Reports of missing persons in innovation and infrastructure to achieve water and sanitation for all

by

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Abstract

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We live in a world where 844 million people lack basic drinking water services, and more than four billion people lack access to safely managed sanitation. Somehow, these people go missing in the process of water and sanitation provision. Reaching these billions requires not only technological innovation but also socio-political ingenuity. This dissertation provides theoretical and on-the-ground insight into key social and political components of technological interventions, or what I call the "invisible infrastructure" of tech-led transformations. I focus on infrastructure in low-income regions and explore how social systems relate to technological systems, particularly in terms of street-level bureaucracy, interdisciplinary research, and pro-poor policy implementation. I employ mixed-methods research approaches, producing social science and spatial datasets as well as rich ethnographic observations and archival work. I conduct analyses through both quantitative and qualitative coding, drawing from and contributing to the scholarship of development studies and practice, city and regional planning, and development engineering—all with the practical hope of one day achieving water and sanitation for all.

In the Introduction of this dissertation, I propose an invisible infrastructure framework for tech-led transformations in order to help render missing people and social dynamics more visible. I describe how invisible infrastructure is the conceptual arc of my whole endeavor in research to unlock water and sanitation solutions. Each of the following chapters of my dissertation uncovers various aspects of invisible infrastructure (summaries below). The chapters are quite distinct from one another in that they: focus on various regional contexts, draw from various theories and disciplines, and use different data sources and analytical approaches. However, the common goal is the provision of water and

sanitation services with an overarching message that certain stakeholders—in particular from marginalized groups—and social dynamics have been rendered invisible. Hence, I consider the chapters as reports of missing persons in innovation and infrastructure to achieve water and sanitation for all.

Chapter 1: Significant development funding flows to informational interventions intended to improve public services. Such "transparency fixes" often depend upon the cooperation of frontline workers who produce and disseminate information for citizens. We study frontline worker compliance with a transparency intervention in Bangalore's water sector, providing one of the first multi-method companions to a field experiment. We examine why workers exhibited modest overall rates of compliance and why compliance varied across neighborhoods. Drawing on ethnographic observation and an original dataset, we find that it is essential to understand how workers prioritize new responsibilities relative to longstanding ones. Perceptions of "core" jobs can be sticky—especially when reaffirmed through interactions with citizens. When family responsibilities take time away from their positions, new tasks are even more neglected. While the street-level bureaucracy and principal agent literatures suggest attributes such as race and education influence compliance, we highlight the importance of financial and familial circumstances.

Chapter 2: Sanitation research focuses primarily on containing human waste and preventing disease; thus, it has traditionally been dominated by the fields of environmental engineering and public health. Over the past 20 years, however, the field has grown broader in scope and deeper in complexity, spanning diverse disciplinary perspectives. In this chapter, we review the current literature in the range of disciplines engaged with sanitation research in low- and middle-income countries. We find that perspectives on what sanitation is, and what sanitation policy should prioritize, vary widely. We show how these diverse perspectives augment the conventional sanitation service chain, a framework describing the flow of waste from capture to disposal. We review how these perspectives can inform progress toward equitable sanitation for all (i.e. Sustainable Development Goal 6). Our key message is that both material and nonmaterial flows—and both technological and social functions—make up a sanitation "system." The components of the sanitation service chain are embedded within the flows of finance, decision making, and labor that make material flows of waste possible. The functions of capture, storage, transport, treatment, reuse, and disposal are interlinked with those of ensuring equity and affordability. We find that a multilayered understanding of sanitation, with contributions from multiple disciplines, is necessary to facilitate inclusive and robust research toward the goal of sanitation for all.

Chapter 3: The COVID-19 pandemic has exposed underlying inequities and inadequacies of infrastructure that require immediate attention. It has underscored the needs of marginalized groups, particularly those who depend

on public spaces for their livelihood and on public infrastructure for access to water and sanitation. Throughout Indian history, prominent figures have made the case for accessible and well-maintained sanitation facilities in public spaces such as marketplaces, railways, and low-income areas, but this call has gone largely unheeded. As a result, during the COVID-19 pandemic, thousands of migrant workers and their families crowded buses, trains, stations, and streets—or were locked down in low-income areas—with no access to clean sanitation facilities. In this chapter, I trace how distress related to epidemics has been linked to advocacy for public sanitation across India's history. I show how disease and war constrained but also inspired past advocates to see their visions fulfilled. Informed by these lessons from the past, I recommend concrete actions for Swachh Bharat Mission-Urban in order to improve its effectiveness for the poor by focusing on public sanitation. I argue that we learn from history that pandemics are precisely when we should prioritize sanitation, especially in public spaces and particularly for the poor.

For the valvemen of Bangalore
and frontline workers

Table of contents

Preface

If you are reading this, you probably know me and may be looking for your name (please know that even if it's not listed below, your name is written on my heart). Or maybe you are incredibly bored (if so, then I suggest you read the Introduction and Conclusion of my dissertation as well—they are a bit... unconventional, though maybe not as unconventional as this preface). Or perhaps you are a grad student trying to figure out how to write a dissertation or, even more generally, how to make it through grad school. If that's you, then you're in luck, since the implied subtitle for this preface is "The Hidden Curriculum of Grad School: Blood, Sweat, and Chai." Thriving in grad school depends not only on books and research acumen, but also on skills and resources that are often unacknowledged or hidden. So watch out for these hidden treasures as I tell you a tale of how I made it in grad school with the help of blood, sweat, and gallons and gallons of chai.

It's a bit gauche to quote yourself, but here I am, doing it anyway. (Academics do it all the time, but it's not pretty.) My purpose is not to increase my citation count, but to remind myself of who I was—pre-grad school. Like you, dear reader, I was wide-eyed, full of anticipation. I submit an excerpt from the personal history statement of my UC Berkeley grad school application as proof:

> Like India, I bring all of my past with me into the future while I take another one of those deliberate steps into graduate school. Past experiences on the Ganges, with school children and at bedsides in the ICU, inform me toward answering the question: What will it take to see "the future we want"? That future for me includes everyone being able to drink a clean glass of water. For such a basic need, I am ready for a lifetime of work ahead of me.

Blood stands for family, and it was during the time of writing my application that the "blood" part of "blood, sweat, and chai" played a huge role in helping me start grad school. Back then, I had just finished working in India for over a decade and was sleeping on the couch of my eldest sister's New York apartment (thanks Una, Adam, Will, Sam, Mia, and Virginia). I wasn't confident in writing academic statements, so I recruited some writing help from my brother-in-law, an English major (thanks Tom), and his sister, a poet (thanks Kak). I hesitantly submitted my application and was unexpectedly whisked away to Asia to help my parents.

I was on a short visa run in Tokyo, sitting at a cafe, overlooking Shibuya, when I received the email. I like to imagine the light turned green and hundreds of pedestrians crisscrossed the street, just as I read the words, "I am pleased to inform you that the Energy and Resources Group [ERG] is recommending you for admission to UC Berkeley." Just like that, it was time to move to California, but my heart trembled thinking about paying $1,500 a month for a one-bedroom

apartment. (Little did I know that it was a steal compared to the current $2,500 a month average in Berkeley!) Luckily, my second-eldest sister opened up her home to me during my first year (thanks Viv). And my then three-year-old nephew gave me his room (thanks Eli). And there I was, starting my Ph.D., sleeping in an Ikea bed, surrounded by Legos and a super cute menagerie of stuffed animals. That's blood. (By the way, they don't have to be your biological family. For many queer people, like myself, sometimes you need to create a "logical" or chosen family. I'll talk about that later.)

Along with blood comes sweat. I picture that movie scene in The Empire Strikes Back when Luke runs and sweats it out through the jungle with his green guru, Yoda, on his back. This scene encapsulates my first (second, third, and fourth?) year of grad school. It's the process of accumulating not only scholarly knowledge, but also acquiring something more, something akin to actual Jedi powers. I'll explain. During my first year, I was recruited for the valvemen project (see Chapter 1) by Professors Alison Post and Isha Ray. We would discuss our research (actually they mostly discussed while I quietly nodded). They would talk shop about this or that scholar or theory, and most (OK, all) of it would go over my head. Until one day, I had read up on a particular section of the literature that they were less familiar with, and they turned to me and asked, "So Chris, what does the literature say?" Suddenly, I became the expert in the group. Even more empowering was when Alison asked me, "What do your intuitions tell you?" My intuitions?! (a.k.a. Jedi powers) Be it during those moments with Isha and Alison, a Google Doc meeting with Alastair Iles, plopping down in a chair in Charisma Acey's office, or organizing a WASH symposium with Kara Nelson, my advisors were always on my back, but they guided me both into and through the jungle we call academia, and I emerged all the wiser.

Grad school was also about chai. During my first summer of grad school, I conducted field research in India, the home of sweet, piping hot chai, where I followed water valvemen and wrote down everything that I saw. I wasn't sure what would or wouldn't be of value for my study, and I wasn't even certain if I was doing my fieldwork correctly. Then it happened. A valveman invited me into his home, sat me down, and gave me a cup of chai. At that moment, I knew I had done something right. We had made a connection. Drinking chai together not only helped me learn more about the valvemen (while following research protocol of course), but it made us pause, look beyond the work, and forge a deeper bond. Though most of the fieldwork I had done in India did not make it into this iteration of my dissertation, I am indebted to the incredible support of my colleagues in India (thank you valvemen, my research assistant Bharadwaj, and friends from NextDrop, IIT-Bombay, BHU, CDD, Good As You, and across Bangalore), for their time, meals, and open homes. Like many a good relationship, it all started with that first cup of chai.

Although blood, sweat, and chai may have been the main ingredients in my grad school experience, they were hardly the only ones. There are, of course, other important ingredients you will need, like funders and reviewers (I acknowledge them in each chapter) and, as I mentioned above, those who—though not blood related—become family, i.e. your chosen family. When I started grad school, I was in a new place, starting a new life. I came out in my first year, and fortunately I found kindred queers in my grad program (thanks Andie, Zach, and the QuERGies). Looking back, it was grad school that helped me discover my chosen family.

As you may or may not have noticed, this "preface" is also secretly an "acknowledgements" section, so I'd like here to recognize those who have in so many ways become my chosen family during grad school. Whether it was in a microbrewery in Bangalore, a random club in Ann Arbor, or around the table at the Berkeley Water Center, my co-authors were amazing to work, hangout, and academically grow up with (thanks Anustubh, Tanu, Sharada, Swati, Will, Yoshika, and Zach). My research and writing groups were also a source of regular encouragement, especially during my final years and through the pandemic (thanks Yoshika and Vero, ERG Water+ Group, my PDL team, and Berkeley fiction writers). I also owe so much to the utterly unique ERG community of students, alumni, faculty, and staff (I'm looking at you Kay and Megan). The life that I started in the Bay Area would be unimaginable without my ERG cohort, Newbies2013 (a.k.a. "the best cohort")—a special shout out to Kripa for supporting me (and many of us) through quals and dissertation writing, and for tying rakhi on my wrist ever since we choreographed our first Bollywood dance together for the ERG Talent Show. Finally, Eric, who I met during my first year in grad school, has been my significant othERGie. My family and his have been a source of strength and joy these past 6+ years (love you Mama P). Eric edited and made me rewrite this whole acknowledgements section even though I only had a few days left to submit my dissertation, but he stuck with me through social upheaval, COVID-19, and grad school, so I'll let that one go. Plus, through it all, he's sparked joy in my life, so going with Marie Kondo, I guess I'll keep him. [Editor's note: Excuse me?]

As I said, I started grad school wide-eyed and full of anticipation, but last year here's something I tweeted:

> Spent time free writing today. The last line I wrote was: "After 6 years of PhD study, there are no good answers. I kind of knew that from the start, but for some reason, at this moment, it makes me a little sad."

Out of all my tweets last year, this one had the most likes, proving that for all grad students the rose-colored glasses eventually come off. I'm at the end of my Ph.D., and I didn't save the world, I didn't get a glass of clean water to everyone. But through my work, I did get some shitty water away from somebody—probably—and became friends with the most dedicated and brilliant people you

could hope to meet. And that is the final secret of the hidden curriculum: The point of it all is for you, dear reader, to figure out what it is that will make our world a better place, find others who will help, and to pursue it together. All the best and fiat lux.

Introduction | Invisible infrastructure

"Unless we alter the conditions in our cities, rid ourselves of our dirty habits and have improved latrines, swaraj can have no value for us."
- Mahatma Gandhi

"Realising any right, including the rights to water and sanitation, will almost invariably require that existing power structures be challenged, so that people who do not enjoy their rights to water and sanitation are given the opportunity to claim these rights."
- Catarina de Albuquerque

"The sewer is the conscience of the city. Everything there converges and confronts everything else. In that livid spot there are shades, but there are no longer any secrets. Each thing bears its true form, or at least, its definitive form. The mass of filth has this in its favor, that it is not a liar. Ingenuousness has taken refuge there. … All the uncleannesses of civilization, once past their use, fall into this trench of truth, where the immense social sliding ends. They are there engulfed, but they display themselves there. This mixture is a confession."
- Victor Hugo

"...water flows uphill toward money."
- Marc Reisner

"My main work is working with the public."
- Bangalore water valveman

1. You and four billion people this morning

Sometime in the last 24 hours, you probably went into your bathroom, turned on the light, brushed your teeth, and used the toilet. If your toilet had a seat and you sat on it, then that seat physically connected you to a system of pipes across your city—if not beyond it. If you imagine yourself as a part of this technological system, then your body completed a cycle of resources through processing water from the tap and produce from farms and markets. When you sit on a toilet, you become part of a flow of infrastructure. This is one of the most intimate connections that you can have with the rest of a municipal system. And you do this every day.

My technological assumptions about you—that you have a bathroom with a working light, running water, and a toilet connected to a municipal piped network—derives from the social suspicions I have about you. You are reading this. I, therefore, assume that you have access to some form of social power. You may not feel like a very powerful person, because, let's be honest, those interested in the social dynamics of toilets are not usually the most powerful people.[1] On the other hand, the fact that you are reading this means that you are

[1] Though there can be an argument against that if you consider Bill and Melinda Gates, Prime Minister Narendra Modi, the United Nations, and various donor organizations like the World

part of a category of people that has the access, time, energy, and ability to read dissertations and think about the politics of shit. This category of people, in my experience, also often has bathrooms, running water, and toilets.

I include you in the Introduction of my dissertation, because my research in academia has been about spotlighting humans who are often hidden or missing. I am going to try to convince you that despite our global pursuit of equitable access to technology and infrastructure, certain people are often rendered invisible. Invisibility has a variety of meanings, including when people and processes should be included but are totally absent, as well as when they are present or even listed as the purpose of a project but are ultimately hidden, ignored, or postponed. Invisibility is also a matter of perspective, i.e. who and what is invisible to whom.

One way of convincing you that people are invisible is by showing you how often you, the reader, and I, the writer, are also often unacknowledged and unseen. This is even though we may be directly or indirectly part of the problem, and you, like me, may be striving to be part of the solution to the challenges of water and sanitation. This is why I will acknowledge you and me at different points in this Introduction. As you know, unlike us, not everyone has access to clean water and improved sanitation. And as you read this, you probably have an innate sense that something is not good about that—maybe even unjust.[2]

2. Missing persons in water and sanitation

We live in a world where 844 million people lack basic drinking water services, and more than four billion people lack access to safely managed sanitation (see Figure 1). These are the missing persons of water and sanitation, proof that somehow people become invisible. Access to basic sanitation is actually decreasing in one out of seven countries, particularly in low- and middle-income regions (WHO & UNICEF 2017). In 2020, COVID-19 has further shown us major limitations in water and sanitation provision for the poor, especially observed when low-income migrants in India attempted to escape urban areas—or became locked down within them—with no access to clean facilities to wash their hands, defecate, or privately manage menstrual hygiene.[3]

Bank, Asian Development Bank, and other national and private donors. However, the fraction of finances dedicated to sanitation is quite small and, in 2020, waning.

[2] I use this informal, second person perspective inspired by and with apologies to Susan P. Shapiro (2005).

[3] See Chapter 3 of this dissertation.

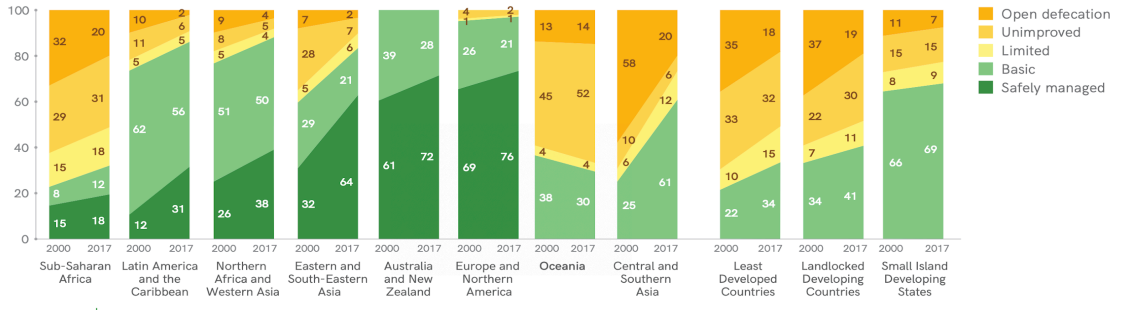


Figure 1 | Regional sanitation coverage, 2000-2017 (%) (WHO & UNICEF 2017)

The locus of my empirical work is in India, a country of an estimated half a billion people without access to safe sanitation (WHO & UNICEF 2017). My historical research traces urban water and sanitation policy in India from the British Raj to today. During India's freedom struggle, Mahatma Gandhi said, "Unless we alter the conditions in our cities, rid ourselves of our dirty habits and have improved latrines, swaraj [i.e. self-rule, independence] can have no value for us" (p. 57, CWMG 1965). Indian leaders have been talking about overcoming water and sanitation challenges for a long time. So what has held India and other low- and middle-income regions back from providing adequate water and sanitation for all?

Part of the challenge is that people—of marginalized groups in particular—go missing or are made invisible, and in this Introduction, I propose an invisible infrastructure framework to help render people and social dynamics more visible. First, I describe the big picture of sustainable development and how water and sanitation solutions are often centered on technology (or tech-led). Second, I explain that though (or possibly due to the fact that) water and sanitation solutions are tech-led, there are critical social challenges, and that people are rendered invisible. Third, I describe the invisible infrastructure framework and how it can render people and social dynamics more visible. Finally, I describe how invisible infrastructure is the conceptual arc of my whole endeavor in research to unlock solutions for water and sanitation for all.

3. Tech-led transformation

Improving water and sanitation is part of the global effort for sustainable development. This is clearly reflected in the United Nations Sustainable Development Goal 6 to "ensure availability and sustainable management of water and sanitation for all." With each iteration of our global goals, the aims of sustainable development have become more clearly articulated over time (e.g., from the Millennium Development Goals to the more integrated Sustainable Development Goals); however as Ian Scoones (2016) has pointed out, what is not as well understood are the processes toward meeting our goals.

In his 2016 *Annual Reviews* paper, Scoones describes four types of transformations in sustainable development: market-led, state-led, citizen-led, and technology-led (from here, tech-led). These transformations can be discussed as solutions. For example, a new toilet designed by engineers (especially one without direct community collaboration) is a tech-led solution, and a policy that promotes the reuse and sale of treated waste is a market-led solution.

Fixes to water and sanitation challenges are often framed as tech-led solutions. Nelson and Murray (2008) and Eawag's *Compendium for Sanitation Technologies and Systems* (2014) summarize the sanitation technologies available for low-income communities. One point of technological complication is that there are a number of primary and secondary products that flow into and out of sanitation systems. Figure 2 lists 20 types of sanitation products. Eawag's compendium attempts to simplify sanitation planning through templates that match products with various technology options. These templates are an example of a tech-led solution.

Figure 2 | Products of sanitation systems (Eawag 2016)

Figure 3 below shows one of those templates. It represents sanitation systems common for cities in low- and middle-income regions, except that many skip the treatment process represented in the green column. As shown, there are 17 treatment technologies to consider as well as pre- and post-treatment options that are not fully listed. The multitude of options (some unfamiliar to local engineers) is part of the complexity of sanitation, but organizations like Eawag attempt to simplify technological planning through tools such as these system templates, textbooks, and capacity building workshops. Using these tools, like in the Figure 3, are a part of a tech-led transformation in sanitation.

