 90% confidence interval of -0.17 to -0.03. In both cases, the estimated impact on arsenic contamination is negative, when considering all four measures combined in the index, although not all declines in individual components are statistically significant. The estimated impact of treatment in the cash treatment arm shows a positive value for the index (0.02 s.d.s). However, the 90% confidence interval does not rule out small relative declines in arsenic contamination, ranging from -0.03 to 0.07. When conducting pairwise comparisons between treatment arms, the null hypothesis is rejected for the comparison between cash and either of the other treatment arms, indicating that the impacts on the arsenic exposure index are not the same for the cash treatment arm compared to either the labor (p = 0.022) or waiver (p = 0.016) treatment arms. Furthermore, the null hypothesis is also rejected for equal effects of the cash contribution arm compared to the waiver treatment arm, at least at the 10% significance level, for three of the four individual measures of arsenic contamination, and for the labor treatment arm, for two of the four measures. However, the impacts are very similar in the labor and waiver treatment arms for the index and for all individual measure of arsenic contamination, and in this case, the null hypothesis of equal effects is not rejected.

The effects on arsenic contamination, as measured in water sources, tend to be larger than the effects measured in household drinking water. When water is stored before drinking, measuring arsenic in household drinking water may underestimate exposure to arsenic contamination due to passive removal. Passive removal is a process in which arsenic oxidizes and precipitates out of water (Ahmed, 2001; Roberts *et al.*, 2004). Passive removal doesn't necessarily eliminate arsenic from the food chain, but it causes arsenic to accumulate in sediments within the storage vessel rather than remaining in the stored water, making it less likely to be detected by water quality tests. Alternative measures of project impact also follow a similar pattern, with larger and statistically

indistinguishable impacts under the labor and waiver treatment arms and smaller impacts under the cash treatment arm. Two alternative measures considered are the fraction of households using at least one project tubewell and the volumetric share of water collected from project (panel b, Table 10). For both of these measures, the null hypothesis is rejected when comparing the cash treatment arm to either of the other two treatment arms. However, the null hypothesis is not rejected when comparing the labor and waiver treatment arms. It's worth noting that both the estimated impacts and the differences between treatment arms could be influenced by spatial spillovers if households used tubewells installed in other communities.

4.2.2 Explaining the differences in impact on arsenic exposure across treatment arms

To understand the differences in impact across treatment groups (cash, labor, waiver, and control), it's valuable to examine the comparisons of tubewell use across these treatment arms. These comparisons are useful because they allow us to break down tubewell use into five multiplicative components. This decomposition helps quantify the extent to which each component contributes to tubewell use and explains the variations between treatment arms. The five components that make up this decomposition are *Geography, Location quality, Community take-up, Geology* and *Household take-up*. All five components independently have predictive power in explaining tubewell use.

The component of *Geography* defines the impact that is determined by the distribution of households and arsenic contamination across space. To quantify the influence of geography, a measure is used that calculates the maximum predicted tubewell use across a 20-meter resolution grid of potentially feasible locations within each community (see Fig. 16). This measure of geography explains 18% of the total variation in tubewell use.

The second component, *Location quality*, measures how predicted use at the selected location compares to the distribution of predicted use across potentially feasible locations within the community. The primary measure of location quality is the predicted tubewell use at the selected location normalized by the measure of geography. This measure takes the value one if the community chooses the location that maximizes predicted use and zero if communities choose the location that minimizes predicted use. Summarized data results reveal that communities tend to choose locations with the highest predicted use under the labor contribution requirement (rank average of mean 0.76) compared to cash (0.70) and waiver (0.72). However, the differences between treatment arms are only statistically significant for the comparison between cash and labor when using one of the three measures of location quality. These differences may arise due to more inclusive discussions. In the labor treatment arm, communities have the highest number of active meeting participants (Labor: 6.5, Cash: 4.9, Waiver: 5.0) and active female participants (Labor: 0.40, Cash: 0.29, Waiver: 0.35). Furthermore, communities discussed the largest number of candidate locations (Labor: 1.65, Cash: 1.42, Waiver: 1.49) without reducing the quality of proposed locations, and communities chose the largest share of sites on public land (Labor: 0.73, Cash: 0.66, Waiver: 0.71).

The third component, *Community take-up*, measures whether or not communities met all the project requirements, including, if applicable, the contribution requirement. Communities met all requirements for 88% of offered tubewells under the contribution waiver and a statistically indistinguishable 85% of offered tubewells under the labor contribution requirement. However, only 23% of offered tubewells were met under the cash contribution requirement (as shown in Table 4, panel a in ***Paper III***). Community take-up explains 29% of the overall variation in tubewell use.

The fourth component, *Geology*, determines whether or not attempted installations were successful. On average, 89% of attempted installations were successful. Failures were due to local geological conditions, such as an impenetrable rock layer or an unstable sandy layer, which are only revealed when installation is attempted. The rate of success, conditional on the attempt, is similar

across all treatment arms. Although geology explains 8% of the total variation in tubewell use, it attenuates rather than explains the differences in tubewell use between treatment arms.

The fifth component is *Household take-up*, which is a residual measure of household take-up. This measure captures how the use of installed tubewells varies after accounting for both geography and location choice. In other words, it represents the extent to which use is higher or lower than predicted given the local geography of population density and baseline arsenic contamination. Summarized data results show that household take-up accounts for 29% of the variation in tubewell use, although this is an upper bound because any errors in measurement in the other four components load onto this residual term. However, no evidence is found for variation in household take-up across treatment arms.

Examining patterns of tubewell use provides valuable insights into the mechanisms that drive overall impact, especially when the intervention primarily works by providing new safe tubewells, across all three treatment arms. At the community level, the impact strongly and linearly correlates with the use of project tubewells. Among the factors influencing the differences in impact across treatment arms, community take-up plays a key role. It both explains a significant portion of the overall impact and systematically varies across treatment arms. Consequently, community take-up is the most important factor in explaining the variations in impact observed across different treatment arms.

4.2.3 Explanation of lower community take-up under cash contribution

The communities involved in the program had to fulfill several sequential requirements, including holding a meeting, selecting a tubewell location, obtaining permission to use land, and raising any required contributions. Field staff recorded instances where communities failed to meet these requirements.

There are several potential explanations for why communities raised cash contributions at lower rates than labor contributions. The most consistent explanation, based on our data, is that households place a monetary value on their time significantly below the prevailing wage, making the labor contribution less burdensome. We have two baseline measures of how households value time in monetary terms: i) Reservation wage: This is the price households would need to be paid to provide a day of manual labor, and ii) Inferred value of time: Households also reported how much they were willing to contribute to a new safe source of drinking water both in cash and time, allowing us to infer a monetary valuation of time that is specific to contribution to a local public good.

The distribution of reservation wages is narrower and closer to the market wage than the inferred value of time. This may reflect adherence to local labor market norms or differences in how households value time spent working individually for private remuneration compared to time spent working collectively for the community's benefit (Figs. 22a and 22b). For the reservation wage and inferred value of time, around 60% and 75% of households, respectively, value their time strictly below the market wage. This implies that the median household perceives the labor contribution requirement as equivalent to 4500 BDT when valued at their reservation wage and 1800 BDT using the inferred value of time. These amounts represent 83% and 33% of the requirement's value if priced at the unskilled daily wage. These findings suggest that households generally perceive the labor contribution requirement as considerably less onerous than a cash contribution requirement. Descriptive evidence supports the idea that cash contributions reduce take-up more than labor contributions because households place a monetary value on their time significantly below the market wage. This low monetary value of time is a common feature in our data across all but the highest wealth quintile and is also observed in poor rural economies worldwide (Kremer *et al*., 2011). This suggests that the preference to contribute labor rather than cash may be quite common and generalizable.