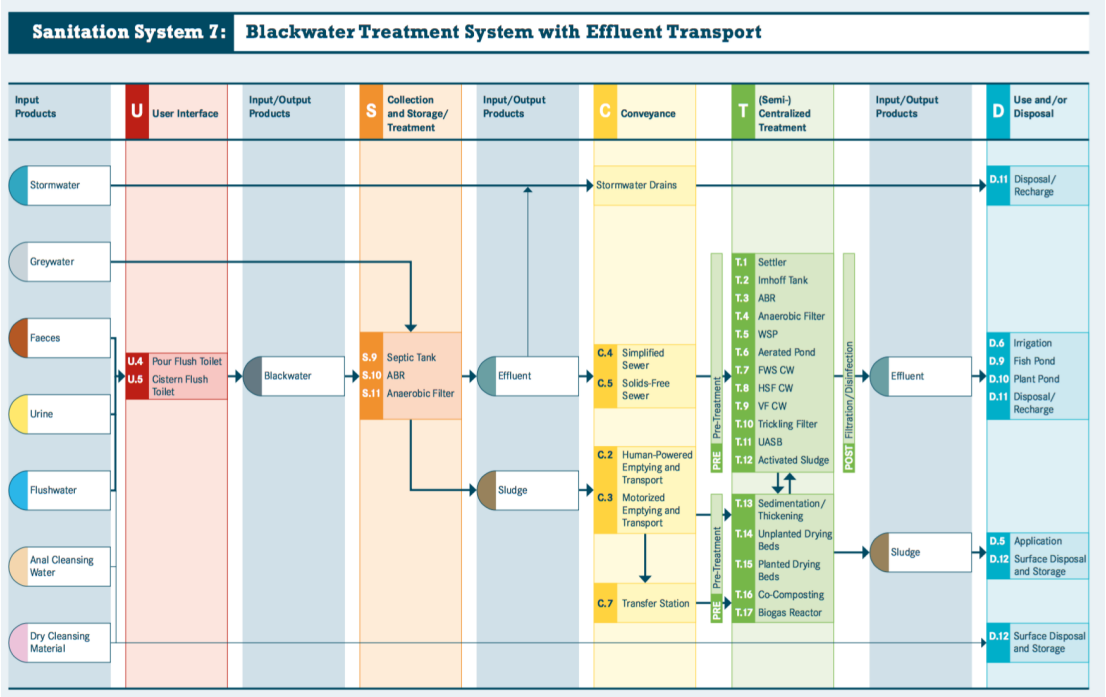


Figure 3 | Sanitation system template for blackwater treatment system with effluent transport (Tilley et al. 2014)

In the journal, *Science*, Larsen et al. (2016) present various solutions to our current and future water and sanitation needs, including technological innovation. They see the Bill and Melinda Gates Foundation's Reinvent the Toilet Challenge as spearheading new ways of thinking about technology, not only as a single artifact (i.e. the toilet) but as part of a sanitation system with multiple components, e.g., instead of a single-stream, waste can be separated and reused. Initiated in 2011, the Reinvent the Toilet Challenge contributed to a global narrative centered on tech-led solutions. The challenge invigorated risk-averse water and sanitation engineers toward considering unconventional technologies. In this way, narratives are powerful.

The power of narratives in part comes from their critical role in political processes. Narratives are the "lifeblood of politics" (p. 173, Shanahan et al. 2018). Taking this a step further, Scoones claims that politics are central to addressing major environment and resources challenges. It is politics that leads to "restructuring the relationships between resources, the state, markets, and society"; thus social justice should be "the core" of our debates about environmental resources (p. 1.6, Scoones 2016). In other words, the narratives we have about tech-led solutions have political implications in terms of restructuring relationships, social equity, and the realization of justice.

For instance, the Reinvent the Toilet Challenge (from here, the Challenge) has had five main criteria for reinvented toilets (see the box titled Reinvent the Toilet

Challenge Criteria). Three of these criteria form a strong tech-led narrative by pushing for resource recovery and off-grid, next-generation innovation. While it is laudable that poor, urban settings are included in the criteria, international development practitioners have critiqued that the Challenge has been overly tech focused, leading to unaffordable solutions (Humphreys 2014). A 2018 Bill and Melinda Gates Foundation report subsequently boiled down first phase adoption of reinvented toilets to three key market entry options: US military housing, government-sponsored tourist sites in China, and UNHCR refugee camps. The report admits that these are not the original "target populations" of the Challenge (Boston Consulting Group 2018). This, I would argue, is an example of how the Foundation's focus on high-tech innovation has led to capital-intensive solutions that limit early adoption only to those who can take on increased risk, excluding the initial target population of poor, urban communities—who have now been rendered invisible.

REINVENT THE TOILET CHALLENGE CRITERIA

- Removes germs from human waste and recovers valuable resources such as energy, clean water, and nutrients.
- Operates "off the grid" without connections to water, sewer, or electrical lines.
- Costs less than $0.05 US per user per day.
- Promotes sustainable and financially profitable sanitation services and businesses that operate in poor, urban settings.
- Is a truly aspirational next-generation product that everyone will want to use—in developed as well as developing nations.

Source: Bill and Melinda Gates Foundation (n.d.)

One could argue that the Foundation is playing a long game; the report does claim that the aim is to "unlock" markets that could ultimately reach the originally intended communities. In this sense, the urban poor are rendered invisible through postponement, i.e. the hope is they will receive improve sanitation—just not yet. There is, however, opportunity for them to have improved sanitation now. For instance, development practitioners have asserted that investing in existing low-tech and social solutions, such as behavior change, could already start providing greater sanitation access to low-income communities (Humphreys 2014).

My critique here is not that tech-led narratives and their associated solutions are corrupt or even inefficient, but that since the primary focus is on technological innovation, community needs and social dynamics become secondary. The development practitioners who have critiqued the Reinvent the Toilet Challenge

promote their own low-tech sanitation innovations, which are also tech-led solutions. Scoones sees this as an alternate tech-led narrative, focused on smaller, more appropriate technology, developed through bottom-up, grassroots innovation. This type of tech-led transformation would more likely be located within communities in contrast to the out-of-context market strategy of the Reinvent the Toilet Challenge. In this sense, it is possible to promote a tech-led transformation while keeping marginalized communities visible to engineers, planners, and decision makers.

Returning to Scoones's transformation types, I note that all four are human approaches, i.e. ways for humans to realize the goals of sustainable development; however unlike for citizen-led, state-led, and market-led solutions, the human aspects and social dynamics of tech-led solutions are not as readily apparent. Technology is often considered apolitical. As a consequence, social processes are rendered invisible, and a tech-led narrative can obfuscate the social justice role of technology and infrastructure. We therefore need to make the connections between technology and social justice more readily apparent for those involved in tech-led transformation.

4. Finding the missing persons

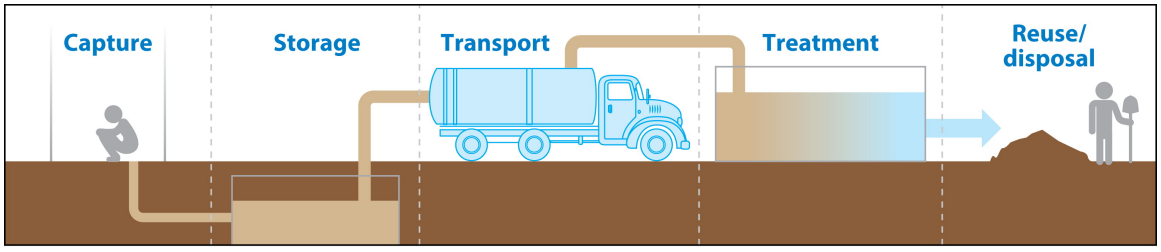
That people are rendered invisible in the water and sanitation sector is self-evident in the data. To reiterate: 844 million people lack basic drinking water services, and more than four billion people lack access to safely managed sanitation. The water and sanitation for all aim of Sustainable Development Goal 6 is pretty clear, but somehow these people go missing or become invisible during the process of water and sanitation provision.

As I mentioned above, I consider invisibility to mean that people are hidden, ignored, or postponed by those in influential positions. This occurs through often unacknowledged social processes. I consider a number of my research subjects as invisible. First, in my research on Indian sanitation history and policy, I note how sanitation data are collected and reported by the Government of India and show how their reporting approach hides the needs of low-income, marginalized groups.[4] In this case, these people are in the data, but they are hidden from decision makers. Second, in my field research in Bangalore, India, I uncover the experience and needs of valvemen who were tasked to send water supply data to the company, NextDrop.[5] On one hand, NextDrop recognized that the valvemen were integral to their data collection process, but on the other hand, they ignored the day-to-day needs of the valvemen. By being under-prioritized in this way,

[4] See Chapter 3.
[5] See Chapter 1.

the valvemen become more invisible to NextDrop, which at least partly explains why the valvemen eventually stopped sending the company data.

Finally, my review team and I established an augmented sanitation service chain.[6] We expanded the technological sanitation chain by adding stakeholders and the social flows and functions between them. People and social processes are totally absent from the conventional sanitation service chain (Figure 4), therefore rendering them invisible to researchers, planners, and policy makers who use it as a framework for sanitation. It was the process of developing an augmented sanitation service chain (Figure 5) that inspired me to consider a more general framework that integrates infrastructure with social systems.

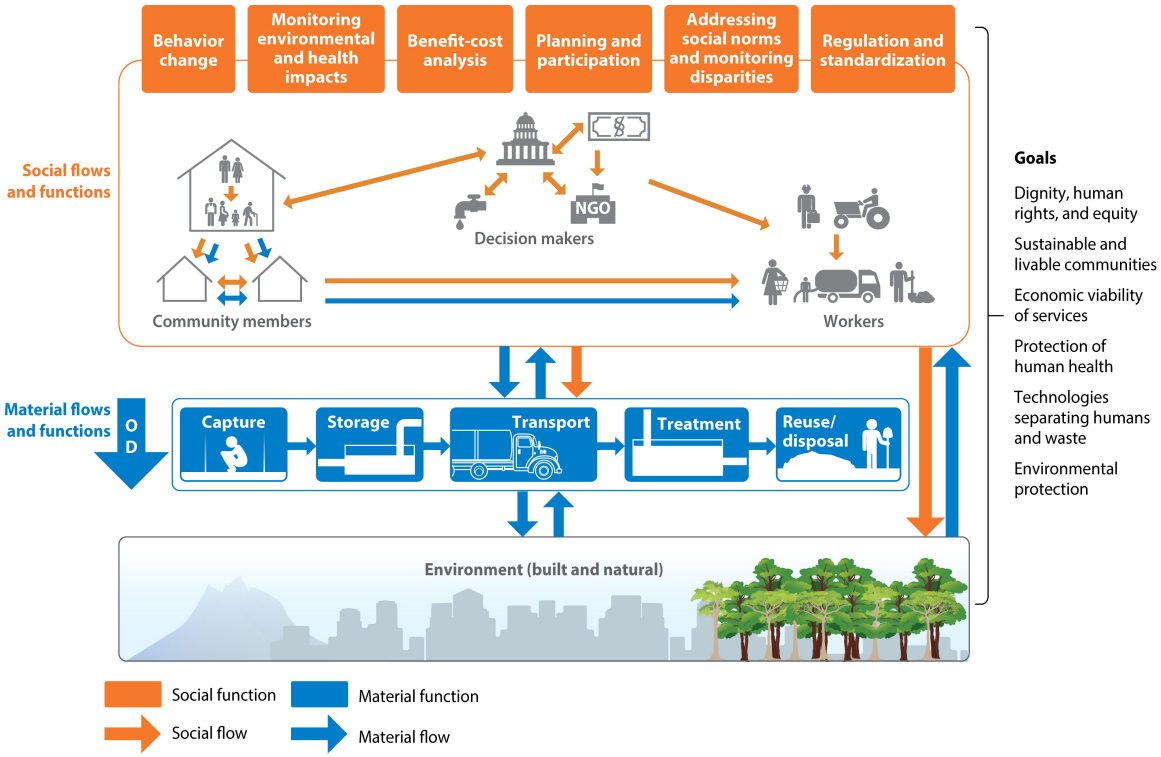


Hyun C, et al. 2019.
Annu. Rev. Environ. Resour. 44:287–318

Figure 4 | Conventional tech-focused sanitation service chain (Hyun et al. 2019)

The focus of my research endeavor has been on the invisible people of tech-led transformation. At the center of each of my research projects is technological innovation and infrastructure, e.g., the sanitation service chain, the public sanitation facilities of urban India, and the NextDrop app. For each project, I have uncovered the people and processes associated with innovation and infrastructure. These people and processes are a social system that have been rendered invisible, and therefore I consider them part of the "invisible infrastructure" of tech-led transformation.

[6] See Chapter 2.



Hyun C, et al. 2019.
Annu. Rev. Environ. Resour. 44:287–318

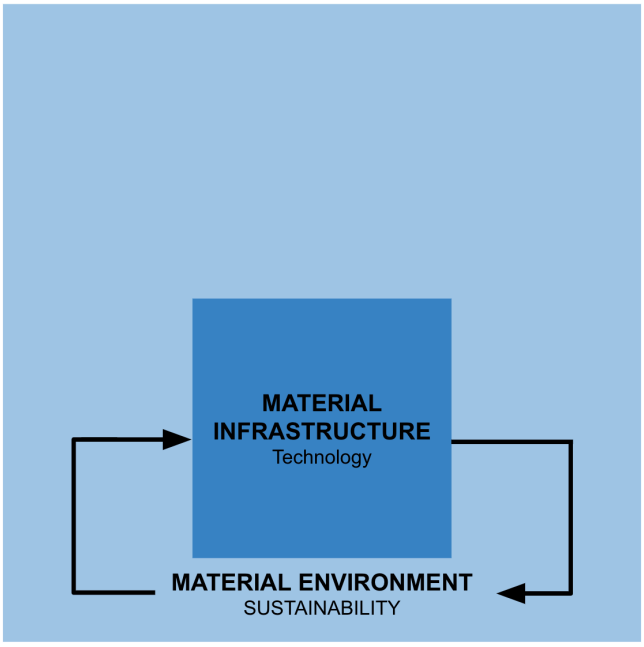
Figure 5 | The augmented sanitation service chain builds on the technological sanitation chain (blue) by including social systems (orange) (Hyun et al. 2019)

5. Invisible infrastructure framework for tech-led transformations

As a step toward theorizing and situating the collected knowledge that has underpinned my entire dissertation research, I propose an invisible infrastructure framework for tech-led transformations. One of my ultimate hopes is that this or some version of this framework can help render people—in particular those of marginalized groups—and social processes more visible to technology and infrastructure innovators, researchers, and decision makers.

As with the augmented sanitation service chain above, the invisible infrastructure framework is based on technological concepts, i.e. material infrastructure and flows, as shown in Figure 6. The dark blue box is analogous to Khalid Kadir's use of the engineer's control volume, where "[t]echnical experts draw a box around a technical problem. … We have inputs and outputs and we deal with what's inside the box" (p. 14, McGlynn 2014). Material inputs and outputs flow in from and out to the material environment. Technology of material infrastructure serves a variety of functions (i.e. actions for a purpose). For example, in sanitation, technological functions include storage, conveyance,

treatment, and reuse (see Figure 4). These functions serve greater material goals for the environment, with sustainability as a universal aim, e.g., as outlined by the United Nations Sustainable Development Goals. Like effluent from a wastewater treatment plant, material flows from infrastructure ultimately increases or decreases environmental sustainability.[7]



Material infrastructure (i.e. technology) is depicted as a control volume with material flows of inputs and outputs which are affected by and affect environmental sustainability.

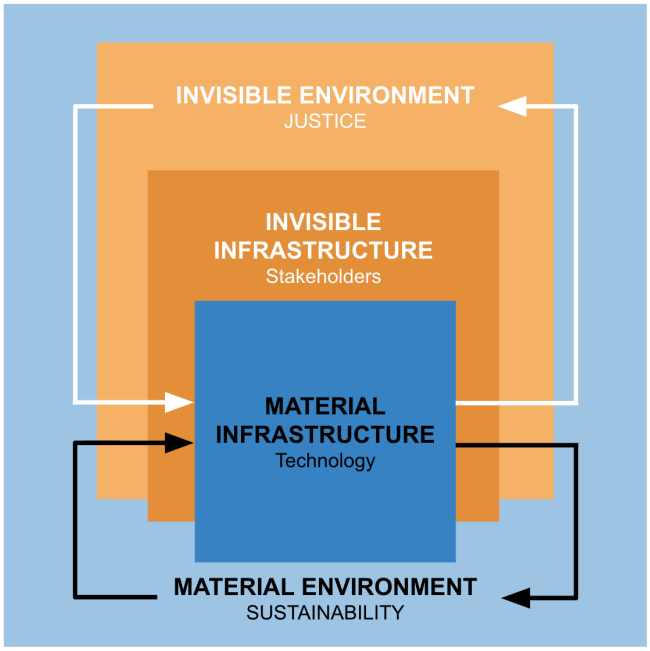
Figure 6 | Material infrastructure and environmental flows

The invisible infrastructure framework (Figure 7) adds the social context within which material infrastructure is developed and operates. It proposes that material infrastructure and the material environment have social counterparts that are often invisible in tech-led transformation projects. Each infrastructure and environment type is depicted as bounded system or control volume nested (at least in part) within one another.

What I have done in Figure 7 is nest systems within each other to provide a platform to discuss how material systems interact with invisible (or social) systems. At the heart of the figure is the material infrastructure or technological system (dark blue square), which is the focus of tech-led transformation projects, e.g., a new toilet design or fecal sludge treatment plant. Fundamentally, the framework suggests that technological systems (dark blue) are embedded in social systems (light and dark orange), which are in turn embedded in environmental systems (light blue). In the most rudimentary sense, the material environment produces and supports people, who further produce technology.

[7] Conceptually, sustainability is politically fraught and multifaceted, however I use it in the framework as it is currently recognized as a shared aim for the environment. There are other concepts to also consider as material aims for the environment, such as resilience and health.

But depending on context and scale, there are reversals as well as forms of mutual production and support. This is why the squares in the figure are not fully embedded within one another, and instead the interactions between systems are represented as overlaps.



The invisible infrastructure framework depicts how **material infrastructure** (i.e. the technology of tech-led transformations) is embedded in the social dynamics of **invisible infrastructure** (i.e. stakeholders that affect and are affected by tech). Invisible infrastructure (like material infrastructure) is depicted as a control volume with invisible inputs from and outputs to the **invisible environment** (i.e. social power systems, institutions, regimes). Invisible flows (white arrows) can be understood as flows of knowledge, influence, or capital between people and institutions. While material flows (black arrows) ultimately increase or decrease sustainability of the **material environment**, invisible flows may enhance or impede social justice in the invisible environment.

Figure 7 | Invisible infrastructure framework for tech-led transformations

As with material infrastructure, the invisible infrastructure (i.e. stakeholders) also has functions and flows. Functions are discrete activities that serve a specific purpose. As mentioned above, in material infrastructure, functions include actions like conveyance and treatment. Physical material, such as water and waste, flow (black arrows) across these functions in infrastructure. I use similar terms for invisible infrastructure (dark orange box). Stakeholders perform various functions related to producing or supporting technology, such as planning, benefit-cost analysis, and standardization. There is also an invisible flow (white arrows) of capital, knowledge, and social influence across these functions. Common functions and flows are listed in the Table 1 below.

A key aspect of the invisible infrastructure framework is the invisible environment (light orange box), which represents the overarching politics within which technological decision making occurs. Just as material infrastructure functions within a larger material environment, invisible infrastructure functions within a larger invisible environment of social power relations. In the invisible infrastructure framework, I consider justice as the ultimate aim of the invisible environment. Like material sustainability, social justice is a contested and multifaceted concept, but it is a universal aim, for example, as is documented in the United Nations Universal Declaration of Human Rights. Thus, the invisible

flows of knowledge, influence, and capital from the invisible infrastructure (i.e. the stakeholders of tech), can impede or enhance justice.