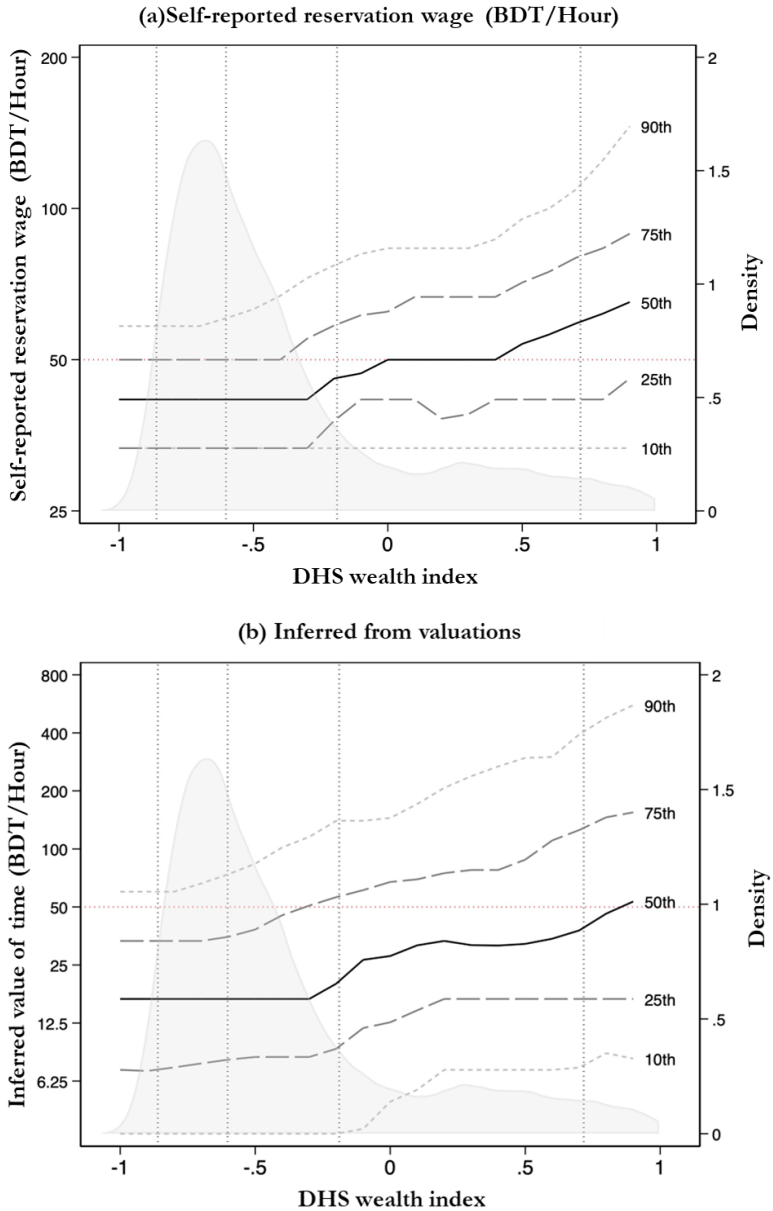

Figure 22: Estimates of monetary value of time. Graphs plot percentiles of the baseline distribution of monetary value of time across households with respect to the DHS wealth index. (a) Reservation wage reported by households. (b) Inferred value of time obtained from two stated preference measures of willingness to contribute to a new safe tubewell in a specific location, identified by the respondent household as maximizing social benefit. Extreme values of the DHS wealth index truncated. Vertical dotted lines show national wealth quintiles. The empirical distribution of wealth in our sample is shaded in grey. Market wage is shown in red.

4.2.4 Effects on cost-effectiveness

Cost-effectiveness is a crucial consideration in program design and planning. On the other hand, the contribution waiver approach emerges as the most cost-effective option. The cash requirement approach was extremely cost-ineffective because of wasted effort in communities that did not successfully install wells (Fig. 23).

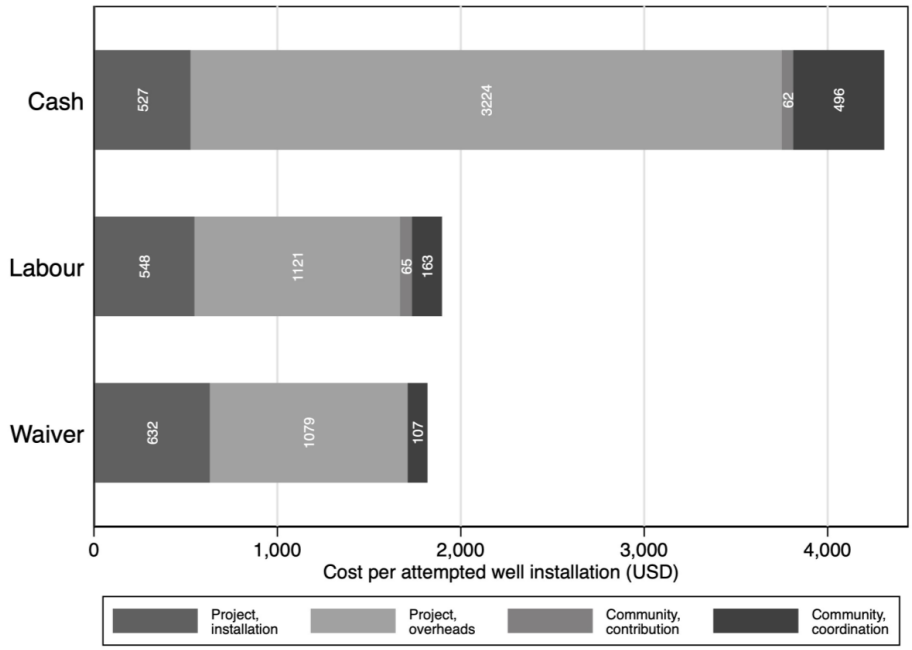

Figure 23: Cost-effectiveness of installed tubewell. Graph shows estimated costs per successfully installed tubewell under each treatment arm. Project, installation: price paid to contractor by NGO. Project, overheads: all other costs, including staff premises, and local travel. Community, contribution: contribution costs to community. Community coordination: estimated community time costs for meetings and coordination. All time costs to community valued at inferred household value of time.

Despite the fact that installation costs are mechanically higher in the contribution waiver approach, it proves to be more cost-effective due to lower overhead costs. This is primarily attributed to reduced coordination and monitoring expenses. The savings from reduced overhead costs outweigh the increased installation costs. When accounting for costs to the communities, using household-specific time cost valuations, the relative cost-effectiveness of the waiver model increases. This increase in cost-effectiveness is not solely due to the absence of contributions but also because of the reduced time required for coordination, further emphasizing the advantages of the waiver model.

4.2.5 Distribution of costs and benefits

Regarding the question of who benefits from the new tubewells, machine learning approaches suggest that tubewell users are exposed to higher arsenic contamination at baseline but are

comparable in terms of income or, in the case of the cash contribution arm, even poorer, than other households in the same communities.

Project records further indicate that in communities that successfully met contribution requirements, cash contributions are shared among more households than labor contributions. Specifically, in the cash contribution arm, no fewer than 6 households contributed to a successfully installed tubewell, with a mean number of contributing households being 14 and a median of 10.5. In contrast, in the labor contribution arm, the number of households contributing ranged between 2 and 12, with a median of 4 and a mean of 5.

4.2.6 Contribution effects on program sustainability

In the previous section (4.1.5), the results focused solely on the effects of decision-making on the program's sustainability. The effects of contributions on program sustainability are presented in ***Paper IV***. Similar to the findings from the decision-making experiment, the more participatory approach exhibits higher sustainability (Fig. 21). However, in the contributions experiment, over the timeframe studied, the difference in sustainability is relatively small, and the confidence intervals do not exclude the possibility of zero impact.

4.3 Understand the effects of community water sources

In ***Paper V***, potential concerns about the effects of the program's technical design and choice of technology on access to safe drinking water are addressed. This section describes the results of the average program impacts on changes in behavior concerning how households obtain quality drinking water from the sources they use, how far they need to walk to collect water, whether they store water in the household before drinking, and the quality of the drinking water at the point of use within the household.

4.3.1 Water quality of drinking water sources at baseline

Our baseline results indicate that households primarily collect water from their own shallow tubewells or from other close relatives living nearby. Arsenic contamination in the study communities (24%) is mostly above the national average (17%), reflecting the targeted recruitment of communities that face arsenic contamination problems. Faecal contamination rates (65%) are above or similar to the national averages (63%).

4.3.2 Comparision of project tubewells and other tubewells

The program offered a total of 179 tubewells across 129 treatment communities. However, the program successfully installed 107 deep tubewells in 82 of these communities as part of **Experiment II**. Table 11 summarizes the water quality in project tubewells compared to other tubewells in the same communities. It is noteworthy that project tubewells almost all have arsenic contamination levels below the WHO threshold, indicating safe drinking water in terms of arsenic content. However, project tubewells are only 13 percentage points less likely to test positive for faecal contamination compared to other tubewells in the same communities. The deep tubewells draw water from an aquifer that is isolated from sources of faecal contamination. Nevertheless, contamination could potentially occur through leakage into the pipe system from shallow groundwater or within the pump body itself. Other research suggests that contamination could also take place through the tubewell mouth (ICDDRB and UNICEF, 2018) and that the tubewell body may act as a reservoir for microbial organisms (Ferguson *et al.*, 2011).

The project data reveals that in communities where the project successfully installed at least one tubewell, the median household is located at a 1.6-minute walking distance from the project source. Approximately 26 percent of households report collecting at least some of their household's drinking and cooking water from a project source. However, only 13 percent of households using the project source report collecting all of their drinking and cooking water from that source. On

Table 11: Comparison of project tubewells and other tubewells.

	Faecal contamination	As contamination (WHO threshold)	As contamination (Bangladeshi threshold)
Difference	-0.13***	-0.58***	-0.35***
	(0.05)	(0.04)	(0.03)
Mean (project tubewells)	0.34	0.06	0.01
Mean (other tubewells)	0.46	0.63	0.34
N	3,399	3,515	3,515

Note: The table reports the regression-estimated difference in contamination rates in project tubewells compared to other water sources in the same communities, from a regression that includes community fixed effects. The table also reports mean contamination levels in project tubewells and other water sourcesinthesame communities. The sample includes water sources that at least one study household reported using for drinking or cooking, in communities in which we installed at least one project tubewell. Standard errors are clustered by community and shown in parentheses. *** $p < 0.01$.

average, in these communities, about 10 percent of drinking and cooking water is obtained from a project tubewell. When we scale these numbers by community size and the number of installed tubewells, we find that approximately 27 households collect at least some water from each installed tubewell, and the total take-up is equivalent to about 11 households collecting all their water exclusively from the tubewell.It's worth noting that households living closer to the installed tubewells are more likely to adopt the new tubewells (Fig. 24). However, even at short distances from installed tubewells, some households do not adopt them, and many of those who do still collect water from other sources. Take-up of the tubewells decreases rapidly with increasing distance from the source. The most commonly cited reason for non-adoption is that the tubewells are too far from the household, even when the tubewells are less than one minute's walking distance away. Additionally, a majority of non-adopters report that women from their households feel uncomfortable collecting water outside the compound. Some households also do not adopt the source because they believe their own tubewell to be safe. Relatively few households mention waiting times, discomfort with using a tubewell on someone else's private land, or a lack of concern about arsenic as reasons for non-adoption (Fig. 25).

4.3.3 Effect of program on access to safe drinking water

The estimated program impacts represent "intent-to-treat" effects, which means they are calculated as averages across all communities where the program was implemented, regardless of whether or not tubewells were successfully installed in those communities. Table 12 data provides the estimated impact on the quality of water sources that households use for drinking and cooking. In treated communities, there is a 5.6 percentage point decrease in the use of water sources with arsenic contamination levels exceeding the recommended WHO threshold (column 1). Additionally, the use of sources with arsenic contamination levels above the Bangladeshi threshold falls by 2.7 percentage points in treated communities (column 2). While the weighted average arsenic contamination level in the sources used by households decreases slightly, by just under 0.1 parts per billion (ppb) on average in treated communities (column 3). These coefficients labeled as "treated" represent the estimated effects of the treatment or intervention on these water quality indicators in comparison to the control group. The following Tables 12-15 report the coefficient as the constant corresponds to the change between baseline and follow-up in the control group, while the coefficient labelled "treated" corresponds to the estimated treatment effect. There is a relatively modest reduction, equal to 2.1 percentage points (Table 12), in the usage of water sources contaminated with faecal matter, and it's important to note that the confidence interval for this

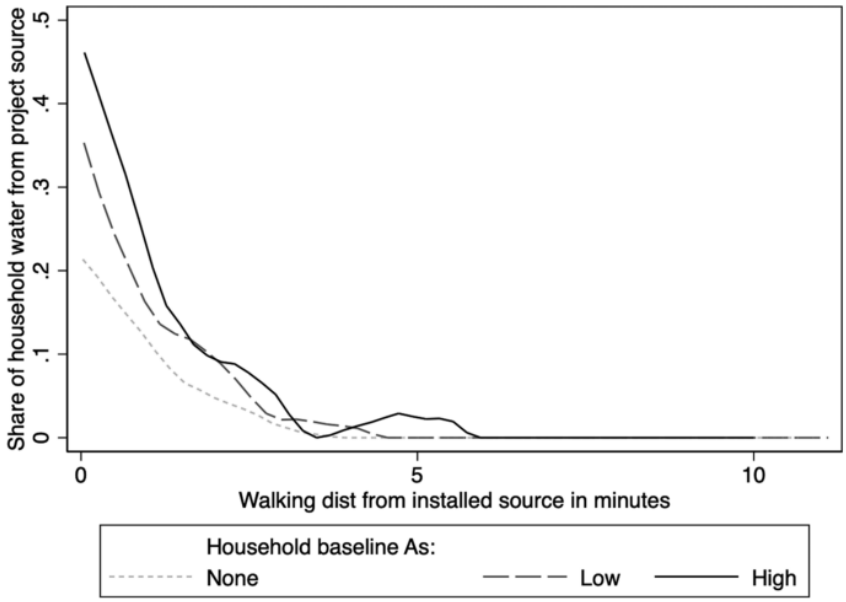

Figure 24: Take-up of project tubewells. Graph shows mean share of drinking and cooking water obtained from project tubewell by distance to tubewell and baseline arsenic contamination in household drinking water. Data from communities in which we successfully installed tubewells.

Table 12: Effect of the program on use of contaminated tubewells.

	Arsenic contamination (WHO threshold)	Arsenic contamination (Bangladeshi threshold)	Arsenic contamination Level	Faecal contamination
	(1)	(2)	(3)	(4)
Treated	—0.056**	-0.027	-0.155	-0.021
	(0.023)	(0.019)	(3.648)	(0.019)
Constant	-0.068***	-0.008	7.642**	—0.035**
	(0.018)	(0.015)	(3.167)	(0.015)
p-value (analytical)	0.02	0.15	0.97	0.28
p-value (RBI)	0.04	0.23	0.95	0.38
Mean at baseline	0.69	0.30	37.27	0.55
R^2	0.03	0.02	0.07	0.04
N	6,051	6,051	6,051	6,051

Note for tables (12-15): The table shows the estimated average program impact on listed measure of use of sources (Table 12), water-related practice (Table 13), storage practice (Table 14) and household water quality (Table 15). Regression in first differences, including stratification controls. Analysis is at the household level with weights applied so that each community counts equally in the analysis. Standard errors clustered by the community are shown in parentheses. p-values obtained from analytical standard errors and randomization-based inference (RBI). * $p < 0.1$, *** $p < 0.01$.