Table 1 | Flows and functions of the invisible infrastructure framework

Systems	Flows	Functions	Environment	Goals
Material	Material flows: water, waste, electricity, biogeochemical, etc.	Material actions contributing to defined purposes: storage, treatment, conveyance, reuse, disposal, etc.	Climate, ecosystems, infrastructure, etc.	Sustainability, including protection of human and environmental health, resilience
Invisible (Social)	Social flows: influence, authority, knowledge, discourse, capital, labor	Social actions contributing to defined purposes: policy making, regulation, monitoring, evaluation, training, budgeting, financing, etc.	Institutions, hegemony, regimes of truth, rule, and accumulation	Justice, including dignity, social equity, realization of human rights, livability, as well as economic viability

So in what way shall we conceptualize the invisible environment in order to make it more just? The invisible environment includes institutions and social systems that are often referred to as hegemony in political economy literature. Watts and Peluso (2013) call such invisible power structures regimes, and considers three types of regimes: truth, rule, and accumulation. Each regime represents different theories of power. Scoones (2016) summarizes the regimes of truth, rule, and accumulation by saying that they are overarching social powers that govern who knows what, who controls what, and who gets what. In the invisible infrastructure framework, I use the three regimes to define the invisible environment in order to explain how the invisible environment may influence invisible infrastructure. I claim that the regimes (i.e. the invisible environment) render various stakeholders invisible and that technology is a material manifestation of social power.

To illustrate, I return to the example of the Reinvent the Toilet Challenge. The five prize winners of the first Challenge competition in 2012 were North American and European universities and institutions (Bill and Melinda Gates Foundation 2012). On one hand you could consider this as the expected outcome of the competition—especially since, other than Singapore and South Africa, North American and European institutions were awarded initial grants the year before (Bill and Melinda Gates Foundation 2013). But if the Challenge targets the billions of people who do not have access to improved sanitation, then why weren't grants awarded to researchers and technology developers in those countries that have the most need? In very simple and broad terms, it is because that is not the way the world currently works. The most expedient approach to achieve technological innovation, in the Gates Foundation's implicit framing,

would be through those who already have the knowledge, control, and means (i.e. social power) to do it—in this case, relatively wealthy universities. However as a consequence, the new technologies of the Challenge have often been capital-intensive and complex, in other words, inaccessible to the billions for whom they were supposedly intended.

This is one example of how the invisible environment can explain how inappropriate innovations are produced and how stakeholders (e.g., lower income universities and target communities) are rendered invisible. This is not to say that the Reinvent the Toilet Challenge has only produced inappropriate technology. I do, however, encourage engineers, researchers, and decision makers to, in a sense, expand system boundaries by including the invisible environment and the role it plays not only in technological innovation but also social justice.

Referring back to Table 1 above, I list material as well as invisible social goals in order to consider how they are coupled. The social goals (e.g., dignity, social equity, human rights, and livability) are aspects of social justice, and designers and decision makers should continually interrogate how these social goals affect and are affected by technological goals. The first United Nations Special Rapporteur on the right to safe drinking water and sanitation, Catarina de Albuquerque, couples material water and sanitation goals to social justice by championing the need to confront regimes of social power:

> Realising any right, including the rights to water and sanitation, will almost invariably require that existing power structures be challenged, so that people who do not enjoy their rights to water and sanitation are given the opportunity to claim these rights. This happens not only through protest or through the courts, but also by means of policy, legislation and regulation, understanding and respecting the key principles of human rights and prioritising the needs of those living in poverty, targets of discrimination, the marginalised, and vulnerable individuals and groups (p. 29, de Albuquerque & Roaf 2012).

Engineers, researchers, and policy makers through tech-led interventions are often unknowingly involved in shaping human rights and social justice. My hope is that the invisible infrastructure framework makes it clearer that they and the tech they promote can either exacerbate or challenge injustice.

6. Finding missing persons in the following chapters

Each of the following chapters of my dissertation uncovers various aspects of invisible infrastructure in the context of water and sanitation for all, especially in urban India. The chapters are quite distinct from one another in that they: focus on various regional contexts (e.g., from the city of Bangalore, to all of India, to all low-income regions), draw from varying theories and disciplines, use different data sources (e.g., quantitative datasets, peer-reviewed literature, archives), and analytical approaches (e.g., empirical observation, mixed method, review,

history). However, the common goal is water and sanitation for all with an overarching message that certain stakeholders—in particular from marginalized groups— and social dynamics have been rendered invisible in the innovation and infrastructure initiatives of each chapter. In this Introduction, this theme has been theorized as the invisible infrastructure framework for tech-led transformations. Though the term "invisible infrastructure" is not invoked, each chapter touches different aspects of the framework as summarized in Table 2 below.

The research projects of each chapter reveal invisible people and systems. For example in Chapter 1 on frontline workers, the water valvemen are quite visible to both the innovators (NextDrop) and government administrators (the Board), but their perspectives and experiences of their own jobs were unknown by these decision makers. Furthermore, both NextDrop and the Board deprioritized valvemen through decreasing communication with them and, in the case of the Board, privatizing their jobs and drastically lowering their compensation. In these ways, NextDrop and the Board increasingly separated themselves from the valvemen who in turn felt ignored even though the valvemen were crucial to the operations of both NextDrop and the Board's technological systems—in other words, the humans of infrastructure were rendered invisible.

In Chapter 2, my collaborators and I show how sanitation systems are represented unevenly and incompletely across the literature of various disciplines, where sanitation-related goals and interactions may be hidden, unknown, or given little attention. We develop an augmented sanitation service chain to include social and environmental systems, providing a fuller picture of sanitation systems, a framework through which collaboration can occur across siloed disciplines.

In Chapter 3, I show how since the 1800s, advocates have been fighting for sanitation for marginalized groups in India, including marginalized laborers and migrants. The fact that these groups did not receive adequate sanitation services while others did is indicative of how invisible they were to decision makers. Prominent actors like Mahatma Gandhi and the city government of Surat were concerned about sanitation for the poor and internal migrants, who still did not get access to the infrastructure they needed. This suggests that, even if marginalized groups are acknowledged by major influencers and decision makers, there are social systems (regimes) that de-prioritize these groups. These systems themselves may be invisible to decision makers. In the chapter, I make practical recommendations to the Government of India for how the poor can be prioritized in sanitation policies, making them more visible to those who determine policy.

Table 2 | Overview of invisible infrastructure in each of the following chapters

Themes	Chapter 1: Frontline workers	Chapter 2: Sanitation in low-income regions	Chapter 3: Clean latrines now
Material infrastructure	Tech innovation, municipal water infrastructure	Sanitation service chain	Public sanitation facilities
Invisible infrastructure: Who is made invisible?	Stakeholders: Frontline and intermediary workers, low-income neighborhood contexts	All stakeholders, social functions, and social flows	Stakeholders: Indians, laborers (caste), low-income (class), migrants
By whom?	Innovators, engineers, government administration	Researchers across disciplines	International, national, and municipal officials
Invisible in what way?	Stakeholder perspectives are hidden, they are de-prioritized	Stakeholders and social dynamics are not included in the sanitation service chain	Stakeholders are ignored, argued away, and under-prioritized in assessments
How is this revealed?	Interviews and participant observation	Literature review	Archives and policy documents
Invisible environment: What theories are employed?	Regimes of rule: principal-agent and street-level bureaucrat theories	Regimes of truth: Interdisciplinarity	Regimes of rule, accumulation, and truth: Colonialism, casteism, classism, justice, policy process
How to render more visible	Reveal how workers view their own jobs and local power dynamics	Framework to bridge disciplinary silos and to include social goals (e.g., dignity and equity)	Advocates speak out for marginalized groups and against hegemony
What we learn about invisible infrastructure	Human perspectives are part of and affect technological systems and innovation for sustainability	Social and environmental systems should be included in technological conceptualizations in order to achieve social goals	Water, sanitation, and justice are interconnected, requiring vision, advocacy, and policy that practically implements inclusivity
Remaining questions	How to conceptualize the relationship between humans and infrastructure?	How do these conceptualizations apply in policy and practice?	From the conclusions of these chapters, what are the recommendations?

While each chapter uncovers hidden people and systems of the invisible infrastructure, questions remain that are at least partially answered by each succeeding chapter (see the bottom two rows of Table 2 above). In this way, I render the invisible infrastructure more visible in order for technology to be developed that gets closer to providing water and sanitation—and ultimately justice—for all.

Chapter 1 | Why frontline workers don't comply: insights from the water valvemen of Bangalore[8]

1. Introduction

More information for lay citizens, cheaply provided and easily accessed, is at the heart of global efforts to "make services work for poor people" (World Bank 2004). The underlying assumption is that transparency improves citizens' experience with service delivery; information about services positions citizens to make better use of them. In addition, citizens armed with information about service provider performance are better placed to press for improvements and to demand accountability. Improved transparency, in other words, promotes a virtuous cycle leading to improved service delivery. Development institutions, telecommunications companies, and national governments have channeled significant funding into informational interventions to improve the quality of public services. A growing body of scholarship in Public Administration, Development Economics, Political Science, and Development Studies now evaluates the efficacy of such policies (Pande 2011; Lieberman, Posner, and Tsai 2014). This paper is part of an impact evaluation of an informational intervention in Bangalore's water sector.

"Transparency fixes" to long-standing problems with service delivery often hinge upon the cooperation of human intermediaries who ultimately supply information to citizens. This is particularly the case in low- and middle-income countries where automated information production and dissemination are not common. For instance, some utilities can afford the technologies to monitor water flows and consumption, and to compile and publish information on these. Others, however, do not possess reliable information on the water they distribute and how much is consumed versus lost in transit. In these situations, utility workers have to manually spot-check flow and pressure along the piped network and turn in logbooks to their superiors. Even interventions with information and communications technologies at their center, such as government-subsidized

[8] Chapter 1 is included here with the permission of my co-authors, Alison E. Post and Isha Ray. Human subjects approval was obtained for this project from UC Berkeley's Institutional Review Board, Protocol 2014-04-625, titled, "Information as a management tool for intermittent water supplies: an impact evaluation from Bangalore, India." The published work with supplemental material can be found at: Hyun, C., Post, A. E., & Ray, I. (2018). Frontline worker compliance with transparency reforms: Barriers posed by family and financial responsibilities. Governance, 31(1), 65-83, doi.org/10.1111/gove.12268.

computer kiosks or cell phone based price retrieval programs, have human intermediaries connecting the "last mile."

Frontline workers in public services are frequently the weak link in the information delivery chain. Researchers and journalists have reported on the reluctance of frontline workers to accept information collection and dissemination reforms, for example in the utilities, transport and banking sectors, because such reforms threaten low-level jobs or cut down opportunities for graft. In some cases, implementing informational reforms have been too time-consuming or costly for frontline workers. In other instances, workers have been enthusiastic and entrepreneurial, acting as a liaison between citizens and the state, or actively promoting health and educational reforms.

Our study focuses explicitly on this theme: we examine why frontline workers do not comply with orders to provide information for transparency initiatives, even when doing so would require little additional time or effort. We analyze a new informational intervention in the urban water sector in India. With insufficient water to meet current needs and inadequate carrying capacity of the water infrastructure, almost all Indian cities provide water intermittently. Households receive water for a few hours a day a few times a week, often at unpredictable times. To reduce the coping costs associated with unpredictable water, NextDrop, a social enterprise, pioneered a text-message based system whereby households were given real-time information on when (or whether) to expect their water on a given day. NextDrop's system relied upon the cooperation of the city's water valvemen, or street-level utility workers, who physically turn water valves on and off, releasing water to small clusters of households at a time. In Bangalore, where NextDrop partnered with the water utility, calling the company to report whenever valves were adjusted became an official part of the valvemen's job description.

Our goal in this paper is to explain both modest rates of, as well as variation in, frontline worker compliance with this attempt to make water schedules more transparent to Bangalore's residents. The paper is a companion to an experimental evaluation of the household-level impacts of NextDrop's services (Kumar et al. 2018). Impact evaluation research for development interventions has increasingly turned to the rigor of experimental research for a credible answer to the question of what works and what does not work. However, experimental research designs cannot provide insights into *why* an intervention succeeded or failed. Our impact evaluation identified non-complying frontline workers as the primary reason for the failure of NextDrop's system. This paper goes beyond evaluation to explain *why* the frontline workers, Bangalore's water valvemen, frequently did not comply. It represents one of the first examples of a

multi-method study designed explicitly as a companion to a field experiment, rather than as an after-the-fact effort to understand null findings.[9]

Drawing on months of ethnographic fieldwork and analysis of an original dataset collected for this project, we find that to understand the overall modest levels of compliance with the system, we must understand how street-level bureaucrats (SLBs) rank new, relative to existing, responsibilities. We argue that prioritization is often tied to how SLBs perceive their jobs. If the new task, for instance an information-oriented reform, is seen as peripheral to the core job, it may not get done. Job perceptions on the ground can be "sticky," especially if these perceptions are reaffirmed through interactions with citizen-clients. In theoretical terms, as we discuss below, this finding affirms the model of the SLB as a "citizen-agent" from the literature on street-level bureaucracy, as opposed to the "state-agent" figure more common to the principal-agent literature.

We find that to understand variation in compliance rates across neighborhoods, we must consider the individual circumstances of the workers who service them. When financial circumstances and family responsibilities constrain the flexibility and attention that SLBs can devote to their work, new tasks can be the first to go. Yet informational interventions are often designed precisely as add-on tasks to SLBs' existing jobs. SLBs are inevitably embedded in particular financial and familial situations, but how these affect their work performance is seldom discussed in the principal-agent and street-level bureaucracy literatures.

In the rest of the paper, we review the strands of these literatures that are particularly relevant for our project; we highlight their contributions to understanding organizational, community, and individual-level influences on compliance. We discuss the text-message based transparency initiative analyzed in this paper, documenting the modest overall levels of compliance we observed among water valvemen as well as significant individual-level variation. We describe our mixed-methods study design, review our findings, and conclude with the implications of our results.

2. Frontline workers: from compliance to understanding

The dominant approaches to studying how frontline workers might react to additional responsibilities are principal-agent theory and street-level bureaucrats theory. Asymmetric information and its implications are central to both these literatures.

[9] See also Ananthpur, Malik and Rao (2014) for an impact evaluation involving a substantial parallel, ethnographic component. See Dunning (2008) and Kaspizewski, MacLean and Read (2015) on how qualitative methods can inform field experimental design and explanations of *why* interventions have the effects that they do.

The principal-agent literature is mainly concerned with "Weber's asymmetry" (Miller 2005), where the principal has the policy-making authority but only the agent has the information needed to implement the policies. The principal therefore has to wrest compliance from frontline workers despite asymmetric information and policy uncertainty. Performance-based incentives or the threat of penalties tend to dominate analyses within this framework (Gailmard and Patty 2012; Shapiro 2005). The SLB literature is more agent-centric; Lipsky's path-breaking work showed that frontline workers exercise discretion in order to, in effect, shape policy from the bottom up (Lipsky 1980). Access to street-level information that their superiors do not have enables such "pragmatic improvisation" (Maynard-Moody and Musheno 2012). Skilled workers such as doctors and veterinarians use their knowledge to navigate between their clients and their superiors (Schott, van Kleef, and Nordegraaf 2016), but experiential knowledge or *mētis* (cf. Scott 1996, 74–75), born of long practice, gives even SLBs with little formal education the confidence to go against their principals. These literatures show that the extent to which information asymmetries and credible threats act as countervailing forces can help explain both compliance rates as well as their variation across neighborhoods and individuals.

We categorize additional explanations of frontline worker behavior into organization-, community-, and individual-level factors. This categorization is implicit in most studies (but see Riksheim and Chermak 1993), and allows us to systematically investigate factors that may explain modest rates of, as well as variation in, compliance with transparency interventions.

Oberfield (2014) defines *organizational influences* as coming from "intra-organizational systems, processes, and dynamics" that shape how SLBs act. Feasible levels of monitoring (Banerjee and Duflo 2006; Miller 2005); robustness of the accountability mechanisms among principal, agent, and citizen (Caseley 2003); corruption within the organization (Bussell 2013); and organizational "culture" (Crook and Ayee 2006); all determine the extent and nature of discretion. Monetary incentives matter, but can backfire if they are too large or too small (Kamenica 2012); non-monetary incentives, such as uniforms, may work to affirm worker identity qua worker and keep the agent from acting against the principal's interests (Akerlof and Kranton 2005). Routines also shape worker behavior, including discretion (Hasenfeld 2000). These studies indicate that levels of compliance are jointly determined by incentives and habitual behaviors. Organizational factors influence overall levels of compliance within an organization and help explain variation in compliance between organizations.

Community influences stem from the localities in which SLBs work and include neighborhood characteristics and social norms. Norms are particularly well-recognized in the literature on police behavior (Shannon Portillo and Rudes 2014; Willis and Mastrofski 2011). SLBs may collectively set norms in the absence of organizational directives (Hupe and Hill 2007), or the community (i.e. the SLB's

ecosystem) may signal its priorities and send SLBs "clues" about what is or is or not important (Kamenica 2012). SLBs also make judgments about community characteristics and about what is "normal" to each context; at worst, they may provide low-quality work in low-income neighborhoods and internally justify this by labeling the residents as "undeserving" (Hastings 2009). These arguments suggest that compliance levels may vary with the socio-economic character of the community served, even for the same frontline worker.

Individual characteristics can explain variations in worker performance on the same job and in the same communities (Oberfield 2014). The most obvious of these are education and experience (e.g., Moynihan and Pandey 2007). But social identity such as age, ethnicity, and gender – of the agent and of the principal – significantly determines an SLB's view of which "rules" must be followed (Akerlof and Kranton 2005; S. Portillo 2012). Dispositional traits such as conscientiousness and open-mindedness (Callen et al. 2015) are predictors of high performance (from the principal's perspective), while professional traits such as the trained instincts of home nurses or teachers (Harrits and Møller 2014) may support or go against the principal's interests. Compliance, in these studies, is explained by a complex combination of personal and contextual factors.

We draw on these studies to outline our expectations about when frontline workers will comply with transparency interventions (and possibly other informational reforms). Overall compliance may be modest because frontline workers' perceptions of their principal job responsibilities are sticky. These perceptions partially derive from the organizations where they work and the communities that they serve, and are reinforced through frequent interactions with those communities. Any new task, unless seen by the agent as a core element of the job, may be neglected. Yet many informational interventions are in fact designed as add-on tasks for the frontline worker: sending notifications, showing citizens how to access government data, etc. Without high-powered incentives or high community demand, such interventions may be especially vulnerable to street-level "non-compliance." Moreover, threats of dismissal if workers do not comply may lack teeth in the face of information asymmetries. SLBs are integrated into informational interventions precisely *because* they possess information their organizational superiors do not.

Variation in compliance across local contexts may stem from two sources. First, as the literature building on Lipsky (1980) suggests, street-level bureaucrats interact differently with different types of clients, for example, across neighborhoods of different socio-economic or ethnic character. Second, variation in the individual characteristics of SLBs, such as education, disposition or motivation could be reflected in variation in compliance. We suggest that additional factors may affect workers' "capacity to cope" (Schott, van Kleef, and Nordegraaf 2016, 603): financial pressures or family obligations, such as the number of children a worker supports or the flexibility of his or her spouse's

occupation, distract SLBs during the workday, particularly when workloads are already heavy. These constraints have been underemphasized relative to other individual characteristics in the SLB literature.

Understanding SLB behavior in informational interventions as a combination of how SLBs understand their work and their personal constraints highlights the challenges of incentivizing compliance with such tasks. In this paper, we show that the water valvemen of Bangalore behave more like agents of their citizen-clients than like agents of the state utility, and that many prioritize tasks intended to address the needs of (what they call) "the public."

3. Compliance with NextDrop's water notification system in Bangalore

Our study focuses on a cell-phone based system intended to help households cope with intermittent water supply by providing them with advance notifications of water arrival times. Over 100 million people in South Asia live with intermittent water supplies (Kumpel and Nelson 2016) with a mean supply duration of 7.2 hours a day (www.ib-net.org). In many cities, water arrives every third or fourth day, for just a few hours at a time. This is because, as cities have expanded, the water supply and/or piped network has been unable to keep up with demand. Furthermore, water supply timings are unpredictable due to erratic electricity supplies. Unpredictable and intermittent water supply is stressful because households have to wait for water to arrive and then quickly fill up every available storage container while it is still on. If they miss a supply period, they must turn to more expensive sources such as water vendors. From the utility's perspective, intermittency also makes it difficult to track and manage the city's flow of water in real time.

In urban India, intermittent water supplies are allocated via frontline utility workers who manually turn the water valves on and off, controlling water flows into "valve areas" of 20 to 200 households. Without flow sensors installed throughout the water system, the valveman assigned to each valve area is the best informed on when to expect the actual water supply, or whether to expect water that day at all (see also Björkman 2015). There is always an information gap between the valvemen and the utility, and between the valvemen and residents.

NextDrop, a social enterprise, aimed to close this information gap and provide utilities and city residents with something they have never had previously—real-time digital information on municipal water flows across the city. NextDrop reasoned that households would be better able to cope with intermittent water supply were they to receive advance notification regarding water arrival times and supply cancellations. To do this, they created digital maps of the valve areas (Figure 1), collected GPS coordinates for households who wanted these

notifications, and placed the households within specific valve areas. The valvemen, after every valve adjustment, were asked to input these data through NextDrop's interactive voice response (IVR) system. NextDrop processed this information and sent a text message (or SMS) to residents telling them when their water would arrive (e.g., "Your water will arrive in 30 minutes"), or if it would be delayed or cancelled. NextDrop piloted their system in the city of Hubli-Dharwad (population ~1,000,000), adjusted their software, and then rolled out their services in Bangalore (~8.4 million) and Mysore (~900,000).

Figure 1: Example of BWSSB Valve Areas (from Subdivision E3, the site of the NextDrop impact evaluation)

The research described here focuses on valveman compliance with the NextDrop system in Bangalore. At an average supply duration of four hours a day, Bangalore has one of the lowest reported water supply durations among Indian megacities (McKenzie and Ray 2009). While an economically vibrant city, it has numerous low-income settlements and widely varying qualities of public services.[10] So there was reason to expect the system to be of use to households. Starting in 2013, and with a Memorandum of Understanding (MOU) with the Bangalore Water Supply and Sewerage Board (BWSSB) in place by 2014, NextDrop started signing up residents to receive real-time water supply notifications on their mobile phones. The service was free because the utility paid

[10] On variation among low-income settlements in Bangalore, see Krishna, Sriram and Prakash (2014).

the company directly. Because of the MOU between the company and the utility, sending notifications became part of the valvemen's official job description.

From the start, the NextDrop staff knew that the valvemen might be reluctant to comply with their notification regime. The entire set up – one in which the BWSSB had administrative authority and the valvemen had knowledge – reflected "Weber's asymmetry." During their pilot in the smaller twin cities of Hubli-Dharwad, NextDrop garnered a workable level of cooperation from the valvemen. The company tried various incentives for them: a point-reward system, social incentives such as recognizing the "valveman of the quarter," and personal assistance such as replacing worn footwear. The company never kept data on incentive-specific performance but believed that the combination of individual and social incentives was effective. Scaling up this highly personalized system to the megacity of Bangalore proved challenging, so NextDrop relied upon BWSSB's hierarchy to encourage valvemen to submit the required data. In effect, the Bangalore rollout substituted the reliance on valvemen's individual incentives for reliance on the utility's organizational structure – arguably a more scalable proposition.

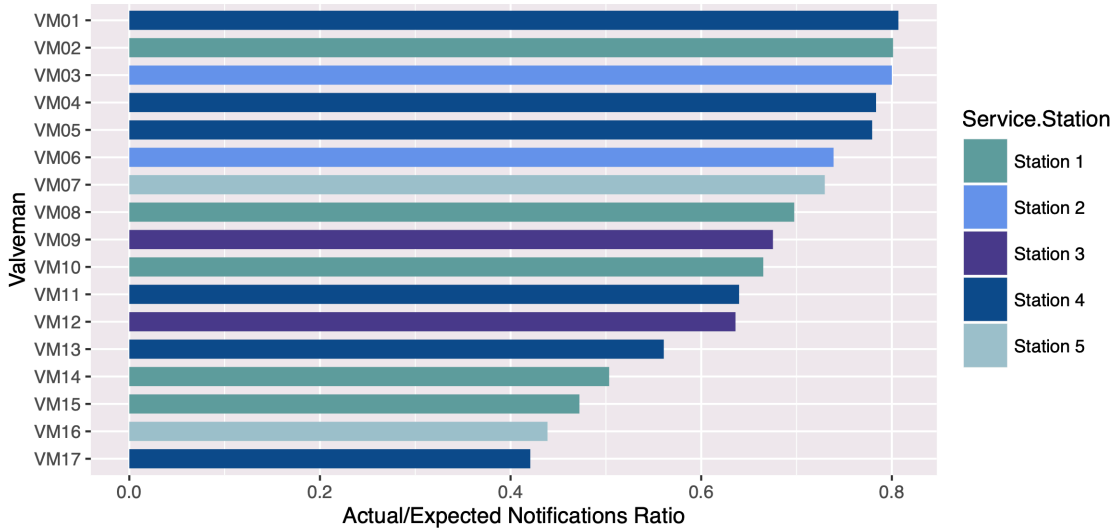


Figure 2: Notification compliance (actual/expected valve opening reports) per valveman of Subdivision A (8-12/2014)

Adding NextDrop notifications to the job description proved only partially successful in Bangalore. Valvemen did not submit notifications all the time and rates of compliance varied substantially by valveman. Figure 2 presents data for one of the utility's subdivisions (to protect valveman anonymity, we call it Subdivision A). It reports the number of notifications sent when opening water valves relative to the number expected based on the utility's official supply

schedule.[11] Each bar represents the ratio of actual to expected reports for an individual valveman. We observe notification ratios between 0.42 and 0.81, or moderate levels of compliance overall. We also observe variation across valvemen within the subdivision and within the same service stations[12] (the different shades represent the five service stations covering Subdivision A). Therefore, even when controlling for organizational factors, the variation in compliance across valvemen is prominent.

4. Study design and data

Our study adopts a mixed-methods approach to understanding why valvemen complied at only modest levels with the NextDrop intervention, and why rates of compliance varied across neighborhoods. We paired extensive qualitative research with water valvemen with the compilation and analysis of an original dataset on the timing and frequency of valvemen's notifications, the characteristics of individual valvemen, and the communities they served. We drew on our qualitative data to understand the overall rates of compliance with the intervention, and on our qualitative and quantitative evidence to understand variation in compliance across neighborhoods.

BWSSB has divided Bangalore into 32 subdivisions for administrative purposes. Our study focuses on Subdivision A, where the company felt that they had resilient relationships with the valvemen. Subdivision A is also far enough from where our research team was conducting the impact evaluation of NextDrop's intervention (Kumar et al. 2018) that the studies could not influence one another.

We measured levels of valveman compliance using NextDrop's notification data for valve openings (Figure 2). To understand why compliance was modest overall, we employed an ethnographic approach; the lead author (with a local translator) conducted open-ended interviews and extended observations of valvemen, as well as dozens of interviews with utility staff, residents, and NextDrop employees in neighborhoods across Bangalore. This gave us a sense of the physical and institutional structure of the municipal water system in which the valvemen carry out their duties. We selected nine out of the 17 valvemen within Subdivision A, who varied significantly in terms of compliance, for further analysis.[13] The bulk of our study focused on these nine – their work histories, their aspirations and frustrations, and their familial and financial circumstances. We took our cue from Maynard-Moody and Musheno's (2000;

[11] Because there were many fewer valve closed and supply cancelled notifications, and the valve opening time information was most useful for NextDrop's notification system, we focused our analysis on the valve opening notifications.
[12] Service stations are water utility offices run by engineers overseeing two to ten valvemen. There are 97 service stations across Bangalore.
[13] The compliance ratios for our case study valvemen ranged from 0.45 to 0.81, covering the full range of compliance observed in Subdivision A.

2012) influential work on street-level bureaucrats, paying close attention to the valvemen's own narratives about their job. Through these observations and interviews we came to understand the ways in which valvemen saw their job, how NextDrop's notification system fit into their ecosystem, and the power dynamics between themselves and the utility. We accompanied each of these valveman on his rounds through his assigned valve areas and his meal breaks at home. We took extensive notes and photographs during these sessions.[14]

We complemented our ethnographic research by collecting and analyzing an original dataset on valvemen, service station, and valve area characteristics in Subdivision A, mirroring the literature's focus on individual, organizational, and community factors. For individual-level factors, we collected information from all nine valvemen on their employment status (permanent or contract), the number and gender of their children, their wives' employment type (coded by the inflexibility associated with the job; housewives were most flexible and babysitters were most inflexible), the vehicle they used for work, their age, and the number of valves for which they were responsible. Our interviews were semi-structured, with potential independent variables systematically collected for all the valvemen, but with enough flexibility to let them discuss their work, lives and constraints on their own terms.

For community-level factors, we visited every valve area (N=233) served by the nine valvemen to code the socio-economic status of the neighborhood, water infrastructure, and street activity: the community-level factors that could influence levels of, and variations in, valveman compliance. We categorized the valve areas as (primarily) low, medium, high, or mixed socio-economic status (SES). A "low SES" area had a high level of domestic activity on the streets (cooking or washing clothes and dishes), narrow roadways, high noise levels, and few trees. A "high SES" area had little noise, high tree coverage, well-maintained homes, and no visible domestic activity. In addition, we counted (non-commercial) cars per five households, number of overhead water tanks through a visual assessment of the area, and the visible residents on the main street of the valve area, usually around mid-day on a weekday. More cars indicated higher SES, more overhead tanks implied less work for the valvemen, while more residents could potentially distract them.

We used these data to analyze whether factors that appeared important in our observations and interviews also explained variation in compliance across valve areas. We first carried out a principal components analysis to determine the extent to which our (potential) explanatory variables were correlated with one another (Vyas and Kumaranayake 2006). We then ran linear regressions to see which independent variables were associated with valveman compliance within each valve area. These simple regressions allowed us to establish whether or not

[14] Sessions with the valvemen were not tape recorded, so as to ensure anonymity and not put our subjects at risk.

individual-level characteristics that seemed to influence compliance from our ethnographic research appeared to hold once we controlled for the valve area context.

5. Empirical findings

In this section, we review our ethnographic evidence from Subdivision A to understand why overall rates of compliance with NextDrop's system were modest. We then turn to our qualitative and quantitative findings to explain variation in these rates across the valve areas.

5.1 Explaining modest compliance levels

Our research found empirical support for three main explanations of the modest rates of overall compliance. First, valvemen perceived their jobs principally as responding directly to "the public"—rather than to the utility's hierarchy—and the public pressed them to perform long-standing water management tasks rather than send NextDrop notifications. Second, valvemen already felt overworked, and viewed the NextDrop notification task as an additional, non-core responsibility. Third, valvemen had privileged knowledge of the water infrastructure, and therefore did not take seriously the threat of dismissal for not submitting notifications.

Valvemen's perceptions of their job: "I work with the public." Our interactions with the valvemen made it clear that they placed more emphasis on responding to pressure from the public than on their formal job description. BWSSB defined their jobs as opening and closing water valves at particular times and fielding residents' complaints. Though valvemen agreed that their job was to adjust water valves, their overriding description was: "My main work is working with the public." This sentiment was a recurrent theme. In explaining why his work was good, one valveman asserted: "I have shown what kind of work I do, how I work with the public." Another claimed: "When I work I forget about my family and friends. These people are my family and friends." This attitude closely reflects a "citizen-agent" meta-identity (Maynard-Moody and Musheno 2000), where frontline workers, while acknowledging the state, perceive themselves as actually working for citizens.

What, then, do valvemen claim they do for the public? "From morning I wake up, I do the work and I take care of complaints." A good valveman is "someone who attends to the problems and stays up day and night until the problems are solved." A bad valveman is someone about whom the public could complain: "He leaves the valves on whenever he wants. He's not punctual." If "the public" complained to the councillor (the elected ward representative), especially at election time: "the councillor complains to the valveman's superiors. His superiors ask him, 'Well? Are you fooling around and wasting time?'"

Consideration of (and pressure from) citizen-clients was particularly evident when valvemen talked about why they, at times, gave their clients extra water. Residents regularly negotiated with the valvemen for water or for repairs to leaky pipes through phone calls and appeals to common decency. If for some reason there is no water supply at the scheduled time, the practice at BWSSB is for valvemen to skip that turn and not hold up the supply for the valve areas to follow. However, valvemen do not always heed this rule: "If I'm supposed to give them an hour of water, and due to power cuts they only get a half hour, then I will give them another half hour." One valveman said succinctly: "I sympathize with these people." We regularly observed this sympathy in practice while following the valvemen on their weekly routes, but we never observed members of the public mention NextDrop. A valveman taking his cue from his clients would not have prioritized NextDrop's notifications.

Valvemen's perceptions of NextDrop's system: "It's just an additional job." Our field observations also clarified the extent to which valvemen juggled multiple job responsibilities, which made a seemingly simple new task feel onerous. While some valvemen claimed that sending notifications had gradually become standard practice, others expressed annoyance: It is "not helpful for valvemen;" "It's just an additional job;" It "hampers my work." One valveman said that if NextDrop wanted him to make notification calls then they should be there when the valves break in the middle of the night. These attitudes prevailed even in the service stations where NextDrop had the most established relationships with the valvemen.

These reactions must be understood in light of the many and varied tasks that make up the valvemen's formal and informal roles. Valvemen convey information between the utility and residents; they negotiate with supervisors, residents, and even state politicians regarding water timing and system repairs. Some of these negotiations are clearly a form of rent seeking, but some are necessary for providing water services ("They need at least two buckets of drinking water; it's just a matter of 10 more minutes"). We were told that the valvemen, who know the water system best, are often called in to perform repairs, even at night, though this is not part of their official job description. In addition, contracted valvemen who are not permanent employees regularly moonlight for odd jobs, such as plumbing work at residential complexes. NextDrop's requirements fell to the bottom of this long list of competing demands.

Valvemen's perceptions of threats and incentives: "I don't worry about being fired." Significant information asymmetries meant that both NextDrop and the utility had difficulty monitoring valveman compliance with the NextDrop system, and that threats of dismissal lacked credibility. NextDrop delivered reports to service station managers each week informing them of the valvemen's notification ratios, but had more trouble monitoring notification accuracy.

Valvemen had the freedom to submit inaccurate information: in following valvemen for hours at a time, we rarely observed them sending notifications to NextDrop, even after adjusting dozens of valves. Sometimes they sent off a series of notifications during tea breaks. Valvemen should have sent messages soon after they had physically adjusted the valves so that the company could send accurate announcements to its clients.

Though most valvemen are contracted out through a private company, they understood their ultimate principal to be BWSSB. As a result of the MOU between the BWSSB and the company, they readily related NextDrop's authority with that of their supervisors. When asked why they complied with the NextDrop system, valvemen would usually say that they did not want to get fired. However, information asymmetries meant that the threat of removal was not completely credible. Valvemen know the location of every pipe and water valve, which the utility does not, because the system maps are incomplete. They know how many rotations particular valves require (see Björkman 2015), how each valve is threaded, and where to check for adequate flow. Valve-specific information is passed on between valvemen without the mediation of a supervisor. With frequent desk-staff changes at BWSSB service stations, such institutional memory is held only by the valvemen. At one station, one of the two valvemen talked back to his supervisors and even to NextDrop's employees. "I don't worry about being fired," he said; he would be difficult to replace because he holds so much tacit information about the water system. A Service Station employee agreed: "The office needs him."

Meanwhile, few valvemen considered NextDrop's sporadic incentive schemes, such as mobile phones for the best valvemen, or a "bonus" of free talk time, as motivating. Some were incredulous at NextDrop's ranking of "best" performance. Others considered the rewards to be paltry, even insulting. Several valvemen said that relational connections with NextDrop were more important than monetary compensation. Contract valvemen wanted NextDrop to treat them more like their government-employed permanent counterparts.[15] They wanted uniforms like the khaki-colored ones that permanent workers wore. Or they wanted NextDrop to provide employee-type identification cards; contracted valvemen had no IDs. Ambiguity with respect to their social category was one of the valvemen's main work-related struggles, with identity-affirming incentives having high symbolic value.

In sum, our research showed that valvemen's perceptions of their roles were sticky and not easily amenable to redefinition. Valvemen saw their roles in terms of their relationship with the public, and the public were not clamoring for notifications. NextDrop notifications were just an additional responsibility; they

[15] What these workers wanted most of all was to be made permanent, with the almost 40% higher salaries and the pensions that accompanied permanent status. Some held out hope that this would happen one day, though others were more resigned.

viewed as more fundamental the tasks of operating the creaky water system and responding to the needs of (often) poor residents. Moreover, the main incentive the utility and NextDrop possessed to promote compliance—the threat of dismissal—was not effective; information asymmetries protected the valvemen.

5.2 Explaining variation in compliance

We observed significant variation in compliance across valvemen and valve areas. We draw on two types of data to understand this variation. Our qualitative observations and interviews suggested that characteristics of the neighborhoods where valvemen worked, as well as individual valvemen's family circumstances, helped explain this variation. Our quantitative analysis suggests that rates of compliance were lower in areas serviced by valvemen shouldering greater financial and familial burdens.

Results of qualitative analysis: community and individual influences. Our rounds with the valvemen showed that community-level factors influenced both the time and inclination that valvemen had to send NextDrop notifications. Low-income areas proved more difficult to work in because of poor infrastructure and more frequent interactions with citizens, as we might expect based on the Indian politics literature.[16] Narrow and unpaved roads were hard to navigate. Chickens and dogs had to be avoided. Residents milled around and confronted the valvemen with water-related complaints. Valvemen sometimes had to go into residents' homes to see if the water was actually flowing through their taps. In the midst of all this activity they constantly took phone calls – from the residents, the engineers, the BWSSB staff. When, the valvemen asked, were they going to send off NextDrop's notifications?

While valvemen also checked water pressure in middle-class areas, they could spot check underground tanks and faucets without encountering residents. But clients in poorer areas depended on face-to-face encounters to know when their water would turn on and to negotiate water supply amounts and timings. Valveman V attests to this: "The higher class people call our superiors and the superiors tell the valvemen the problem. The lower class people come to me directly, and I have to explain to them directly…I lose a lot of time talking to people." These observations suggest that valvemen who serviced predominantly low-income neighborhoods would have sent supply notifications less regularly; they are consistent with the data on compliance rates for individual valvemen.

Accompanying valvemen on their rounds and discussing their workdays also revealed many individual-level factors affecting compliance. In brief, valvemen under the double pressure of financial need and family duties sent notifications less regularly. Less compliant valvemen had more children at home, and in

[16] Scholars contend that the urban poor must pressure politicians and government officials to obtain services, whereas the middle class have privileged access to the state via associations and other channels (see Harriss (2005) and Ghertner (2011) for reviews).

particular more daughters. More children indicate increased financial need, and, for many Indian families, having a daughter means that the family must save for (future) dowry expenses. Every non-permanent valveman with three or more young children sought outside jobs, generally plumbing or driving, which could force him to deviate from his valve adjustment schedules (and concomitant notifications). A low-scoring valveman with three daughters was matter of fact about it: "We ask our relatives for help – if you help us now, we'll help you when your daughters get married." We also observed that less compliant valvemen had wives in low-wage low-flexibility jobs, such as dishwashing or babysitting in other people's homes. This indicates a valveman's need for additional income and also time constraints on his wife; domestic service, especially babysitting, demands long hours away from home. The valveman is then left with more family-related responsibilities, especially if there is a sick child or minor emergency at home. On several occasions, we observed valvemen picking up sick children from school, or going home to take the laundry off the clothesline before the rains came, right in the middle of the workday. Contract workers faced particular difficulties with these sorts of burdens because their salaries were almost 40% lower than permanent workers' salaries. For a moonlighting valveman with three children but no spouse at home, NextDrop's notifications were not a priority.

Results of quantitative analysis: individual-level factors. To complement our qualitative research, we created a dataset including a range of individual and valve area characteristics (described above). We conducted a preliminary covariate analysis with PCA and then ran linear regressions of the dependent variable (actual / expected notification ratio for each valve area) against the community and valveman characteristics that we observed to be associated with compliance in our qualitative research.