Table 13: Effect of the program on transport and storage.

	Distance HH-WS (m)	Distance IIH-WS (min)	Observed storage	Reported storage
	(1)	(2)	(3)	(4)
Treated	-0.147	0.065**	0.002	0.003
	(1.041)	(0.027)	(0.028)	(0.032)
Constant	-2.801**	0.012	-0.134**	-0.040
	(0.685)	(0.024)	(0.024)	(0.029)
p-value (analytical)	0.89	0.02	0.95	0.93
p-value (RBI)	0.93	0.02	0.95	0.92
Mean at baseline	31.40	0.81	0.73	0.76
R^2	0.01	0.01	0.02	0.02
N	5,832	5,729	6,050	6,051

Note: HH= household; WS = water source.

effect includes zero (column 4). Moreover, the reduction in faecal contamination in water sources is roughly one-third of the reduction observed for arsenic contamination.

The relatively smaller effect on reducing faecal contamination can be largely attributed to the patterns observed in Table 11. According to the data in Table 12, while the water sources provided by the project are nearly free of arsenic, they are only 28 percent less likely to have fecal contamination compared to other tubewells in the same communities. Consequently, not all households that adopt project tubewells are able to reduce their exposure to faecal contamination at the source.

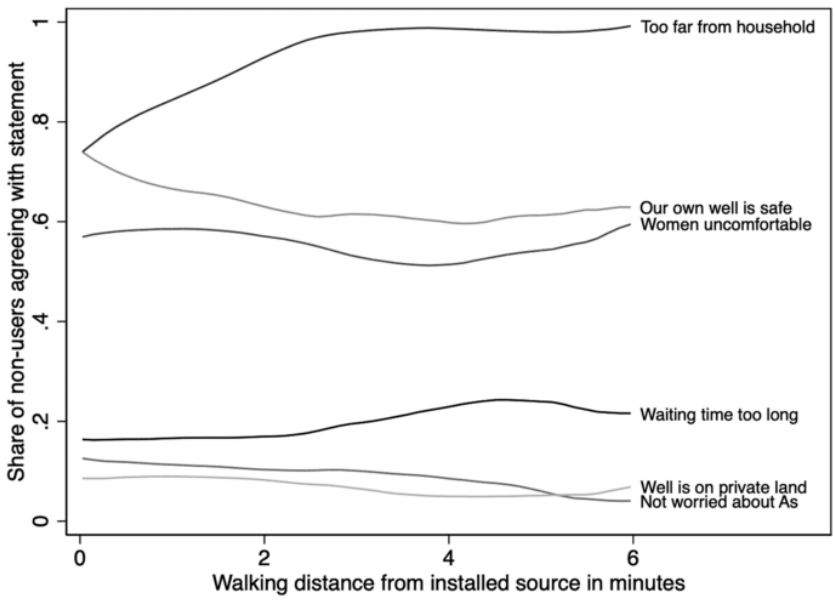

Figure 25: Reasons for not using project tubewells.

Table 14: Effect of the program on storage conditions.

	Containers are uncovered (self-reported)	Containers are on the floor (self-reported)	Containers are uncovered (observed)	Containers are on the floor (observed)	Water is scooped (observed)
	(1)	(2)	(3)	(4)	(5)
Treated	0.023	0.008	0.040*	0.025	-0.002
	(0.039)	(0.030)	(0.021)	(0.019)	(0.022)
Constant	-0.351***	-0.092***	0.383***	0.484***	0.439***
	(0.033)	(0.027)	(0.018)	(0.016)	(0.020)
Only endline data	-	-	√	√	√
p-value (analytical)	0.55	0.78	0.06	0.20	0.93
p-value (RBI)	0.63	0.82	0.04	0.24	0.92
Mean at baseline	0.54	0.74	-	—	-
R2	0.04	0.02	0.02	0.01	0.01
N	6,051	6,051	5,902	5,997	6,029

When adjusting these estimates to account for the fraction of offered tubewells that were actually installed, the results suggest that each installed project tubewell has an impact roughly equivalent to motivating 10 households to transition from sources with arsenic contamination at the WHO-recommended level to sources that are free from arsenic contamination, as well as encouraging 5 households to switch from sources contaminated with faecal matter to sources that are free from faecal contamination

Table 15: Effect of the program on household water quality.

	Arsenic contamination (WHO threshold)	Arsenic contamination (Bangladeshi threshold)	Arsenic contamination Level	Faecal contamination
	(1)	(2)	(3)	(4)
Treated	-0.022	-0.004	3.756	0.002
	(0.020)	(0.018)	(2.865)	(0.020)
Constant	-0.096***	-0.023	1.218	-0.033*
	(0.016)	(0.015)	(2.414)	(0 017)
p-value (analytical)	0.27	0.82	0.19	0.93
p-value (RBI)	0.36	0.87	0.25	0.93
Mean at baseline	0.62	0.24	28.97	0.65
R^2	0.02	0.01	0.04	0.03
N	6,051	6,051	6,051	6,051

Table 16: Effect of source water quality, transport and storage on household water quality.

	Drinking water faecal contamination			
	(1)	**(2)**	**(3)**	**(4)**
Source faecal contamination	0.242*** (0.015)	0.224*** (0.015)	0.245*** (0.015)	0.225*** (0.015)
Travel lime HH-WS (mins, reported)	0.015* (0.008)	0.018** (0.009)	0.0I6** (0.008)	0.018** (0.009)
Observed storage	0.081*** (0.010)	0.070*** (0.010)	-	-
Constant	-0-012 (0.010)	-0.015*** (0.002)	-0.023** (0.010)	-0.024*** (0.001)
Treatment unit fixed effects	No	Yes	No	Yes
R^2	0.07	0.14	0.06	0.14
Obs	5,728	5,728	5,729	5,729

Note: HH= Household; WS = Water source. Regression in first differences. Analysis is at the household level with weights applied so that each community counts equally in the analysis. Community fixed effects where specified. Standard errors clustered by the community. *p< 0.1, **p< 0.05, ***p<0.01.

4.3.4 Effect of source water quality, transport and storage on household water quality

The effects of changes in source water quality, walking distance, and storage practices on the quality of household drinking water is assessed through a difference-in-difference equation. Table 16 presents the findings, indicating that switching to a water source contaminated with faecal matter increases the risk of contamination in household drinking water by approximately 22 to 24 percentage points. Additionally, for every one-minute increase in travel time to the water source, the risk of contamination rises by around 1.5 to 1.8 percentage points. Furthermore, the act of storing drinking water increases the risk of contamination by approximately 7 to 8 percentage points. These estimated effects remain consistent across various specifications.

It's worth noting that when omitting controls for changes in storage practices, the estimated effects of travel time on drinking water contamination slightly increase. This happens because longer travel times are weakly associated with increased water storage, which can contribute to contamination.

The difference-in-difference methodology provides causal estimates, assuming that the changes in the factors on the right-hand side of the equation are not correlated with other changes in behavior, such as hygiene practices, that could also impact fecal contamination in household drinking water.

4.3.5 Simulation effect of increasing take-up on program impact

The simulation results presented in Figures 26 and 27 illustrate the hypothetical effects of increased take-up patterns on program impacts. These simulations show that increasing take-up further reduces the use of arsenic-contaminated water sources, although the returns diminish as take-up increases. This diminishing effect is due to the fact that households with higher baseline arsenic contamination levels already collect more of their water from the project tubewell, leaving less room for further increases in take-up.