We regressed valve area compliance rates against each individual-level independent variable, controlling for the socio-economic class of the valve area (233), with the standard errors clustered by the nine valvemen (Table 1). We then ran two separate omnibus models, with the number of children and number of daughters, respectively. The regressions suggest that the number of children, and in particular girl children, is strongly associated with compliance. One additional child is associated with a seven percent decrease in compliance, while an additional girl is associated with an 11% decrease (Table 1, Models 1 and 2). These individual-level characteristics are statistically significant despite the small number of cases. Having a wife working in an inflexible occupation is also associated with lower rates of compliance in some specifications. Coefficients for valveman characteristics are comparable if we substitute alternative measures of valve area socio-economic status, such as the number of cars per five households for the general class score.

Table 1 | Subdivision A valvemen NextDrop notification system compliance (8-12/2014)

Dependent Variable: Valvemen Compliance per Valve Area

	M1: Girls	M2: Children total	M3: Wife employ	M4: Employ status	M5: Vehicle	M6: Age	M7: Valves	M8: Full model	M9: Full model
Individual characteristics									
Number of girls	-0.11 (0.02) ***							-0.13 (0.05) ***	
Number of children total		-0.07 (0.01) ***							-0.14 (0.06) **
Wife's employment			-0.05 (0.03) *					0.03 (0.04)	0.05 (0.05)
Employment status				0.05 (0.04)				0.03 (0.04)	-0.11 (0.09)
Vehicle					0.05 (0.04)			0.06 (0.03) *	0.08 (0.02) ***
Age						-0.01 (0.00)		0.01 (0.01)	0.01 (0.00) ***
Number of valves							-0.00 (0.00)	-0.00 (0.00)	0.00 (0.00)
Valve area characteristics									
Middle class valve areas	0.02 (0.06)	0.05 (0.05)	0.04 (0.04)	0.04 (0.04)	0.01 (0.06)	0.03 (0.04)	0.03 (0.04)	-0.02 (0.07)	-0.02 (0.07)
High class valve areas	-0.02 (0.07)	0.02 (0.06)	0.05 (0.07)	0.09 (0.05)	0.03 (0.06)	0.05 (0.05)	0.07 (0.03)	-0.07 (0.07)	-0.07 (0.07)
Mixed class valve areas	-0.06 (0.01)	-0.02 (0.09)	-0.05 (0.09)	-0.03 (0.08)	-0.06 (0.08)	-0.05 (0.07)	-0.05 (0.08)	-0.07 (0.10)	-0.07 (0.10)
N	233	233	233	233	233	233	233	233	233
Multiple r^2	0.21	0.16	0.09	0.03	0.06	0.04	0.02	0.24	0.24
Adjusted r^2	0.19	0.15	0.07	0.01	0.00	0.03	0.00	0.21	0.21

Results of linear regressions with standard errors clustered by nine valvemen. Results that are significant here remain significant when clustered standard errors are omitted. *: p<0.1; **: p<0.05; ***: p<0.01.

Our data analysis highlights the importance of specific family and financial constraints that have received little attention in SLB or principal-agent literatures thus far, but that may be quite common in rapidly growing cities that are under economic pressure to outsource their street-level workers. Given the limited number of valvemen we could follow and our reliance on observational data, however, we do not claim causality; rather, these associations suggest hypotheses worthy of further exploration.

6. Discussion and implications

Informational interventions intended to improve the quality of public services have been promoted for both efficiency and transparency. Such "transparency fixes" to long-standing service problems often depend upon the cooperation of public sector workers who ultimately produce or disseminate information for citizens. This study analyzed a text-message based intervention in the urban water sector, through which the utility's customers could get advance

notifications of when their water supply would be turned on. This was meant to reduce the cost of waiting and stress that intermittent and unpredictable water supplies typically entail. The entire intervention hinged on the cooperation ("compliance") of the valvemen, the frontline workers of the urban water system.

We draw on months of ethnographic fieldwork and analysis of a new dataset compiled for this project to understand the overall modest levels of compliance with the system, as well as variation in compliance across neighborhoods. We find that how SLBs rank new "add-on" tasks relative to existing responsibilities may be critical to the success of informational interventions. Prioritization is tied to how frontline workers see their job. We find that Bangalore's valvemen perceive themselves as serving "the public" ("*I sympathize with these people*"), even though they are fully aware of the power of their employers, the water utility. Their knowledge of the systems they maintain serves as a countervailing power; they know that even if they deviate from their narrow job descriptions they cannot be easily replaced ("*The office needs him*"). Similarly, while NextDrop viewed compliance with rules and targets as an important facet of their jobs, the valvemen themselves took their cues from the citizens, none of whom pressed them for NextDrop's notifications ("*It hampers my work*"). Our ethnographic data suggested that the citizen-agent over state-agent role was most pronounced when valvemen worked in densely populated lower socio-economic status communities ("*I lose a lot of time talking to people*"). Valvemen appear to internalize such communities as more needy of extra services and more likely to complain directly to them, which in turn makes it more time-consuming to serve them.

Because valvemen serve at the frontline of the water system, they are besieged by instructions at every turn, from citizens, engineers, councillors, and members of the legislature. These stakeholders could be seen as contributing to a "multiple principal" problem (Shapiro 2005), but the valvemen's overall reaction was one of "coping toward clients" (Tummers et al. 2015). This complicates the conventional incentive design / information asymmetry narrative that still underlies much principal-agent theory and organizational practice. It supports a "citizen-agent" narrative for frontline workers (Maynard-Moody and Musheno 2000; 2012) that could well lead to low performance measures from the principal's point of view.

There is no inherent contradiction between this finding and the literature on rent-seeking behavior. SLBs have often resisted reforms aimed at streamlining and disseminating information to the public for government-provided services. The literature on petty corruption has argued that such resistance stems from the potential loss of rent-seeking opportunities (because customers can directly access information, bypassing the SLB), or the threat of job losses. Rent-seeking undoubtedly occurs in Subdivision A, but the valvemen that we observed did not seem to fear that NextDrop's system would reduce their rent-seeking

opportunities. The giving and taking of small amounts of money to keep a valve open longer, or to enter a house to examine the plumbing, would have little impact on a valvemen's incentive or ability to notify NextDrop. Pipe leaks or temporary power outages could easily explain any deviations from the scheduled openings and closures. As Meyers and Vorsanger (2003) argue, multiple and co-existing motives reflect complexity rather than contradiction.

Given how valvemen understood their core jobs, whom they understood to be their main clients, no public pressure to submit notifications, and the utility's limited ability to offer credible threats, NextDrop's notification system fell to the bottom of the priority list. Our analysis of variation in compliance suggests that this was particularly the case for those with significant family responsibilities. Variation in the number of dependent children, and in the nature of their wives' outside employment, was associated with variation in compliance. More children and less help at home led to more moonlighting for side jobs and more domestic responsibilities competing with formal responsibilities. Our work points to the usefulness of looking not only at individual characteristics, as the SLB literature has done, but also to workers' family and financial constraints. Our observations also revealed associations between the socio-economic status of citizens, the interactions between anxious citizens and their valvemen, and the modest compliance of the valvemen by the phone-based metric that tracked them. Circumstantial heterogeneity made for heterogeneous compliance among Bangalore's water valvemen.

Our study had three limitations that must moderate our conclusions. First, all observation-based work suffers from the Hawthorne Effect: in our case, the possibility that valvemen will not speak rudely to their clients or accept bribes in the presence of an outsider. However, given the convergence of our ethnographic observations and our regression results, we are confident that the effect was small at best. Second, our sample size of nine is small and purposive, so we cannot argue that our observations in Subdivision A can be generalized to all of Bangalore. Third, we could not compare the impacts of the other individual-level factors, such as cognitive abilities or attitudes, which have featured prominently in the SLB literature, to the family and financial factors we investigated. Rather, we argue that the individual-level drivers of action (or inaction) that we highlight are worth investigating in Bangalore and beyond, as they may help to make sense of observed variations in frontline worker performance in other cities and for other public services.

7. Conclusion

Since Lipsky's (1980) groundbreaking work, SLB studies have revealed many community- and individual-level factors that shape frontline worker behavior. We add two specific insights to this literature. First, our valveman case highlights the difficulty of an added informational task becoming part of the routine,

because of the stickiness of workers' perceptions of their own jobs. Many transparency-oriented interventions are add-ons to established routines. Worker perceptions will be even stickier when they are reinforced by the communities in which the workers are embedded; in effect, the job is co-produced by the SLB and the citizen-clients and rather than just by the SLB and his superiors. Informational tasks may be especially vulnerable to worker non-compliance in such contexts, especially when clients do not affirm the importance of submitting information. This suggests that those designing transparency initiatives implemented by frontline workers should ensure that information collection directly (and visibly) benefits workers themselves, or their clients. Moreover, threats to punish workers for not submitting information may not be credible, because information asymmetries can provide even relatively uneducated SLBs with significant leverage. More broadly, our findings suggest that all studies of transparency interventions should pay attention to how frontline worker compliance was obtained (Kumar et al. 2016).

Second, we highlight the importance of financial and family burdens as constraining the capacities of frontline workers. These life burdens can take frontline workers away from their jobs, physically and mentally, and have been underemphasized in the SLB literature. Our analysis shows that individuals in highly varying personal circumstances will "comply" to highly varying degrees, and this is a genuine challenge for incentive design. Our analysis also offers a counter to the popular imagination, at least in India, in which frontline workers are thought of (if at all) as people who will only work if given a "tip."[17] As our valvemen lamented: "The public wants their work to be done, but nobody knows our problems." This suggests that positive incentive schemes—particularly if they are large enough to substantially reduce workers' financial burdens—may improve compliance rates among those facing challenging family circumstances.

More broadly, our study suggests that scholarship on local public goods provision pay greater attention to street-level bureaucracy. Frontline workers are ubiquitous in the water, electricity, telecommunications, medical, and transportation sectors, especially in the global South, where systems are less automated. Future work on understanding (and incentivizing) these workers should pay particular attention to how they, rather than just the public agencies, see their jobs. It should pay attention to their family and financial circumstances, as these may play a significant role in their job performance. This would be important for all research on public goods provision, well beyond informational interventions or water. In agreement with several scholars on whose work we draw, we recommend moving beyond a compliance framework to an understanding framework in all such studies. Frontline workers should no longer be analyzed as complying with or deviating from a "system" that they should service. Rather, they should be analyzed as integral components of (in

[17] See, for instance, the Indian website ipaidabribe.com

our case) the urban water system, which, in addition to having disposition and agency, also have their cracks and their fissures.

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Chapter 2 | Sanitation for low-income regions: a cross-disciplinary review[18]

1. Introduction

Unsafely managed excreta harm human health overall and child health in particular. They damage the quality of air, soil, surface water, and groundwater. Yet most of the world's excreta today are unsafely managed or not managed at all. Nearly two decades after the United Nations (UN) identified sanitation as a global development priority, more than four billion people, mostly in low- and middle-income countries (LMICs), lack access to safely managed sanitation (1). Two-thirds of all human waste generated remains unsafely disposed of (2). Despite sanitation's economic promise of multifold investment returns and numerous cross-sectoral benefits—from improving health to educational attainment for girls (3, 4)—realizing universal and sustainable sanitation access has proven to be an elusive task. The call for "adequate and equitable" sanitation for all in Sustainable Development Goal (SDG) 6, with "particular attention" to be paid to women, girls, and vulnerable populations, has lent new urgency to the design and dissemination of affordable, accessible, and safe sanitation systems.

Sanitation policy for low-income regions has been, and still is, driven by the need to reduce open defecation (OD). Recent work has emphasized the human and environmental importance of goals other than public health. These goals include sustainable resource recovery from waste (5), financial and time savings (6), and sanitation as a vehicle for human rights (7) and gender equality (8). Reducing the burden of disease, protecting the environment, increasing economic viability, and safeguarding human rights are all valid goals. In policy and practice, however, differences in how diverse goals are prioritized can lead to contestations about how safe sanitation is to be defined. It is possible to eliminate OD at the expense of dignity and rights, for instance; it is possible to set up waste-to-energy initiatives without sufficient attention to public health. We posit that dissonance between goals may impede progress toward achieving universal access, and a clear articulation of diverse goals and the linkages and gaps among them will benefit both researchers and practitioners.

Diverse goals and diverse priorities are also a feature of disciplinary perspectives within sanitation research. Research on sanitation in low-income regions remains

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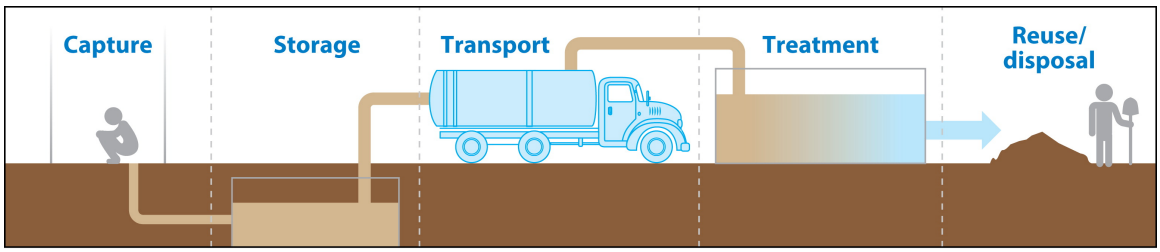
dominated by a focus on containing and removing fecal waste to prevent the spread of disease. These concerns are squarely within the domains of environmental engineering and public health. They are the basis for the sanitation service chain—an established framework describing the multiple functions of waste management from capture to disposal (see Figure 1). With notable exceptions, it is only over the past 20 years that the literature has expanded to environmental science, economics, planning and institutional analysis, cultural studies, and gender studies. This diversity has expanded the boundaries of traditional sanitation research, adding richness to our understanding of this complex topic. It has also led to multiple, sometimes disparate, definitions of what sanitation is, what it does, and whom it is for. Most significantly, it has implicitly embedded the conventional sanitation service chain within the many financial, social, and political contexts in which waste flows take place.



Hyun C, et al. 2019.
Annu. Rev. Environ. Resour. 44:287–318

Figure 1 | The conventional sanitation service chain, showing the functions of capture (e.g., toilets, pits), storage (e.g., pits, septic tanks), transport (e.g., trucks, pipes), treatment (e.g., centralized or on-site), reuse (e.g., fertilizer), and final disposal (e.g., discharge to environment). Figure adapted from References 18 and 29.

The past decade has seen several excellent reviews of sanitation, either alone or combined within water, sanitation, and hygiene (WASH), written from the perspective of a specific discipline (e.g., engineering) or with a focus on a specific impact (e.g., socioeconomic status). Examples include reviews of low-cost sanitation technologies (5), the health impacts of sanitation (9, 10), shared toilets and toilets in informal settlements (11, 12), social marketing (13), behavior change models and experiments (14, 15), the health and education impacts of school sanitation (16), and gender and sanitation (17). Each perspective emphasizes different functions of, and thus priorities for, safe sanitation; therefore, discipline-specific recommendations for progress toward SDG 6 may not always be adequate "for all." Our review takes a broad view and covers sanitation research in engineering, public health, environmental science, economics, planning, and the social sciences. Our goals are to understand the overlaps and differences among these perspectives in how sanitation is seen and why it is important, and thus to facilitate constructive discussion toward greater convergence on safe sanitation for all.

2. Baseline understandings of sanitation

There are two widely used frameworks within which sanitation is often defined in research and practice. The first is SDG 6, which includes specific indicators to define and measure progress toward the UN sanitation goals (1). The Joint Monitoring Program (JMP) is the designated custodian for tracking progress toward SDG 6. The second is the sanitation service chain, which is a descriptive framework rather than a measurement tool, and which has been popularized by the Water and Sanitation Program of the World Bank and the Bill and Melinda Gates Foundation (18, 19). Both the SDG framework and the sanitation service chain are regularly referenced by the disciplines reviewed in this article.

2.1. Sanitation and Sustainable Development Goal 6

In 2000, the international community adopted eight Millennium Development Goals (MDGs) to make and track progress on key dimensions of well-being. Each goal had a set of targets; each target had indicators to measure and report progress. Improved sanitation was included as a target under MDG 7 ("Ensure environmental sustainability"). The target was to halve, by 2015, the number of people without access to improved sanitation. The indicator "improved" sanitation was coined by the JMP to describe a sanitation facility that hygienically separates excreta from human contact, primarily during toilet use. Pour-flush toilets connected to sewers or septic tanks, ventilated improved pit latrines, pit latrines with a slab, and composting toilets were considered "improved." Public, shared, or open pit latrines were "unimproved."

Between 1990 and 2015, 2.1 billion people gained access to improved sanitation and the number practicing OD fell to ~892 million (1), but the MDG sanitation target was not met. The MDGs were critiqued for aiming only to halve the proportion of the population without improved sanitation, thus encouraging countries to target easily accessible rather than difficult-to-reach groups (6, 20). Furthermore, critics argued that the improved-unimproved binary did not reflect the rise of shared toilets, which, while categorized as "unimproved," still provided access to many communities (21, 22). Others advocated for safe waste handling and disposal to be recognized as essential for safe sanitation (5), while gender and health scholars argued for menstrual hygiene management (MHM) as a key component (23, 24).

With the replacement of the MDGs by the SDGs in 2016, sanitation became part of a stand-alone goal. SDG 6 has eight targets, three of which are particularly relevant for this review. Target 6.2 states the following: "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." This now-universal target reflects the explicitly human rights orientation of the SDGs overall; the MDGs called for significant improvements in access to water and sanitation without regard to specific

groups such as women or people with disabilities (see the box titled Human Right to Sanitation). Target 6.3 aims to reduce the proportion of untreated wastewater by 50% and increase recycling and safe reuse; Target 6.6 aims to protect and restore "water-related ecosystems" such as rivers and aquifers. SDG 6 represents a significant expansion of the definition of what safe sanitation is, specifically calling attention to marginalized sections of society and to wastewater treatment as part of a safe sanitation system. Furthermore, in the SDGs, several targets and indicators within one goal (e.g., health or education) reference other goals (e.g., water and sanitation). This feature is an explicit recognition that no human right stands alone, and it encourages policy makers and practitioners to go beyond their traditional jurisdictions and seek intersectional solutions to development goals.

HUMAN RIGHT TO SANITATION

In 2010, the United Nations (UN) explicitly recognized the human right to water and sanitation (160). The UN Committee on Economic, Social and Cultural Rights clarifies the right to sanitation, where sanitation is "a system for the collection, transport, treatment and disposal or reuse of human excreta and associated hygiene [for which] States [i.e., governments] must ensure that everyone, without discrimination, has physical and affordable access to sanitation in all spheres of life, which is safe, hygienic, secure, socially and culturally acceptable, provides privacy and ensures dignity" (161). Through identifying "rights-holders" and "duty-bearers" (usually states), the human rights approach adds a legal dimension to sanitation (157). As with all rights, states can aim for "progressive realization," or continual and steady progress toward ensuring the right for all. The language of this right clearly includes provision of sanitation hardware, but also legal and institutional arrangements, financing, and systems of accountability for sanitation (157). The rights to water and sanitation are often called "gateway" rights, meaning that these rights are precursors to meeting other rights, such as health and education.

What was once the "improved" sanitation indicator is now called "basic" sanitation in the JMP's new sanitation service ladder. The SDG indicator of progress for Target 6.2 is the population proportion using "safely managed" sanitation (1), in which basic—but not shared—toilets are used with the waste being adequately treated either on- or off-site. The conceptual and practical jump from basic to safely managed sanitation is enormous, given that, in 2015, 68% of the global population had basic sanitation but only 39% had safely managed sanitation. Estimates for safely managed sanitation were not available from the least developed countries, where the proportions are likely to be even lower than the global average of the available data (25).

Together, SDG Targets 6.2, 6.3, and 6.6 provide an ambitious framework to guide sanitation policy. Key indicators remain missing, however, for the realization of significant aspects of SDG 6. Indicators do not yet exist for measuring gender-equal access, access for marginalized groups or people with disabilities, or safe wastewater recycling and reuse. For example, the indicator for tracking progress on Target 6.2—the proportion of the population using safely managed sanitation services—cannot, by itself, measure gender-equal access or access for vulnerable populations. Furthermore, while JMP tracks national-level data on primary sanitation access in homes, schools, and healthcare facilities, it has yet to expand to workplaces, refugee settlements, or public places (26). These are especially important for the homeless, migrants, low-income women, and other vulnerable groups (8); even people with household access to toilets may revert to open defecation if they are away from home. The inevitable gaps in the survey- and census-based data that the JMP relies on to track progress—and the mutually reinforcing nature of the sanitation indicators and the data used to measure them—call for a more detailed understanding of where key gaps in sanitation coverage exist and how they can be better quantified.