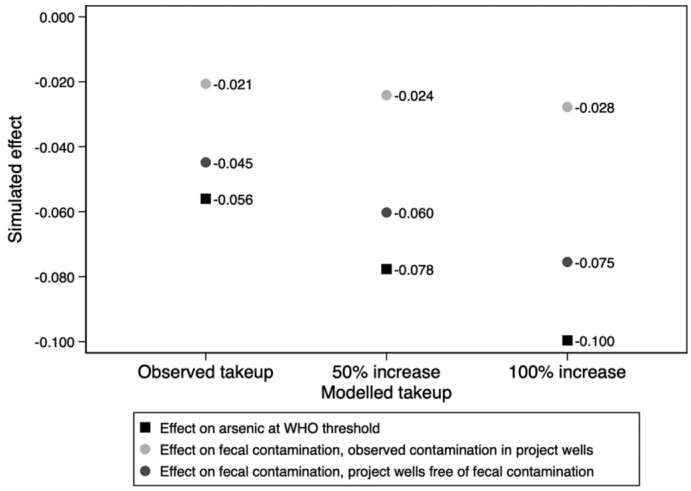

Figure 26: Simulated changes in use of contaminated water sources under increased adaptation scenarios. Graph shows simulated effects on use of sources with arsenic and faecal contamination under indicated scenarios.

Consequently, increasing take-up weakens the relationship between baseline arsenic contamination and take-up. Specifically, when take-up is doubled, there is a 78 percent increase in the reduction of the use of arsenic-contaminated water sources. This suggests an elasticity of impact to take-up of 0.78 for arsenic contamination.

In contrast, increased take-up has a smaller proportional effect on the use of sources with faecal contamination. When take-up is doubled, while holding constant observed rates of faecal contamination in project tubewells, there is about a 33 percent increase in the reduction of the use of sources with faecal contamination. This implies an elasticity of impact to take-up of 0.33 for faecal contamination.

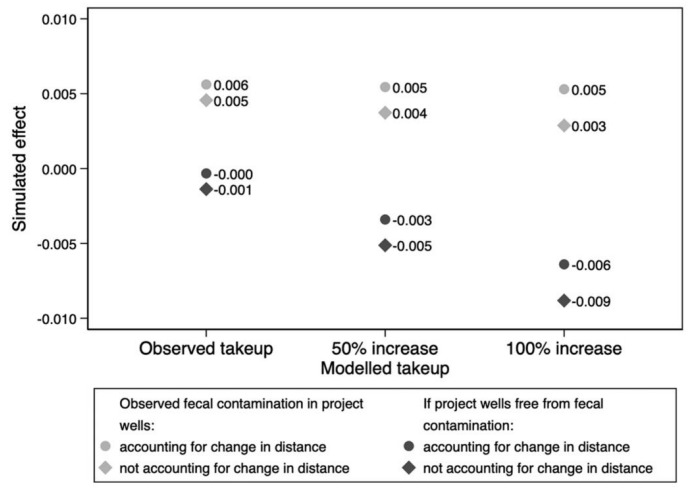

Figure 27: Simulated changes in household drinking water quality under increased adoption scenarios. Graph shows simulated effects on faecal contamination in household drinking water under indicated scenarios.

It's important to note that while this exercise evaluates the impact of doubling take-up, a wider range of take-up scenarios was not explored in the study. However, the general conclusion drawn from these simulations is that increasing take-up can lead to lower baseline arsenic concentrations and higher walking distances among the additional adopters. Additionally, improving targeting for both arsenic and faecal contamination is challenging because these two variables are negatively correlated.

These findings have implications for program design and interventions, highlighting the need to consider the specific contamination profiles and baseline conditions when planning efforts to increase take-up of safe water sources.

4.4 Effects of tubewells cleaning and maintenance practices (Exp. III)

4.4.1 Cleaning effects on water quality of deep tubewells and shallow tubewells

The study measured the cleaning effects on tubewell water quality by detecting *E. coli* and total coliform contamination before and after tubewell cleaning. Here are the key findings regarding water quality before cleaning:

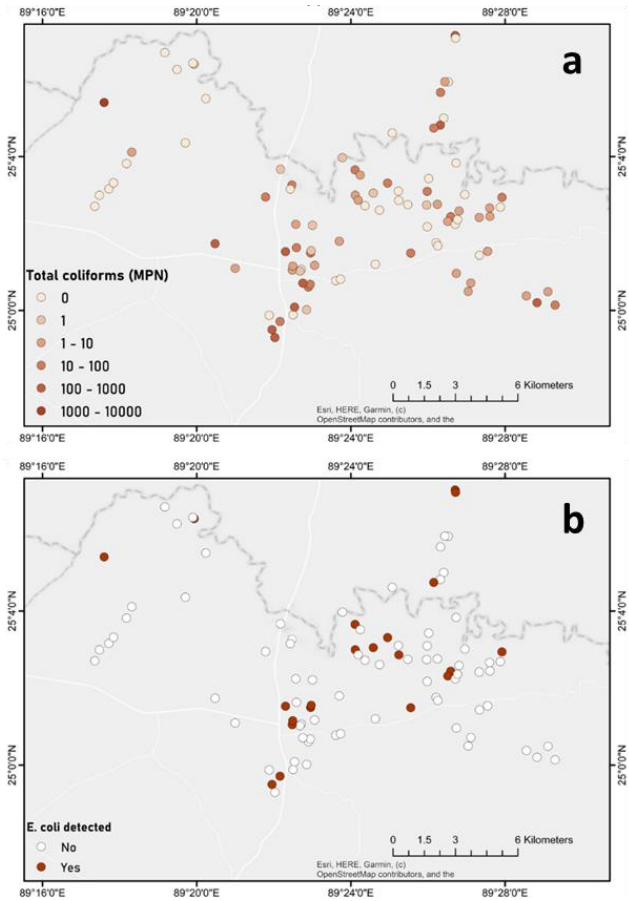

Figure 28: Water quality in deep tubewells before cleaning. Maps show deep tubewells that were functional at the time of the study by water quality. a) concentrations of total coliforms; b) wells with presence of E. coli.

Before cleaning, the study found that 62% of the tubewells (58 out of 94) were contaminated with total coliforms. Among these, 34% had low levels of contamination (below 10 CFU/100 ml), 17% had moderate contamination (between 10 and 100 CFU/100 ml), and 11% had high contamination (above 100 CFU/100 ml).E. *coli* contamination was detected in 22% of the tubewells, with 19% categorized as low risk (below 10 CFU/100 ml) and 3% as intermediate risk (10-100 CFU/100 ml) (Fig. 28) according to WHO (2017) classifications.

When comparing shallow and deep tubewells, it was observed that nearby shallow tubewells had higher rates of total coliform contamination, but lower rates of E. *coli* contamination compared to deep tubewells. However, the differences between the two types of tubewells were small and not statistically significant.

Even the modest advantages of deep tubewells over shallow ones that we described in ***Paper V*** appear to have attenuated three years later. This could be due to various factors, including different measurements of contamination, variations in the comparison samples of shallow tubewells, or changes in contamination levels in deep tubewells over time (Ercumen *et al.*, 2017).

Overall, the findings indicate that there is room for improvement in tubewell cleaning and maintenance practices to reduce contamination levels, particularly regarding faecal pathogens like E. *coli*. These results underscore the importance of ongoing efforts to ensure the safety of drinking water from tubewells, which are widely used as a source of drinking water in rural areas of Bangladesh.

4.4.2 Effect on Total coliforms and E. coli

The study examined the effects of different cleaning and disinfection methods on total coliforms and *E. coli* contamination in tubewell water.

Figure 29 visualizes the effects of Flushing alone had limited effects on contamination in control tubewells (those that were not cleaned). Total coliform concentrations were slightly lower in samples taken from tubewells before and after flushing (panel a). Interestingly, total coliform concentrations actually increased on average after caretakers cleaned the tubewells (panel b). Contamination was generally lower after flame disinfection, but the improvement was incomplete, and in some cases, contamination became substantially worse (panel c). Only disinfection with the weak chlorine solution consistently reduced contamination. No tubewell had contamination above 10 CFU/100 ml after cleaning with weak chlorine, and a large share (83%, 20 out of 24) were free from contamination (panel d). Statistical analysis confirmed that only disinfection with weak chlorine led to a statistically significant reduction in contamination relative to flushing alone, and the null hypothesis of no effect could be rejected. The effects of disinfection with weak chlorine were also statistically different from the effects of the caretaker's regular standard of care and flame disinfection.