2.2. Sanitation Service Chain

While SDG 6 sets out global sanitation goals and the targets through which progress toward these goals should be tracked, the sanitation service chain is a descriptive framework with distinct technological steps. The chain as a whole describes the flow of waste from capture to disposal. While precursors of the chain concept (5, 27, 28) can be found in the literature, the Water and Sanitation Program began to diagram and use the terms "sanitation value chain" and "sanitation service chain" in their reports (19, 29), while international development and engineering institutions generated reference literature, standardizing the concept (30, 31). In one of its most widespread forms, the sanitation service chain includes the functions of capture (e.g., toilets, pits), storage (e.g., pits, septic tanks), transport (e.g., trucks, pipes), treatment (e.g., treatment plants, on-site treatment), and reuse (e.g., fertilizer) or disposal (e.g., discharge to environment) (see Figure 1).

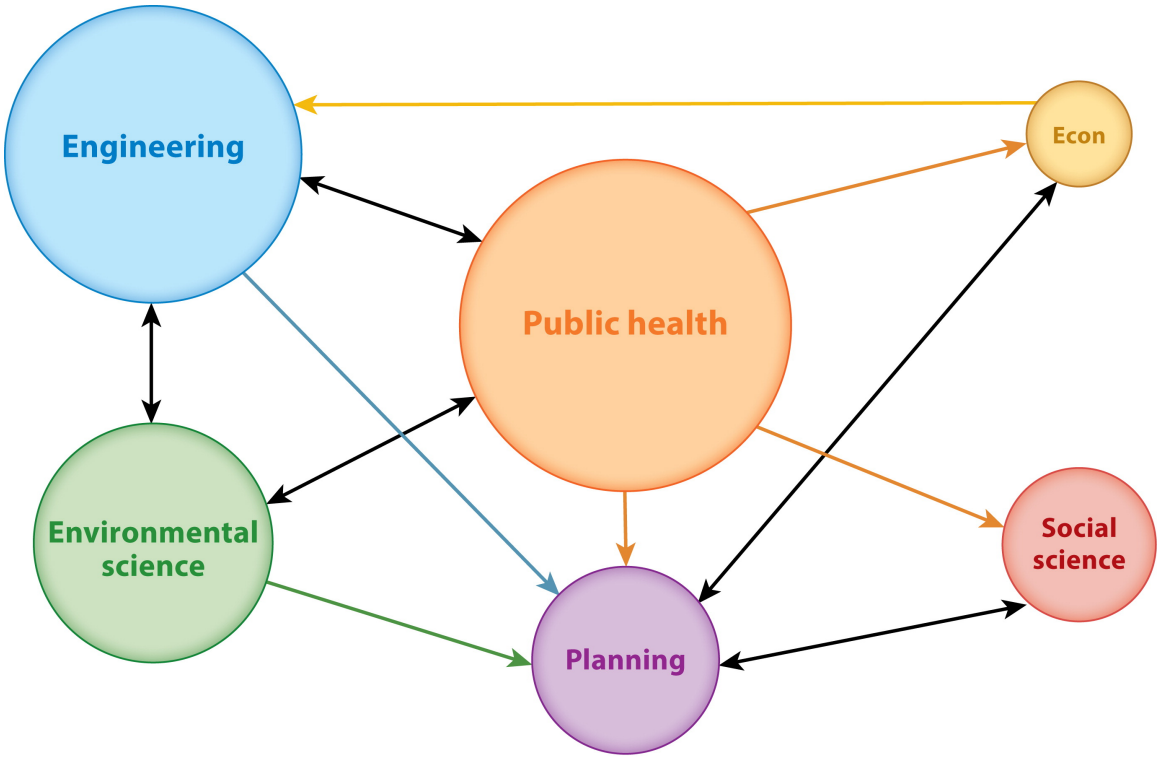
The framework is general and can represent most types of sanitation systems, both safe and unsafe—from open pits or flush toilets to truck-based fecal sludge management (FSM) or sewer-borne disposal—as shown in Shit Flow Diagrams (SFDs) (32) and other sanitation planning tools (31). Not all existing sanitation systems employ all the functions; for example, many LMIC systems convey waste straight to reuse without safe treatment. However, it is assumed that safe sanitation systems should cover all the functions. As with the SDG indicators, labor conditions, social factors, and financing are not explicitly included in the sanitation service chain; it primarily describes managed waste flows from the engineering and public health perspectives. The material flows of the chain, however, cannot exist without nonmaterial flows of political power and finance. We anchor this cross-disciplinary review to the sanitation service chain; we

propose an augmentation of the conventional chain to better reflect the understandings of sanitation across multiple disciplines and among multiple actors.

3. Disciplinary understandings of sanitation

There is an ancient tale of six blind men who were curious about what an elephant looked like. Each touched a part of the animal, and each concluded that the entire elephant resembled the part that he had encountered. Each understood a partial truth and yet none could imagine the enormous creature in its entirety. Sanitation research is likewise a world of partial perspectives.

To understand how diverse disciplines "see" sanitation, we collected more than 4,000 references in disciplinary and multidisciplinary peer-reviewed journals, as well as from publications of influential implementing organizations. We were not guided by a single focus or question; therefore, this is not a systematic review. Our primary search terms were "sanitation," "toilet," and "latrine," anywhere in the document other than the bibliography. We further collected relevant literature through researcher judgment and expert input. We focused on research outputs; we did not include, for example, policy- or advocacy-based reports prepared by donors or implementers. We also did not include papers published before 1990, the year from which the MDGs started tracking global progress on sanitation. Based primarily on journal type, we organize the literature in the sanitation space into six distinct, albeit partially overlapping, disciplinary perspectives (Figure 2). For each perspective discussed below, we (a) define its history and scope, (b) summarize its key current and emerging themes, and (c) discuss how it is represented—or not—in the sanitation service chain. A multiperspective view of sanitation, going beyond the conventional service chain, can lead to a fuller understanding of the flows, functions, and actors that comprise sanitation systems—in other words, of what sanitation is, what it does, and whom it is for.



Hyun C, et al. 2019.
Annu. Rev. Environ. Resour. 44:287–318

Figure 2 | Disciplinary perspectives on sanitation. The size of a circle (not to scale) illustrates the amount of literature that we encountered within that perspective compared to others. The arrows represent a relatively high level of one perspective contributing to—or being referenced by—another (e.g., public health literature is heavily cited in social science, economics, and planning literature). Double arrows represent approximately equal referencing between perspectives. We have omitted connections consisting of few references.

3.1. Engineering

3.1.1. History and scope. Engineering research has contributed over many decades to designing, developing, and evaluating the physical infrastructures and technologies necessary for sanitation. Engineers have primarily designed toward two major goals: (a) separating humans from excreta and (b) minimizing impacts of excreta and sanitation systems on human health and environmental quality. The engineering perspective has been a significant pillar of sanitation research, with most research concerning the large, centralized, waterborne systems that became widespread across the cities of high-income countries (HICs) throughout the twentieth century (33). Among the perspectives considered in this review, engineering is most closely tied to the conventional sanitation service chain because it deals explicitly with the physical flow of excreta.

3.1.2. Current and emerging themes. Many research themes in engineering derive from sharp contrasts in sanitation coverage and infrastructure types between LMICs and HICs. In HICs, recent contributions aim to increase the sustainability of centralized wastewater management by reducing energy, chemical inputs, and environmental emissions (34, 35). Ongoing systems-level research aims to assess the sustainability of new treatment and reuse technologies, increasing data quality for more precise modeling and customizing analyses to local conditions (36).

In contrast, much of the engineering research on sanitation in LMICs recognizes the centrality of solutions that emphasize either (a) centralized collection and treatment approaches that are less costly and require less electricity, operation, and maintenance than those common in HICs or (b) on-site sanitation without waterborne sewerage (37). An estimated 1.8 billion people use on-site sanitation systems (OSS) that require FSM rather than waterborne removal in sewers (38). FSM has emerged as a priority research area for developing options for the safe collection, transport, treatment, and reuse of fecal waste from pit latrines and septic tanks. It is being recognized as a long-term solution for low-income regions and not simply a stopgap until transitioning to waterborne sewerage (30). Both centralized and on-site FSM techniques are being evaluated for their system-level environmental and economic effects, as well as contributions to achieving the SDGs (39–41).

In HICs, the wastewater treatment sector has become slow to change because of large capital investments in existing centralized infrastructure. In contrast, excreta management in LMICs can be extremely innovative because of differing design constraints as well as lower sunk costs (42, 43). In the past, sanitation has been tailored to HIC constraints; however, designs deemed state-of-the-art in HICs have been unsuccessfully exported to LMICs (43). Future failures can, it is argued, be avoided or minimized only with thorough analysis, rigorous definitions of success, and careful risk mitigation (44). More recently, engineers have recognized that decentralized treatment approaches originally developed for unsewered settings in LMICs may have potential in HICs as well, to improve existing on-site systems, to augment centralized systems, or for temporary uses such as emergencies.

Some new technologies and approaches, such as container-based toilets and shared facilities, do not currently meet the SDG definition of safely managed sanitation (2, 38). Given the potential usefulness of these solutions for informal settlements, the definition of "safely managed" sanitation may need to be reexamined (45). New standards are also needed to bring legitimacy to innovative solutions so that they can be scaled-up, including certification of technologies (e.g., safe wastewater reuse) (44). At current expansion rates of centralized excreta management, the majority of people in Asia and Africa will still not experience safely managed sanitation by 2050 (34). To address these

disparities, new definitions and designs of safely managed sanitation must be reimagined for extreme scarcity and cost-effective scalability (43).

3.1.3. Engineering and the sanitation service chain. Engineering research addresses several functions of the sanitation service chain. With respect to capture, research has contributed to developing and comparing toilet designs for various low-income settings (5, 31). For LMICs, however, such studies have not sufficiently considered the user experience (e.g., odors, lighting, privacy); insufficient attention has been paid to cultural practices (e.g., washing versus wiping, freedom associated with open defecation, dislike of storing feces in a pit close to home) (46) and to gender- and ability-based design for toilet access. New toilets are being designed with human-centered principles and iterative testing between the laboratory and users in the field (47).

The storage and transport functions are tightly linked for centralized sanitation systems, and the main alternative to conventional sewerage is simplified or condominial sewerage (37). For on-site systems, storage and transport are often delinked; where on-site storage occurs in septic tanks and pit latrines, safe emptying and transport have been a major challenge. New work aims to (a) redesign pits for easier emptying (40) or (b) employ container-based sanitation, particularly in urban informal settlements, making sanitation storage mobile and thus advancing innovative toilet design and collection strategies (48). Recent research also focuses on improving the efficiency and safety of emptying pits with portable mechanical equipment and safer transport to minimize contaminant emissions and protect workers (40).

Engineering research on the treatment function aims to develop new technologies—or improve existing technologies—by understanding the biological, physicochemical, and mechanical mechanisms through which excreta constituents can be transformed. Historical research areas include low-cost wastewater treatment technologies such as stabilization ponds (49) and on-site treatment through composting or ecological sanitation (31). Recent advances include anaerobic biological treatment to reduce energy use (35); on-site toilets that reduce emissions and combine capture, storage, transport, and treatment (47, 50); and treatment processes specifically designed for fecal sludge (30, 40).

Further along the sanitation service chain, while the practice of reusing treated wastewater and excreta for beneficial purposes has long been recognized (51), recent work emphasizes innovative technologies to facilitate resource recovery. For example, a global spatial analysis identified a large potential to meet fertilizer demands through nutrient recovery and modest potential for energy recovery, while simultaneously meeting multiple SDGs (41). To facilitate resource recovery, new capture, storage, and transport options are being explored, including decentralization to create products closer to the site of reuse (39, 40, 52), as well as source separation of feces, urine (see the box titled Urine and Resource Recovery), and greywater (34). Reuse can also reduce harmful

environmental impacts of excreta disposal, such as nutrient-induced eutrophication (34).

URINE AND RESOURCE RECOVERY

Urine separation is part of a larger body of research on source separation, or separately collecting and treating household waste streams, such as greywater, food waste, urine, and feces (162). One motivation for urine separation is to facilitate the drying of feces; however, as urine treatment processes have developed (163), urine-derived products have become increasingly plausible and attractive. While feces have long been recognized as a source of useful products, over the past two decades urine has been identified as a low-volume, low-pathogen concentrated source of nutrients. Comprising only 1% of the wastewater volume, urine contains 80% of the nitrogen, 50% of the phosphorus, and 70% of the potassium that humans excrete (164). Urine's high nutrient concentration makes it particularly suitable for production of excreta-derived fertilizers in both sewered and unsewered settings (165). In waterborne sanitation, recovering concentrated nutrients from urine at the toilet can improve treatment efficiency and reduce required inputs while preserving aquatic ecosystems (166). In regions without waterborne sewerage, urine-derived fertilizers can be produced at lower cost than synthetic fertilizers and sold to offset costs of toilet construction and excreta collection (167).

3.2. Public Health

3.2.1. History and scope. The public health perspective focuses on human health outcomes related to sanitation, where health is defined by WHO as "a state of complete physical, mental, and social well-being" (53). The public health–defined goal of sanitation is to protect human health through the complete separation of excreta from human contact. There is a long and illustrious literature on the health consequences of inadequate sanitation, so much so that in 2007, a British Medical Journal readers' poll named the "Sanitary Revolution" the greatest medical advance since 1840 (54). Inadequate sanitation has been linked to diarrheal illness, soil-transmitted helminth infection, trachoma, adverse birth and maternal health outcomes, malnutrition, schistosomiasis, and growth faltering (9–11, 55–57). Public health literature on sanitation also includes the study of healthy behaviors (e.g., toilet use) and, more recently, of exposure to animal excreta (58). Major themes in this perspective include (a) interrupting the transmission of pathogens, (b) toilet use and access for vulnerable groups, and (c) intervention strategies and challenges, including behavior change (i.e., adoption and consistent use of toilets).

3.2.2. Current and emerging themes. Diarrheal illness, a leading cause of death among all age groups, is the most commonly measured health outcome in WASH literature, and estimates of the disease burden attributable to inadequate sanitation rely heavily on this outcome (59, 60). Severe diarrhea can have lasting consequences, especially for young children (61). Systematic reviews of sanitation-related outcomes typically cover a range of combined WASH interventions (9, 10), making it difficult to isolate the health outcomes of sanitation alone, especially in observational (as opposed to experimental) studies (62). Details on type, coverage, usage, and quality of sanitation interventions are often poorly reported; these omissions are unfortunate given that these factors may determine the reduction in exposure to feces.

Sanitation interventions are typically conceptualized as interrupting transmission of fecal pathogens from feces to a susceptible host. Tools borrowed from engineering and microbiology are used to identify specific fecal pathogens responsible for specific health outcomes, model associated health risk (e.g., through quantitative microbial risk assessments), and prioritize transmission pathways for intervention (e.g., the SaniPath tool) (63, 64). Recent research has explored environmental enteropathy, linking enteric infections from fecal pathogens to nutrient malabsorption (61). Understanding that nutrition and sanitation may interact has led to changing intervention strategies. For example, the recently completed WASH Benefits (rural Kenya and Bangladesh) and SHINE (rural Zimbabwe) studies were large, randomized-controlled trials that included combined WASH and nutrition interventions (65–67); the implications of this work for future sanitation research are still being explored.

A growing body of public health sanitation research focuses on women and girls, who are at higher risk of assault and psychosocial stress related to the lack of privacy and safety when urinating and defecating (68). The field's dominant focus on pathogens fails to account for these nontraditional—and often socially taboo—outcomes (69). However, a focus on menstruators is beginning to expand the public health definition of sanitation (see the box titled Menstrual Hygiene Management in Schools). Qualitative research on psychosocial stress among women and girls suggests that sanitation-related activities should be broadly defined to include fetching water for sanitation use and personal hygiene, bathing, menstrual management, and changing clothes (70).

MENSTRUAL HYGIENE MANAGEMENT IN SCHOOLS

Menstrual hygiene management (MHM) in schools has received recent attention because of the potential connections between school attendance for girls and the presence of safe facilities. School toilets in low-income settings are often poorly maintained and lack menstruation-sensitive water and sanitation facilities (4). They may not be gender-segregated or even have doors, making it difficult to change sanitary products. The inability to safely and privately dispose of a product leads girls to throw it into the toilet, which makes the school toilet (even more) unusable (147). Although there are few rigorous studies on menstruation and girls' attendance, there is evidence that, without water and convenient facilities for MHM, girls avoid school at least some of the time (16). Recent work suggests that absenteeism overall decreases with clean toilets in schools (14), and that sex-specific school toilets increase girls' enrollment (168). Almost all the literature on MHM, and on sanitation and gender in general, treats gender as a binary identification, with little recognition of gender diverse identities. The research on academic performance and safe MHM is inconclusive; however, shame, discomfort, fear of staining one's clothing, and other deeply stressful conditions have been extensively documented. Several authors have found that shame and fear interfere with girls' abilities to concentrate in class when they are menstruating (169). This is also a kind of school absence, albeit not one that is captured in enrollment or attendance data.

The public health perspective includes active debates on how to implement effective sanitation in low-income settings. Toilet infrastructure is necessary but known to be insufficient for ending open defecation and achieving health gains (71, 72). Contextual factors at the household, community, or societal level that encourage toilet uptake have largely been ignored in the literature (14); however, these are important determinants of toilet use. The subfield of social epidemiology explores the sociocultural determinants of health: toilet-first (supply-side) narratives list financial constraints as the primary driver of differential sanitation access, while demand-first (demand-side) narratives argue that sanitation interventions need to address social norms and socioeconomic barriers simultaneously (73). Another debate concerns shared versus private toilets: Increased health risks and poorer maintenance are associated with shared toilets (11), but an exclusive focus on disease outcomes undermines benefits such as dignity and privacy that shared solutions could provide (12).

Community-led total sanitation (CLTS) is a strategy that focuses on social motivation and peer pressure, rather than financial support, to construct toilets and change sanitation behaviors (74). In a randomized trial in Mali, CLTS was found to increase private toilet access and reduce under-five mortality, even

though the simple facilities constructed with local materials would not be considered “improved” by JMP's definition (75). However, the overall evidence of CLTS's effectiveness in sustaining behavior change has been questioned (76). Reports of fines, coercion, and shaming as punishment for open defecation within CLTS programs have also prompted reminders that public health goals should not be prioritized over human rights; marginalized individuals are particularly vulnerable to tactics that may reinforce social hierarchies (77).

Overall, public health research is beginning to acknowledge that a narrow focus on reducing diarrhea or increasing child growth falls short of capturing sanitation's full benefits for health, as defined holistically by the World Health Organization (WHO). Additionally, while household sanitation has been the primary focus thus far, there is a growing emphasis on sanitation in schools and healthcare facilities; the SDG goal of universal access covers these non-household settings (16, 78).

3.2.3. Public health and the sanitation service chain. In terms of the sanitation service chain, public health acknowledges multiple steps at which fecal pathogens can be released into the environment. However, public health strategies are primarily concerned with waste capture or lack thereof (i.e., open defecation). The literature's main focus has been on toilets, with systematic reviews often defining sanitation as the use of facilities to reduce contact with human feces (9). However, contact with fecal pathogens can occur at any point along the sanitation chain; for example, if waste captured at the household level is applied untreated to agricultural fields, workers will be exposed. Mainstream health research thus underestimates the benefits of full, community-wide sanitation coverage (10). The later steps in the sanitation chain illustrate clear gaps in public health research. For example, worker exposure to sewage is a major health problem in countries such as India, where an estimated two million sanitation workers are tasked with the removal and transport of waste in high-risk conditions (79). Occupational health and safety regulation represents a critical intersection between public health and the establishment of safe sanitation systems; this is gradually emerging as a research (and policy) theme.