Figure 30 visualizes the effects of cleaning on *E. coli*. A substantial share of tubewells tested positive for *E. coli* after flushing (24%, 6 out of 25) and after caretakers cleaned the tubewells (33%, 8 out of 24). *E. coli* presence increased slightly after caretakers cleaned the tubewells. No tubewell tested positive for *E. coli* after disinfection with the weak chlorine solution, and only one did so after flame disinfection.

These findings suggest that proper disinfection with a weak chlorine solution is an effective method for reducing total coliforms and *E. coli* contamination in tubewell water. It provides a practical approach to improving water quality and reducing health risks associated with faecal contamination in tubewell water sources.

The study underscores the effectiveness of disinfection with weak chlorine as one of the best practices for cleaning deep tubewells and improving water quality. The key steps involved in this cleaning approach include dismantling, scrubbing, and disinfecting with a weak chlorine solution. This method consistently reduces contamination and can significantly enhance the safety of drinking water from tubewells. The findings suggest that if caretakers can be trained and

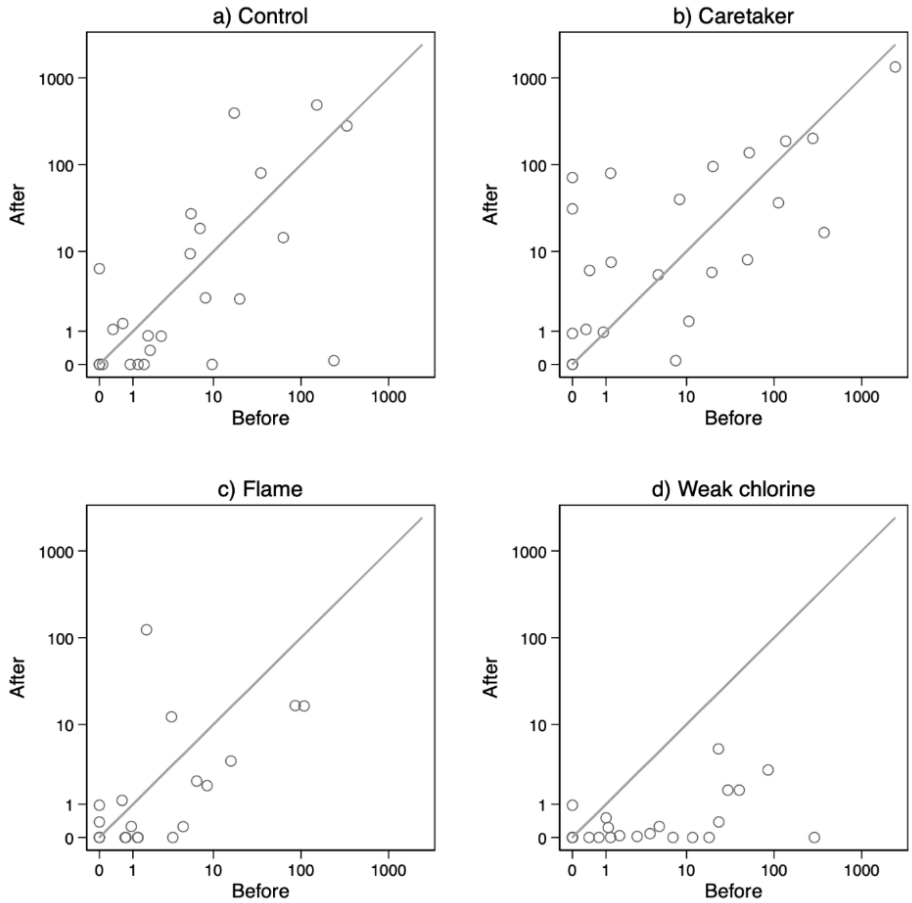

Figure 29: Effects of cleaning on total coliforms (MPN). The figures summarize contamination with total coliforms before and after flushing and, where applicable, cleaning, under each treatment arm and for the control group. All axes show MPN of CFU/100 ml, plotted on an arcsinh scale. Each hollow circle represents one tubewell. Points are jittered for readability. The diagonal line plots the locus of points that would reflect equal contamination before and after flushing and/or cleaning.

incentivized to adopt and sustain these cleaning practices at a low cost, deep tubewells, coupled with increased support for cleaning and maintenance, could remain the most cost-effective way to ensure safe drinking water access for rural communities in Bangladesh.

However, the study also highlights that faecal contamination of deep tubewell water remains a significant challenge in providing safe drinking water in rural Bangladesh. Therefore, addressing this issue may require complementary interventions in project design, such as training programs to improve tubewell maintenance, or exploring alternative approaches to providing safe access to drinking water.In summary, a robust and low-cost tubewell cleaning protocol has the potential to reduce or eliminate faecal contamination at the point of collection, but it may need to be accompanied by broader initiatives to ensure long-term water safety and access for rural communities in Bangladesh.

4.5 Effects on caretakers' training workshop to reduce faecal contamination and improvement of maintenance of tubewells (Exp. IV)

Paper VII presents the results of a caretaker training workshop aimed at evaluating whether training caretakers to more effectively clean community tubewells can lead to improved water quality.

4.5.1 Training effects on improvements to microbial water quality

The results of the caretaker training workshop are promising (Fig. 31). After 13 to 17 months of training, water quality tests showed a significant improvement in tubewell water quality among tubewells for which caretakers received training in effective cleaning techniques, compared to a control group of tubewells.

Thirteen months after training, in January 2023, the share of tubewells that tested positive for *E. coli* was only 2% in the treated group, while it was 14% in the control group. Similarly, the share of tubewells testing positive for any coliform bacteria was 30% in the treated group, compared to 55% in the control group. These results indicate a substantial reduction in contamination levels in the treated tubewells. Four months later, in May 2023, when temperatures were higher (which can encourage bacterial growth), the share of control tubewells testing positive for *E. coli* and coliform bacteria had risen to 19% and 77%, respectively. However, in the treated tubewells, these shares

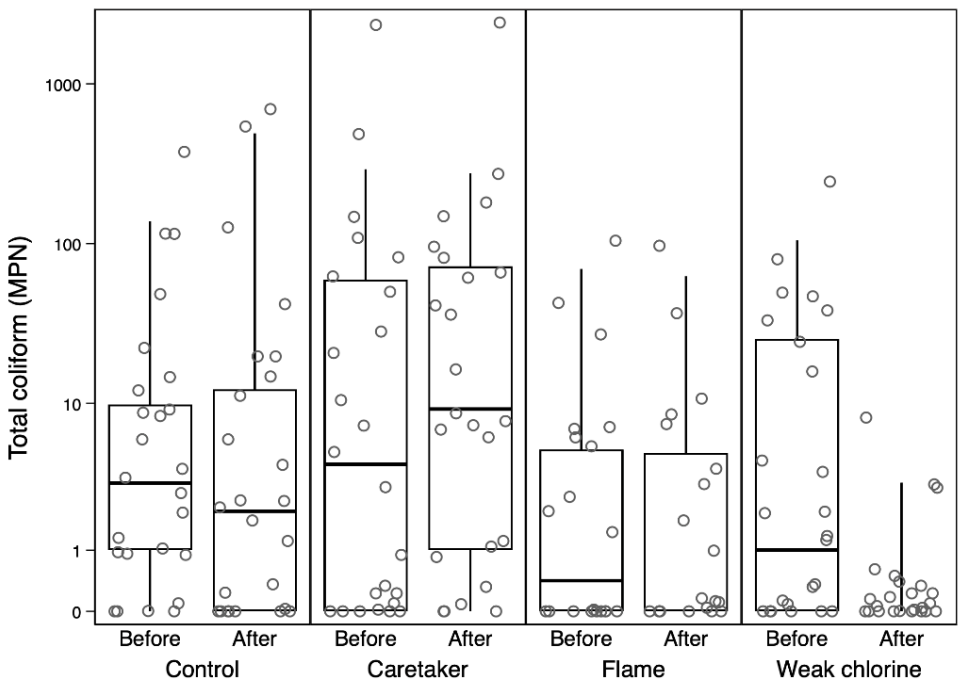

Figure 30: Effects of cleaning on E. coli presence. The figures summarize E. coli presence before and after flushing and, where applicable, cleaning. Each hollow circle represents one tubewell. Points are jittered for readability. Bar shows mean rate of E. coli presence and 90% confidence interval.

were significantly lower, with only 4% testing positive for *E. coli* and 46% testing positive for coliform bacteria. These differences between the control and treated tubewells were statistically significant.

In summary, the training intervention appears to have had a positive and lasting impact on water quality, almost eliminating the risk of exposure to *E. coli* and significantly reducing the risk of exposure to any coliform bacteria. These findings suggest that effective training of caretakers can play a crucial role in improving water quality and ensuring access to safe drinking water.

4.5.2 Improvements on knowledge and practice in water quality despite imperfect adherence to the cleaning protocol

The study demonstrates that improvements in drinking water quality were observed despite imperfect adherence to the cleaning protocol. Here are some key findings related to the caretaker training:

Knowledge Improvement: Thirteen months after training, caretakers who received training were much more likely to correctly name elements of the cleaning process compared to caretakers of the control group. This suggests that the training effectively increased their knowledge of proper cleaning techniques (Fig. 32a).

Knowledge Retention: While there was some spillover of knowledge to the control group and slight fading of recall among the treated groups four months later, overall, knowledge retention remained relatively stable (Fig. 32b).

Practice of Cleaning Elements: The study found that the share of caretakers who reported regularly practicing the cleaning elements was lower than those who recalled the elements. Thirteen months after training, caretakers who received training alone reported practicing an average of 0.6 cleaning elements out of 1.0 elements recalled. For caretakers who received both training and supplies, both recall and practice were higher, with an average of 1.6 elements recalled and 2.0 elements recalled, respectively (Figs. 32c and 32d).

Water Quality Improvement: Despite imperfect adherence to the cleaning protocol, substantial improvements in water quality were observed. This suggests that even moderate changes in cleaning behavior can effectively enhance drinking water quality.

Behavioral Changes: It's possible that increased awareness of cleanliness from the training may have influenced caretakers' behavior in ways that were not directly measured, such as encouraging users to avoid introducing contamination into the tubewells when collecting water.

These findings emphasize the importance of knowledge and training in improving water quality, and even partial adherence to best practices can lead to significant positive outcomes in terms of water safety and quality.

4.5.3 Potential cost-effectiveness

Our study was not intended to directly assess the health outcomes of the training intervention. The results of the training workshop study suggest that training caretakers of community tubewells to clean the tubewells more effectively can have a significant impact on water quality and public health. Using meta-analytic estimates of the effects of water treatment on mortality that account for all the potential causal pathways between water quality and mortality (Kremer *et al.*, 2023), we estimate conservatively that if the intervention were successfully scaled, it would avoid the death of one infant for every 89 tubewells whose caretakers were trained, at a cost per life saved of US$2034 and per DALY gained of US$25 at current prices and exchange rates or $18 in 2010 International Dollars. These estimates assume that the effects decay from those we observe at seventeen months to zero after a further seventeen months. These estimates are conservative because we assume that mortality effects only accrue to tubewell users who entirely avoid exposure to coliform bacteria, thus disregarding the substantial reductions in concentrations of bacteria to which tubewell users are exposed, and that mortality benefits only accrue to children under five.

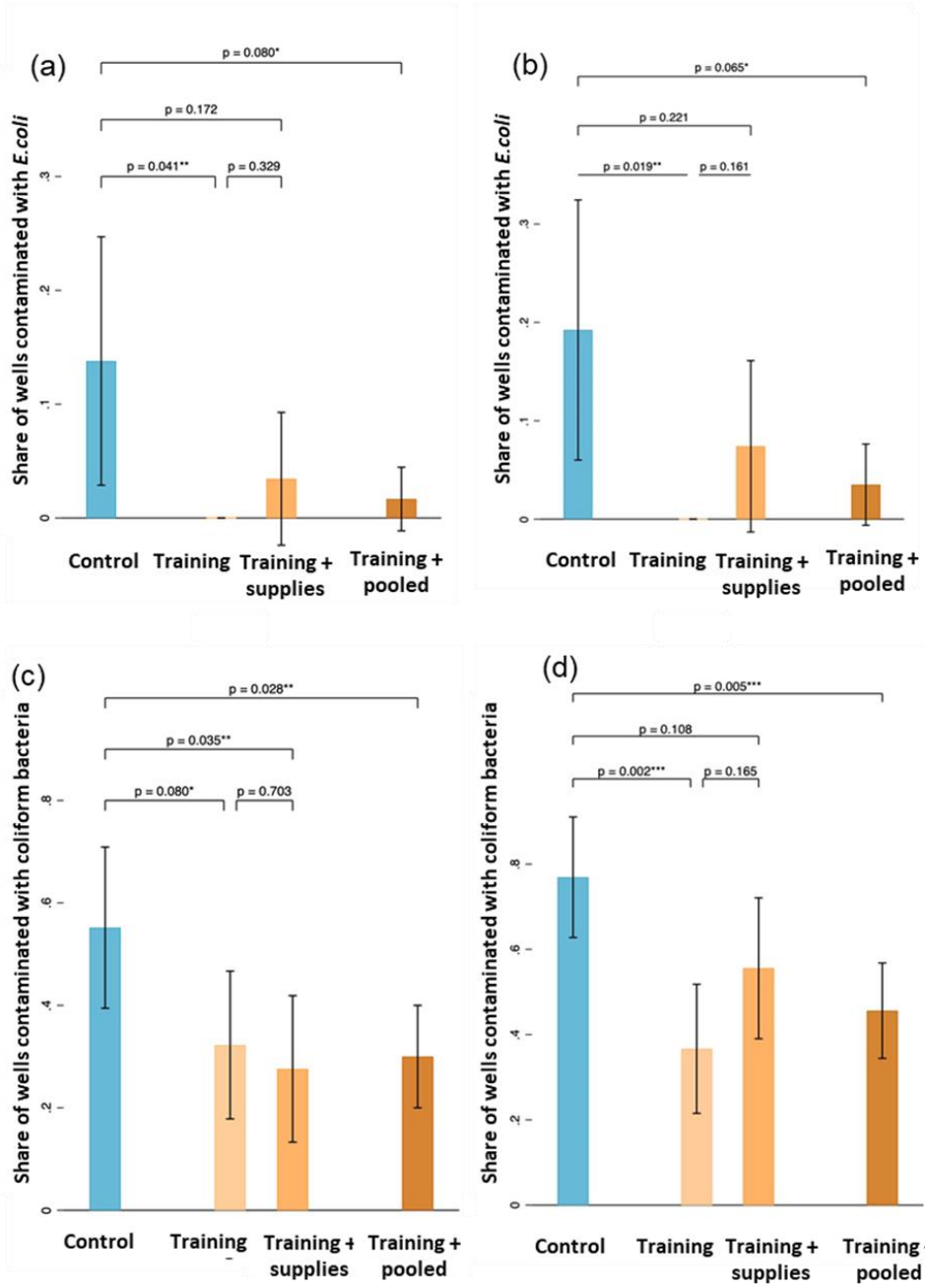

Figure 31: Presence of E. coli and coliform bacteria in samples of tubewell water; (a) and (b) show share of wells contaminated with E. coli; (c) and (d) show coliform bacteria after 13 and 17 months training, respectively. 90% confidence intervals and p values obtained from a regression of a dummy variable for contaminant presence on treatment arm indicators. Standard errors are robust. * p < 0.1, ** p < 0.05, *** p < 0.01.