3.3. Environmental Science

3.3.1. History and scope. The environmental science perspective highlights interactions between sanitation and the Earth's systems. It includes environmental quality, which assesses the impact of sanitation systems (or lack thereof) on chemical and biological contaminants released to the environment, and environmental microbiology, which extends from public health to infectious disease ecology. Overall, environmental science frames sanitation as a source of pollution emissions as well as a means of mitigating emissions through engineered systems. Such research informs environmental engineering and management, including monitoring, decision making, risk assessment, and regulations for sanitation and environmental quality. Three major themes

specific to sanitation in LMICs have emerged from the recent literature: (a) reuse over disposal, (b) pollution and emissions, and (c) climate change.

3.3.2. Current and emerging themes. While the idea of excreta as a resource is not new, it has recently resurfaced through the de facto reuse of wastewater-impacted surface water (80). Globally, 65% of irrigated croplands are in catchments highly impacted by urban wastewater, affecting 1.37 billion residents, the majority of whom live in countries with low levels of excreta treatment (80). Wastewater irrigation productively reuses the nutrients but, if the wastewater is inadequately treated, irrigation increases exposure to biological and chemical contaminants for farmers and consumers. Similarly, fecal sludge can be anaerobically digested to produce biogas, but digester effluent can release contaminants to the environment (5). Producing excreta-derived fertilizers, energy, or irrigation water can simultaneously incentivize sanitation management and provide valuable agricultural inputs (81, 82), exemplifying sanitation's role in the food-energy-water nexus (83) and its contribution to a resource-efficient circular economy (81, 84). Regardless of discharge method (wastewater, fecal sludge, or open defecation), the majority of excreta enter the environment unsafely treated (2). When properly treated, safe sanitation reuse can reduce anthropogenic impacts on global biogeochemical cycles of nitrogen, phosphorus, and carbon (84).

Environmental microbiology has focused specifically on microbial pollution resulting from the lack of adequate sanitation, as well as its effects on the quality of water bodies and aquatic species (85–87). Recent work has tracked microbial sources, examined effectiveness of fecal indicator bacteria, and measured specific human pathogens to more precisely assess the contributions of inadequate excreta collection and treatment on environmental emissions (88, 89). Researchers in this field maintain that increasing toilet coverage will attenuate risk, but they recognize that increased coverage alone may not reduce pathogen exposure, suggesting the need for a more holistic, site-specific approach (71, 90).

Chemical emissions from sanitation systems are also important to environmental science. Nutrient-induced eutrophication (87, 91) and trace organic contaminants (e.g., pharmaceuticals) can harm ecosystems and, potentially, human health (92). Recent advances in high-resolution instruments now enable contaminant monitoring at lower concentrations. Sanitation systems also emit airborne pollutants, both directly (e.g., nitrous oxide and methane) and indirectly (e.g., emissions associated with energy use) (36). On-site sanitation systems often employ anaerobic digesters, which can reduce greenhouse gas emissions and recover energy, but which require reliable water access (93) and careful containment to prevent methane emissions (94).

A reversal of the usual focus on sanitation's impact on the environment is research on the environment's impact on sanitation. Hydrologic cycles have mixed influences on diarrheal disease risk: short-term extreme rainfall events can

increase risks due to unimproved sanitation, but long-term rainy seasons have a net positive flushing effect on diarrheal disease (95). Recently, animals—specifically ruminants such as cows and goats—have been identified as contributors to fecal contamination in urban and rural households (58); there are no global goals, however, for the management of farm animal waste, although its mass is four times higher than that of human fecal waste (38). Plants can also reduce excreta loads: Wetlands, for instance, can be leveraged to reduce nutrient and carbon loads from sanitation systems (81, 96).

Expanding on the above, the environmental science perspective has begun to consider the effects of climate change on sanitation, describing both positive and negative impacts. In areas likely to become more arid, on-site sanitation infrastructure may more effectively contain pathogens as groundwater tables drop and floods decline in frequency (97). In coastal areas, declining freshwater availability, increased flooding, and higher rates of extreme weather events threaten the effectiveness of sewerage and septic systems using water to convey excreta (97). Environmental science perspectives on how climate change influences sanitation systems inform engineering approaches toward resilient, adaptive sanitation systems with multifaceted controls to safely manage excreta (98).

Several contested ideas have emerged within this perspective. While increasingly sensitive instruments can detect lower contaminant levels, these measurements require context, as detection may not correlate with effects on human health or aquatic ecosystems (89, 91, 92). There is also a debate between centralized, decentralized, and hybrid sanitation systems on account of their differential effects on the environment (e.g., consolidated emissions with centralized treatment versus distributed emissions with decentralized treatment) (34, 52). Lastly, there is tension between safeguarding public health at the expense of environmental quality, because the environmental impacts of on-site sanitation systems and open defecation are often given lower priority than their public health impacts in LMICs (92).

3.3.3. Environment science and the sanitation service chain. Within the sanitation service chain, the environmental science perspective emphasizes capture, reuse, and disposal. Inadequate capture and disposal are seen as major sources of environmental emissions, while storage, transport, and treatment are secondary. Storage attenuates microbial (but not other) risks, and emissions may occur during transport of excreta. Reuse systems and technologies are not as mature in this literature as their disposal-oriented counterparts. The environmental science perspective emphasizes the non-built (or "natural") environment; it identifies new contaminants that should be measured and attenuated through engineered treatments, such as trace contaminants of emerging concern (92), antibiotic-resistant genes (99), and microplastics (100). These studies often motivate engineering investigations into attenuation

mechanisms and broader-scale treatment, such as remediation of surface water bodies. Therefore, environmental science overlaps substantially with environmental engineering because the latter controls emissions from sanitation systems.

3.4. Economics

3.4.1. History and scope. The economics perspective highlights the quantifiable benefits of sanitation (or the costs related to the lack thereof), the preferences and purchasing power of the users of sanitation, and the allocation of resources for the provision of sanitation. Relevant subfields include environmental economics, development economics, public policy, and parts of political economy in LMIC contexts. Overall, sanitation is sparsely covered in top-rated economics journals and not at all in top public policy journals; most of the relevant literature is located in interdisciplinary journals that focus on water and sanitation. Prominent themes include (a) sanitation as a proxy or outcome variable, (b) benefit-cost ratios for sanitation services, (c) cost calculations for services, (d) the political economy of sanitation, and (e) production efficiency modeling.

3.4.2. Current and emerging themes. Sanitation "access" is treated in economics journals as an explanatory or proxy variable for income, which is itself a proxy for welfare (101). "Access" is also used as an outcome variable when estimating the impact of income on willingness to pay (WTP) for environmental improvements (102, 103). Definitions of access are inconsistent, ranging from access to any type of "improved" sanitation to access to the local utility's sewer system. Economists also assess the impacts of various interventions on sanitation-related outcomes such as toilet access and use. A cluster-randomized trial in Bangladesh, for example, found that subsidies were effective at increasing toilet construction and use, but information campaigns were not (104). Social welfare investments in Nicaragua and Bolivia and foreign aid targeted at water and sanitation also increased access to a toilet (105).

Sanitation-related investments can be evaluated through benefit-cost ratios (BCR), where a BCR of greater than one means that benefits exceed costs. In a review of interventions that included improved access to water and sanitation (including treatment and disposal), the BCR was greater than one in all regions of the globe (106). Similarly, in Southeast Asia, the BCR of on-site sanitation technologies was found to be large and positive across all studied countries, while the BCR for sewerage was lower, but still greater than one, in all but one country (107). BCR can be used as a tool to determine subsidies for sanitation, but generalization is a challenge because the ratio can vary considerably across locations and over time within the same location (108).

In interdisciplinary journals, sanitation is analyzed as a service with associated supply costs and demand preferences, which vary widely by site and by technology. CLTS programmatic costs (e.g., community engagement activities)

were roughly three times the cost of private investments in toilets in Ghana and Ethiopia (109). The costs of emptying pits and septic tanks depends on many factors including fuel, mass of waste material, proximity to a disposal site, season, and labor (110). Condominial or simplified sewer designs have been found to cost slightly over one-quarter that of conventional sewerage (111). On the demand side, there is ample evidence of user WTP being lower than the cost of toilet construction: In rural Benin, a 75% subsidy would be needed to reach 50% coverage (112). In urban Senegal, tenants were less likely to invest in sanitation, but as likely to pay for emptying, compared to owner-occupied households (113). However, a study of formalized pit-emptying services in Bangladesh found that the average WTP covered only half of the costs (114). Low demand and adoption—even where toilets exist—and the challenges of stimulating demand or behavior change have been widely reported across LMICs (9, 115).

Going beyond households and small communities, political economy research has contributed to important sanitation themes such as autonomy, accountability, decentralization, privatization, participation, and pro-poor policies. There is no consensus, however, on the effectiveness of any of these policies across studies. For example, in Mexico the interaction of decentralization with the commercialization of the water and sanitation sector led to local political conflicts without service improvements (116). In Brazil, participatory, decentralized budgeting improved access to toilets and in turn reduced infant mortality (117). A meta-analysis examining the effectiveness of service provision by "bottom-up approaches," led by NGOs or community-based organizations, often in collaboration with utilities, found that interventions with greater participation of community members were more successful at increasing access, as were services focused on individual as opposed to shared toilets (118). Increased autonomy and accountability in publicly managed water and sanitation utilities have also improved production efficiency (i.e., cost per unit of treatment) and service quality, but not cost recovery (119). In a review of production efficiency studies, benchmarking (i.e., a means to increase accountability through cross-utility comparisons) and increased production scope or scale had a positive impact on production efficiency (120). Overall, political economy of sanitation studies are mostly policy-driven rather than theoretical, and they have overlaps with the domain of urban/sanitation planning.

3.4.3. Economics and the sanitation service chain. Sanitation is depicted in the service chain as a material flow of waste through the environment and through society. But the flows of capital and labor—as determined by financial choices made at the individual, municipal, or national level—determine this material flow. That being said, the economics perspective does not address the full scope of the sanitation service chain; in many cases, sanitation is equated with toilet access (i.e., capture). Even where transport, treatment, reuse, and disposal are

included, many papers focus on centralized systems, overlooking on-site or decentralized options. For example, an otherwise comprehensive report on water and sanitation in Karnataka, India, ignored all on-site systems, despite these being common throughout the state (121). Studies that focus on just a part of the sanitation service chain inadvertently conceal the complexities that determine capital and labor allocations within sanitation systems. Furthermore, any mention of MHM or women's and girls' needs in general is largely absent from economic analyses.

3.5. Planning

3.5.1. History and scope. Planners broadly view sanitation as a service that is essential for creating more livable and sustainable communities. With this in mind, much of the current literature critiques overly technological (and elitist) approaches to past planning (122, 123). To avoid this, planners often approach problems by considering the "planner's triangle"—a triangle made up of social equity, economic growth, and environmental protection, within which convergences and conflicts can be negotiated (124).

The planning perspective encompasses multiple strands of literature that range from highly instrumental to highly theoretical. Some of the more theoretical and critical literatures are covered in the social science perspective below. This section reviews recent research on the practice of planning and governance. Sanitation-related studies focused on LMICs tend to come from development practice with a few prominent studies coming from the more conventional city and regional planning field. There are also studies that originate from engineering-oriented institutions, in particular the growing literature on "sanitation planning." Below, we categorize sanitation research into the subliteratures of (a) city and regional planning, (b) development planning, and (c) sanitation planning.

3.5.2. Current and emerging themes. One of the main contentions in sanitation-related planning research is the disharmony between "modern" centralized infrastructure and the contextual realities across LMICs, often related to the need to consider informal settlements. Conventional city and regional planning research has focused little on the problem of sanitation. In fact, instead of a "wicked problem," in which one set of solutions throws up a new set of challenges, Rittel & Webber (125) called sanitary sewers an "easy problem" that had been dealt with—at least from an HIC perspective. While centralized sewer networks were a significant part of constructing the "modern city" ideal in HICs, sanitation systems in LMICs are often on-site or hybrid (e.g., septic tanks and underground sewers utilized in the same community) (126). Furthermore, in LMICs, networked infrastructure that should unify a city instead splinters it—thus creating a "colonial core" and a periphery consisting of those "not acknowledged as citizens of the network city, even if they are the majority of the population" (122, p. 83). These differences, then, drive planners to consider not

only what is planned, but also who is doing the planning. Instead of relying on examples from HICs, there is a growing call for planning from the Global South or South–South planning (123, 126). At a more local level, there is also a concern about who participates in various phases of sanitation projects (127) and which stakeholders are left out in sanitation planning (82, 128). Roy highlights the need for deeper, on-the-ground forms of planning participation, building on the Appadurai phrase, "the politics of shit," to emphasize the need for planners to consult the defecators themselves (123, 129).

Development planning and practice literature, as opposed to conventional planning literature, deals more directly with sanitation's political and governance complexities. Sanitation in LMICs is considered comprehensively in terms of both scale and breadth—from the appropriateness of multilateral sanitation agreements (e.g., the SDGs) to contestations over land tenure at the neighborhood scale. Environment and Urbanization has offered a year's worth of special issues on sanitation, touching on multiple planning-related challenges (130, 131). What these and other development planning studies have shown are the diverse conditions under which international sanitation norms (e.g., SDG 6) eventually have to be, but are not yet, realized.

Dense urban settlements, where sanitation has been neglected or even ignored (132), have been of particular concern in development planning. Scholars argue that "low-cost" market-based sanitation options that are promoted by domestic and international NGOs may not serve the poorest slum dwellers (133); shared toilets are often unsafe, unclean, and unusable (11), yet private household toilets may be impossible in such spaces (131). Given this reality, improvements in the number, maintenance, and hygiene standards of shared sanitation—which is more scalable and attainable than single-household toilets—may need more attention (21, 22).

McGranahan (134) identifies four "institutional challenges" of sanitation in LMICs, especially in the context of development planning: challenges of collective action, coproduction, affordability, and tenure. Planning problems related to sanitation technology can be understood within these institutional concepts (135). The planner's triangle provides another way of considering these challenges, where "property conflicts" are tensions between social equity and economic growth, "resource conflicts" are tensions between growth and environmental protection, and "development conflicts" are tensions between environmental protection and equity. Planners often use several framings that are not in themselves solutions but are helpful heuristics, or ways in which to explain complex problems (124).

The term sanitation planning has been used broadly in city and regional planning, but it increasingly refers to planning approaches used by development practitioners and engineers. CLTS is a popular intervention to eradicate open defecation in South Asia (74). Beyond this, development practitioners have

created planning strategies and tools such as Sanitation 21, community-led urban environmental sanitation, city sanitation plans, and the JMP service ladder (136). A widely adopted advocacy tool used to assist planning is the SFD (32). Many of these approaches, however, have been only partially implemented, if at all, creating opportunities for future research in sanitation planning. Furthermore, enabling environments, regulations, and enforcement for planning approaches—although called for in policy documents—have not been adequately researched.

3.5.3. Planning and the sanitation service chain. Considering the comprehensive nature of sanitation planning, this perspective addresses many components of the sanitation service chain, but unevenly so. Historically, planners have focused on sewerage as developed in HICs. With urban challenges in LMICs, researchers have turned their attention to open defecation and toilet building, or the "front end" of sanitation. There are also calls for planning at the "back end" of sanitation—the sanitation service chain beyond the toilet—in terms of technology, affordability, stakeholder participation, and reuse. The integration of governance and infrastructure with economics is where the planning literature extends the current, and technology focused, sanitation service chain. Relatedly, planners are also concerned with the challenges of tenure and equity—neither of which the conventional sanitation service chain can readily address.

3.6. Social Sciences

3.6.1. History and scope. Our final perspective comprises anthropology, geography, political ecology, critical urbanism, and gender studies. Sanitation is treated within the social sciences as a service essential for dignity and citizenship. Historically, sanitation was not a main focus of the social sciences; the "indecent" nature of human waste once made it a taboo subject for explicit discussions within social and policy studies (137). By now, however, toilets and their place in society, culture, and politics have become established research themes. Sanitation-related themes have even been the focus of art, film, and photography.

A sizeable body of work drawing on science and technology studies has analyzed why so many seemingly well-designed sanitation interventions fail in LMICs (138). For instance, a large number of studies we reviewed focus on India. With its enormous slum population and its estimated half-billion people still practicing open defecation (1), India has become a key ethnographic site for understanding sanitation as a social and cultural service (see the box titled Sanitation Challenges in India). We categorize and review three notable approaches within the social sciences that seek contextual understandings of both successful and unsuccessful interventions: (a) values and attitudes (i.e., what drives households to adopt toilets), (b) social disparities (i.e., the unequal impacts on different groups of how sanitation is defined and promoted), and (c) cultural politics (i.e., space and bodies as political objects in sanitation practice).

SANITATION CHALLENGES IN INDIA

Sanitation literature has historically had a disproportionately large number of studies on India. With more than 500 million people still practicing open defecation (OD) (1), the consequences for child diarrhea and long-term stunting have been severe (141). India's neglect of sanitation in urban planning has led to inadequate and unusable facilities in its sprawling slums (131, 170); the lack of accessible toilets is especially stressful for girls and women, who have high needs for privacy and safety (145, 171). In 2014, the Government of India launched a massive campaign, Swachh Bharat Mission, to build toilets and eliminate OD, with a 2018 budgetary allocation of ~$2.5 billion (172). Social marketing campaigns (e.g., "No toilet, no bride!") are also actively promoted. Sanitation uptake and maintenance have been especially hard in India (72, 141) where taboos have traditionally designated (only) the most marginalized castes as toilet cleaners. While the manual removal of feces from unsewered toilets is illegal, it still provides employment for these groups. New technologies for safe fecal sludge management and new business models for sanitation services, both strongly backed by the Bill and Melinda Gates Foundation, have become active sites of research and pilot-level projects in several Indian states.

3.6.2. Current and emerging themes. The values approach seeks to explain the adoption and use—or nonuse—of household toilets, and argues that few households seem to want or use toilets for health reasons. Freedom from shame is essential if women are to use toilets regularly (23), although shaming may be an "effective" tool against open defecation (139). Status, urban proximity, wealth, and education (140), coupled with attitudes toward open defecation (46), are also likely to drive toilet use. In rural India, however, even wealth and education are weakly associated with adoption (141); the authors surmise that culture, in this case the Hindu concept of caste purity, is responsible for the de facto devaluation of household sanitation. This literature overall calls for a contextual understanding of the value of sanitation beyond its role in health and beyond household-level characteristics.

The core disparities in the sanitation literature are well-known: Only 39% of the world has access to safely managed sanitation, and rural–urban and interquintile divides remain sharp in almost all LMICs (1). Recent work has argued that standard measures of access or availability underestimate disparities; the processes and practices through which sanitation is accessed are themselves highly unequal (2, 142). Factors that allow one person's "safe" toilet to harm another through unregulated disposal, for example, must be recognized as sanitation injustice (143). The labor of sanitation, meaning the unprotected conditions in which pit latrines are cleaned and the waste moved out of the

community, is also a form of sanitation injustice; the majority of India's manual cleaners are low-caste women who contend with daily assaults on their health and dignity (8, 144). These disparities and human rights violations are mostly invisible in national or international sanitation policy documents (79).

Research on gender disparities has shown that women without safe sanitation face unique stresses—from walking long distances to being assaulted—as they find ways to defecate, urinate, and manage their menstruation (145). For social as well as biological reasons, women and girls need more privacy, time, and space in the toilet than men do, but sanitation facilities are seldom designed around these needs (146). The shame and taboo associated with menstruation have become a global mental health issue (23), which has led to calls for girl-friendly school sanitation (147, 148) (see the sidebar titled Menstrual Hygiene Management in Schools). Toilet promotion programs such as CLTS are starting to include MHM in their training and outreach (149). However, gender-equal access to public toilets as part of equitable urban design (150), transgender-inclusive toilets (151), and the role of accessible public toilets in liberating women and girls when they are away from home (8) remain understudied themes.

Finally, the cultural politics approach takes infrastructure, place, and the human body itself as terrains over which meanings are made and power is exercised. Unequal and fragmented infrastructure produces unequal and fragmented cities (122). When sanitation is provided by a mixture of sewers, users' associations, small-scale providers, and political patronage, then power over infrastructure services becomes a form of everyday power over citizens (152). Furthermore, inadequate sanitation in informal settlements leads to coping mechanisms and daily inconveniences that reproduce urban inequalities through lived, bodily experiences (153), but also to forms of collective action and political performance such as theater and art (154). Open defecation itself can be considered a threat to public health (which is the prevalent policy discourse) or a threat to the expected social order (which may be only implicitly acknowledged) (155). Through these studies, researchers "see" sanitation infrastructure, governance, and the body as mutually shaping one another.