The cost per DALY averted is more than 100 times lower than GDP per capita in Bangladesh, the threshold long used by the WHO to identify highly cost-effective interventions (Hatfield *et al.*, 2020), and renders the intervention comparable to some of the most apparently cost-effective interventions in infant, child, and maternal health (Stenberg *et al.*, 2021). The estimate is similar to the cost-effectiveness of water treatment with chlorine tablets (Kremer *et al.*, 2023), with the important caveat that water treatment with chlorine tablets requires ongoing resupply, whereas the training intervention has the potential for persistent effects on water quality even without further interventions.

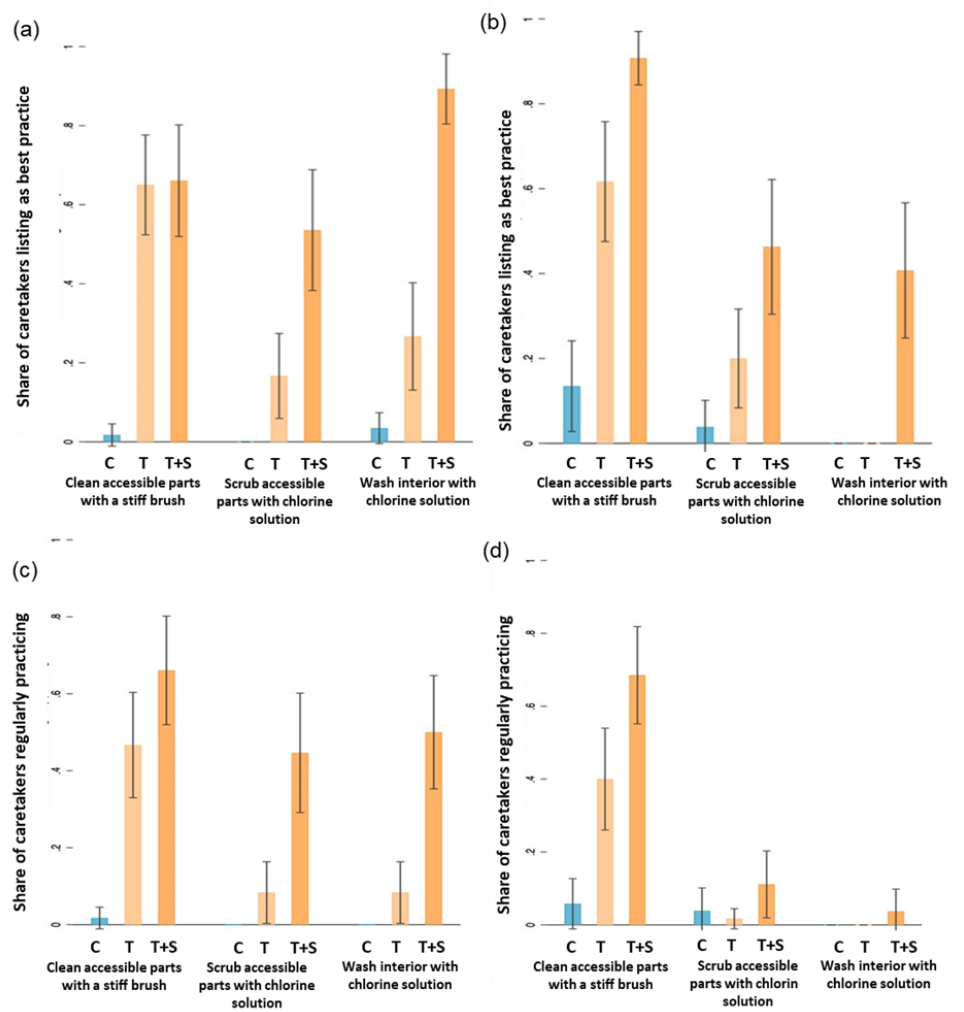

Figure 32: Comparison of the influence of knowledge and practice towards the cleaning process of the wells; (a) and (b) show share of caretakers reporting knowledge; and (c) and (d) regular practice of the labeled elements of the cleaning protocol, after 13 and 17 months training, respectively. 90% confidence intervals obtained from a regression of a dummy variable for knowledge or practice on treatment arm indicators. Weights applied so that each well counts equally. Standard errors clustered by well. * p < 0.1, ** p < 0.05, *** p < 0.01.

While the study focuses on tubewell cleaning, its findings highlight the broader potential of training interventions to enhance water quality. The effectiveness of such interventions may vary across fields and contexts, but this study demonstrates their positive impact in the context of improving water quality. In summary, the training workshop study underscores the value of investing in training caretakers to clean community tubewells effectively. This intervention offers substantial health benefits, is highly cost-effective, and plays a crucial role in ensuring safe drinking water access and improving public health outcomes.

5 SUMMARY OF THE FINDINGS AND CONTRIBUTION TO SCIENCE AND THE DEVELOPMENT PRACTITIONERS FOR SUSTAINABILIY OF WATER SUPPLY PROGRAMS

The key findings and implications of this study were largely gained through experimenting with different interventions in the project life cycle over fifteen years. The work described in this thesis aimed to contribute evidence-based causal effects on how to increase access to use safe drinking water and enhance the sustainability of drinking water supply programs in rural areas in Bangladesh. It also describes the implications of the for policymakers and development practitioners for designing, planning and implementing future interventions.

This study finds that community involvement in decision-making boosts access to safe drinking water, with Regulated Community Participation (RCP) being more effective than a Top-down (TD) approach (***Paper I***) . The effects of these approaches vary across different contexts, but both top-down and unrestricted community-based decision-making have similar impacts on safe water usage (***Paper II***). The study also suggests that the RCP approach offers greater welfare gains, but participatory approaches may affect costs. Furthermore, sustainability is higher under RCP or consensus-based decision-making, and the RCP approach outperforms the top-down one in sustainability (***Paper IV***).

The Contributions experiment is the first of its kind, evaluating the effects of requiring communities to contribute in cash or labour to a project, compared to no contribution. It found that imposing cash contributions reduced project impact and increased costs (***Paper III***). Labour contributions also increased costs but had no detrimental effect on impacts.

We found that a deep tubewell construction program in rural Bangladesh successfully reduced exposure to arsenic but did not address faecal contamination (***Paper V***). Households using these water sources faced challenges in eliminating faecal pathogens due to recontamination during transport and storage. Additional interventions beyond community sources, such as improved maintenance or alternative safe water provision, may be needed to tackle faecal contamination effectively.

Another experiment demonstrated that using a weak chlorine solution to clean tubewells consistently improved water quality by reducing faecal contamination, compared to other cleaning methods (***Paper VI***). However, when caretakers attempted cleaning themselves using their own standard practices, water quality sometimes worsened. Practical training workshops were effective in reducing contamination with *Escherichia coli* (*E. coli*), resulting in significantly improved water quality, despite some imperfections in caretakers' recall and compliance with the cleaning protocol (***Paper VII***). Proper cleaning and maintenance practices are crucial for reducing faecal contamination in rural Bangladesh.

The results underscore the effectiveness of Randomized Controlled Trials (RCTs) in addressing complex and long-standing causal questions. While these findings provide valuable insights, it is important to note that numerous open questions still exist in various fields of study. RCTs continue to be a valuable tool for researchers to explore and uncover answers to these remaining questions, contributing to a deeper understanding of complex issues and informing evidence-based decision-making.

6 REFERENCES

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