3.6.3. Social sciences and the sanitation service chain. In terms of the sanitation service chain, the social sciences clearly address access to and the value of toilets (capture), indirectly discuss storage, uniquely address the conditions of the labor that conveys the waste from toilet to disposal site (transport), do not discuss treatment, and just touch on the inequities created by unregulated disposal or reuse. This perspective is most strongly associated with the understanding of sanitation as a human right (see the sidebar titled Human Right to Sanitation). The gendered nature of almost every link in the sanitation chain is front and center in this perspective, especially with respect to front-end access, back-end labor, and MHM. The social sciences highlight perceptions, processes, priorities, and politics—all of which are invisible in the fundamentally "physical" flows of

waste that the traditional sanitation service chain comprises. They define sanitation as a service that shapes the daily human experience, and they connect that seemingly small experience to larger networks of pipes as well as of power.

4. Discussion

The sanitation service chain provides a useful framework for understanding the physical flows and functions comprising sanitation systems. Across all disciplinary perspectives that deal with low-income regions, the sanitation literature's primary focus is on capture (e.g., eliminating open defecation, increasing toilet access) with the next level of scrutiny on disposal. The overarching emphasis on capture reflects the earliest and still-dominant focus of sanitation: to separate the human body from its own pathogenic waste.

In its traditional format, the sanitation service chain challenges us to think of the flows of excreta beyond toilets as they are processed through physical infrastructure. At the same time, the current chain bounds the sanitation sector's understanding of what it takes to maintain this flow from capture to eventual reuse and disposal; it de-emphasizes the social, financial, and political "flows" that shape, and indeed make possible, the material flows of waste. An augmented version of the sanitation service chain, showing nonmaterial flows and the stakeholders who shape—and are linked by—these flows, would make clear the simultaneously physical and social nature of the sanitation system. Our cross-disciplinary review suggests that an expansive view of the sanitation system is important for interpreting, and thus achieving, the SDG 6 target of adequate and equitable sanitation "for all."

4.1. Flows and Functions of a Sanitation System

As this review shows, engineering and public health remain the largest bodies of literature represented in the sanitation space. The review also shows that the intellectual domain of sanitation has gone beyond these two perspectives to encompass environmental science, economics, planning, and social science. These additional perspectives explicate the nonphysical flows within which the physical flows of waste are embedded. Environmental science emphasizes the flows of contaminants into the environment that result from inadequate sanitation. Economics analyzes the flows of investments and financing that households and utilities must procure to install sanitation infrastructure, as well as the types of infrastructure that the resource base can support. Planning is concerned with the flows of policies and decisions, with varying levels of community participation that determine where and for whom sanitation infrastructures are built or not built, and with who maintains what is built. Finally, the social sciences bring in flows of power and labor, along with the economic and gender inequalities that shape the—often invisible—constraints within which planning, economic, public health, and engineering decisions are

made and executed. These social flows run between and across stakeholders, but unlike waste flows, they are multidirectional.

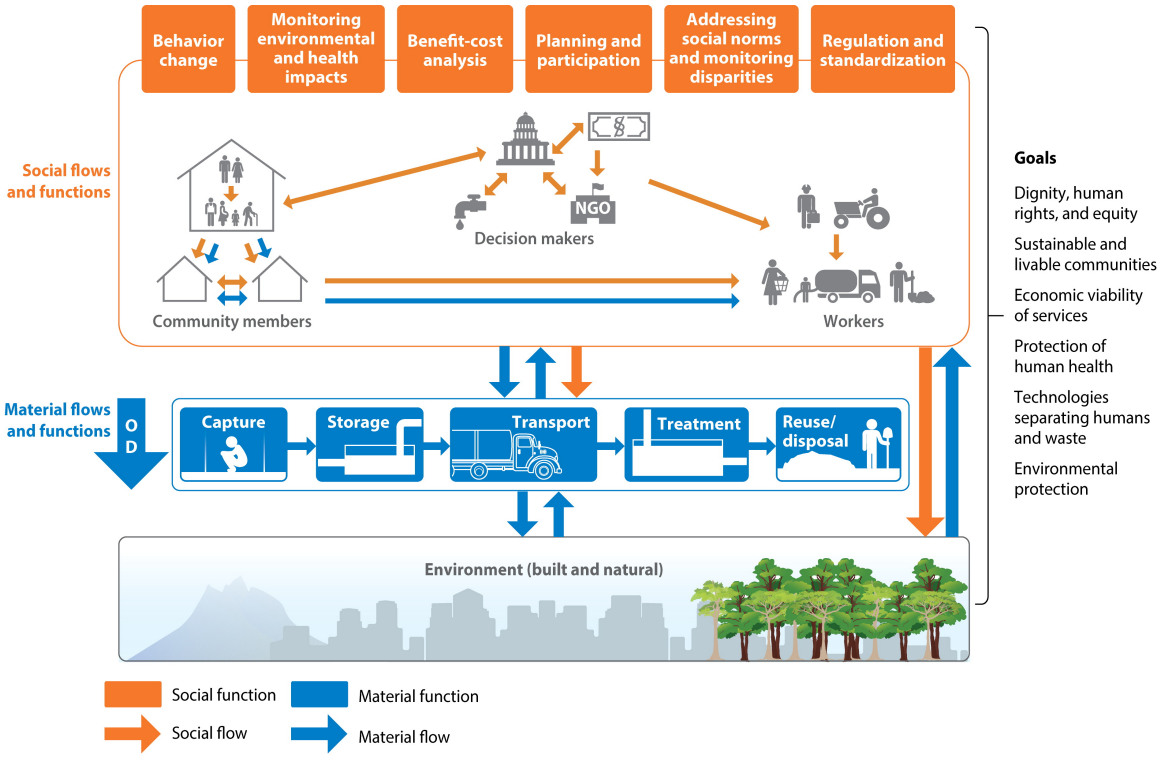
Table 1 | Sanitation system flows, functions, and goals as addressed in the literature

Disciplinary research perspectives	Flows[a]	Conventional functions addressed[b]	Additional functions addressed[c]	Goals supported[d]
Engineering	Feces, urine, water, pathogens, nutrients, chemicals	Capture, storage, transport, treatment, reuse, disposal	None	Technologies separating humans and waste
Public health	Pathogens, psychosocial stressors	Capture	Behavior change, monitoring health impacts	Protection of human health
Environmental science	Pollution, hydrologic, biogeochemical	Transport, treatment, reuse, disposal	Monitoring environmental impacts, risk assessment	Environmental protection
Economics	Finance, labor	Capture	Benefit-cost analysis, impact assessment	Economic viability of services
Planning	Decision making	Capture, transport	Planning, participation	Sustainable and livable communities
Social sciences	Political power, labor	Capture, transport	Addressing social norms, analyzing disparities	Dignity, human rights, and equity

[a] Flows include both material and social sanitation system flows.
[b] Conventional functions addressed lists the conventional sanitation service chain functions that are emphasized in each literature.
[c] Additional functions addressed lists the social functions beyond the conventional sanitation chain reported in each literature.
[d] Goals supported identify the sanitation goals supported by each area of research.

This interdisciplinary perspective highlights the additional sanitation-related functions that are absent in the original, engineering-oriented sanitation service chain (see Table 1). By functions, we mean processes or actions that are part of a sanitation system. In the research literature, public health has extended sanitation's "pure" function of interrupting transmission pathways (e.g., through toilet use) by emphasizing social behavior as a component of a sanitation system. Environmental science emphasizes monitoring and risk assessments as a function of safely managed sanitation, an explicit acknowledgment of sanitation's potential third-party effects. Economics contributes benefit-cost and impact assessments of sanitation for households, communities, and utilities.

Planning considers participatory decision making and the process of planning itself as part of safe sanitation. Finally, the social sciences foreground the need to analyze and address social disparities and norms in order to achieve adequate sanitation for all. This list of the social functions of sanitation is not comprehensive; for instance, the research literature scarcely addresses the critical processes of regulating technology and safety standards for sanitation services (44). Furthermore, as with the physical functions in the conventional service chain, the list is normative; there is no assumption that all sanitation systems will employ all these functions, or that these functions will be carried out in a sustainable and inclusive manner. The flows and functions emphasized within each disciplinary perspective support the goals that each perspective prioritizes for a safe and sustainable sanitation system (see Table 1).



Hyun C, et al. 2019.
Annu. Rev. Environ. Resour. 44:287–318

Figure 3 | An augmented sanitation service chain. This augmented chain expands the material functions (blue boxes) and flows (blue arrows) of the conventional service chain by including the environment (bottom), social functions (orange boxes) and flows (orange arrows), and main stakeholders. Social flows include decision making and financial power, and/or ability to affect others. Stakeholders are grouped as community members (households, etc.), decision makers (donors, governments, utilities/service providers, NGOs), and workers (construction workers, truck and plant operators, sewer workers, farm laborers, domestic workers, etc.). OD refers to open defecation. The various material and social functions, flows, and actors of the chain determine the goals (right), although not part of the chain.

4.2. An Augmented Sanitation Service Chain

We thus propose an augmented sanitation service chain that encompasses the social flows and functions through which the material flows and functions take place (see Figure 3). In particular, the currently people-free sanitation chain should expand to include the main stakeholders in the sanitation space, to make explicit that social functions shape material functions and that various actors are affected by the way in which these functions are carried out. It is not clear from the conventional chain, for instance, that a household with a pit latrine poses exposure risks for sanitation workers and other households, or that regulations and their enforcement shape the physical flows of waste. The main stakeholder categories are community members, decision makers, and workers, with social flows of power, influence, decision making, and finance linking them. Actors within each category are not homogeneous; some are more vulnerable than others at different geographic and political scales. An augmented chain that makes visible the key stakeholder categories and their positions, both vis-à-vis the conventional sanitation functions and one another, provides a heuristic for researchers to communicate across disciplines, and can assist those in siloed research programs to be more aware of sanitation's on-the-ground realities and nonconventional "functions."

4.3. Sustainable Development Goals: Rights, Interlinkages, and Sanitation Research

Unlike their predecessors (the MDGs), the SDGs are grounded in the Universal Declaration of Human Rights (156) and in the intersectionality of these rights. In essence, a claim to a right is a claim to power: "Realizing any right, including the rights to water and sanitation, will almost invariably require that existing power structures be challenged…" (157, p. 29). The progressive realization of the right to sanitation, therefore, calls for progress at the intersection of technology, planning, health and economic policy, and political action. Recent policy-oriented papers have supported these ideas. The SDGs as a group, also unlike the MDGs, are explicitly interlinked. UN documents routinely discuss the linkages between SDG 6 and the other SDGs, such as for poverty alleviation, ending hunger, sustainable cities, gender equality, education, and health. (They rarely link SDG 6 with SDG 8 on "decent work," however, showing the widespread tendency to neglect labor conditions for sanitation workers.)

The augmented sanitation service chain of Figure 3 attempts to capture the main linkages among flows, functions, and actors within sanitation systems, incorporating technological and health assessment "functions" but also those of collective action and confronting social norms. In this sense, the augmented chain more closely adheres to the inherently cross-disciplinary spirit of the SDGs than the traditional chain does. At the same time, the prominence of actors such as sanitation workers serves as a reminder that, although some of SDG 6's targets address key linkages, the indicators do not fully reflect these interconnections.

Sanitation research therefore has the potential to both reflect on and improve the interlinkages of the SDGs, by working across perspectives and across functions.

To take but one example, sustainable sanitation in the face of climate change would require environmental scientists and public health scientists to model the emissions and subsequent health outcomes of sanitation systems; engineers to design resilient treatment systems; economists to analyze the extent and distribution of the costs and benefits of resilient systems; planners to think through how to design and site urban sanitation systems; and urban geographers and gender specialists to assess the terms of access under which sanitation systems would promote adequacy and equity for all (97, 158). This may make sanitation seem like the prototypical "wicked problem" (125), but we contend that not recognizing this characteristic amounts to not recognizing the range of legitimate stakeholders and values that inhabit the sanitation world. In other words, if the reality and challenges of sanitation in LMICs cross disciplinary perspectives, then sanitation research, too, has to cross disciplinary perspectives. Many urban and rural areas of LMICs are implementing or expanding their sanitation systems; the time has come for sanitation researchers to collaborate toward designing systems that contribute to health and cleanliness, and also to climate change adaptation, to sustainable food systems, and to human rights for the poorest communities.

5. Conclusion

"[It's] not rocket science," declares a recent UN video on water and sanitation (see 159), implying that meeting the SDG goal of universal access to sanitation should surely be simpler than rocket science. We argue that this may not be the case. This review was motivated by the hypothesis that achieving adequate and equitable sanitation for all (i.e., SDG 6) would be both slow and challenging because different researchers and practitioners subscribe to different visions of what sanitation is and what it is for (see Table 1). The research we reviewed across all six disciplinary perspectives (see Figure 2) shows that the common core of sanitation research remains the protection of humans and the environment from exposure to potentially harmful waste. Across the perspectives, however, there is variation in how this purpose is to be approached, and of the extent to which the purpose of sanitation goes beyond limiting harmful exposures (see Figure 3).

In broad strokes, the engineering perspective approaches the separation of humans from waste through the design and implementation of physical technology. Public health research investigates human health risks and seeks ways in which to promote safe sanitation practices. Environmental science approaches this purpose through monitoring and management, but of the larger environment. Economics optimizes costs and benefits to see this purpose realized, while planning seeks to realize it through efficient, and hopefully

equitable, service provision and governance. The social sciences consider this purpose fully realized only when human rights, gendered needs, and dignity are protected and affirmed. Additionally, many scholars and practitioners, not only from gender studies but also from health, microbiology, and engineering, are calling for the social taboos that still haunt sanitation to be publicly confronted. These approaches and their specific contributions are central within each disciplinary perspective, but they are not as apparent, and thus not as central to scholars and practitioners across the sanitation sector. Seeing, understanding, and valuing these differences can facilitate constructive conversations across epistemic communities and collaborations toward sanitation interventions that simultaneously serve multiple, and mutually compatible, purposes for all.

6. Future issues and recommendations

- In terms of the sanitation service chain, studies on storage, transport, and reuse remain understudied functions across disciplinary perspectives; this is especially true for unsewered and hybrid systems. Cross-disciplinary work from system design to standards and regulation to final governance is needed to ensure both sustainability and equity.
- The cities of low- and middle-income countries (LMICs) are searching for integrated waste management solutions that incorporate water resources, wastewater, fecal sludge, stormwater, and municipal solid waste; sanitation research can usefully support these efforts.
- Sanitation research on specific vulnerable and/or underserved communities in LMICs is small but growing; these include homeless and migrant populations, refugees, and social groups considered to be at the margins in terms of ethnicity, caste, religion, gender identity, etc.
- Sanitation research for public settings beyond schools and health facilities is (very) small but growing; these settings include workplaces, markets and community spaces, transit centers, and other locations outside the home. New models of financing, planning, and management for these settings, from traditional to more participatory methods, should be evaluated for sustainability and inclusivity.
- Almost all the disciplines engaged in sanitation research neglect the safety and living conditions of sanitation workers around the world. Sanitation research "for all" must necessarily include occupational health and quality of life for those who work at each step of the sanitation service chain.
- Sanitation, and in particular menstrual hygiene, remains immersed in cultural norms of shame in many parts of the world. For sanitation research to serve all its necessary functions, changing norms around sanitation and gender, ability, age, and the body in general, must become a practical and research priority across disciplines.
- Finally, sanitation-related "grand challenges" across disciplines and across sectors include climate change, housing, transportation, and the

food-energy-water nexus. Future and emerging research on these cross-sector themes should explicitly incorporate the results of sanitation research.

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Chapter 3 | Clean latrines now—a pandemic history lesson[19]

1. Pandemics, public sanitation, and the poor

At the start of the COVID-19 lockdown in India, thousands of low-income migrant workers and their families packed buses, trains, stations, and streets—or were quarantined in low-income areas—with little to no access to clean toilets or public facilities to wash their hands (Sur and Mitra 2020). Even after hundreds of thousands of public toilets were constructed since 2014 through the Government of India's Swachh Bharat Mission-Urban, crowds were stuck at stations with literally no place to go, creating a heart-wrenching display of the consequences of the continued lack of public sanitation across India's cities.

COVID-19 has highlighted our current limitations and our need to rapidly improve sanitation and hygiene services for low-income, marginalized groups. Effective pandemic control requires the adequate provision of sanitation (WHO 2020). India is of particular concern because sanitation access remains less than universal, especially for the underprivileged.

Individual household toilets have increased significantly in recent years due to Swachh Bharat Mission-Urban (UNICEF 2019); however, there is a lack of attention paid to public spaces, where access to public sanitation is especially critical for underprivileged urban communities, including India's over 100 million internal migrants (Census 2011). Even where provided, public facilities are prone to disrepair (Cardone et al 2018), forcing users to choose between unhygienic toilets and open defecation—the reduction of which is the main aim of Swachh Bharat. During pandemics, the stakes are even higher for low-income individuals who must judge the safety of crowded public toilets versus open defecation (Caruso and Freeman 2020).

A clean public toilet is a necessary, albeit insufficient, component of a safe public sanitation system. The sanitation service chain includes toilets or ventilated pits for the capture of human waste, tanks for storage, trucks and pipes for conveyance, as well as technologies for treatment, reuse, and disposal. Furthermore, sanitation chain infrastructure depends on: the availability of water, solid waste management for drains and pipes, the health of non-human natural environments, and the social dynamics between decision makers, community members, and sanitation workers (Hyun et al 2019). Cities therefore must include the entire sanitation service chain and these interacting systems in

[19] I wrote Chapter 3 in 2020. It is a manuscript submitted for publication.

order to truly declare the provision of public sanitation that protects both human and environmental health.

The COVID-19 pandemic has heightened national awareness of how limited sanitation services are for marginalized groups. Through lockdowns and public health campaigns, we have become more collectively sensitive to how the health of one community is affected by the lack of sanitation services in other communities—especially among the poor. This is not a new story. Throughout history, prominent figures during epidemics, or in anticipation of epidemics, have made the case for accessible and well-maintained sanitation facilities in public spaces such as bazaars, railways, and low-income areas. Even today, this call remains inadequately heeded.

In this chapter, I trace how distress related to epidemics has been linked to advocacy for public sanitation across India's modern history. I show how Florence Nightingale, Mahatma Gandhi, and the government of Surat were influenced by the fear of epidemics in calling for improved sanitation in the public spaces of low-income communities and in transit systems. They focused not only on the construction of public toilets but also on the proper maintenance of public infrastructure, modes of conveyance and treatment, the role of decision makers, and the protection of workers. I show how disease, war, and economic hardships constrained but also inspired visions of public sanitation for the poor. Informed by these lessons from the past, I conclude by recommending concrete actions for Swachh Bharat Mission-Urban in order to improve its policy for the poor by focusing on the assessment of public sanitation. We can clearly see from history that pandemics are the critical moments when we should demand adequate sanitation—a moment now that we should not let pass us by.

2. Nightingale: sanitation for Indians

During the British Raj in India, British nurse Florence Nightingale fought for sanitation for all—for Europeans and Indians. Her call to India started in 1857: "'Lord, here I am, send me' has always been religion to me. I must be willing to go now as I was to go to the East" (Vallée 2006: 8). Though she was never able to visit the subcontinent due to illness, she wrote and debated with prominent officials about India for over forty years until her death in 1910: "My interest in India can never abate" (Vallée 2006: 6). Nightingale's "instigation" led to the set up of the Royal Commission on the Sanitary State of the Indian Army in 1859 (Gourlay 2016: 1), which published its 1863 report (hereafter the "Report"), alarming British authorities about the poor sanitary conditions among European soldiers in India.

Nightingale's sanitation concerns for India, however, did not end at European barrack walls. During the years of writing the "Report," two of Nightingale's consistent complaints were that: (1) there were little to no health and sanitation

data on "native" soldiers and (2) Europeans used caste as an excuse to ignore the unsanitary conditions of Indian communities. In 1861, she wrote:

> We have hardly any evidence about the native troops and I hope that you will name some witnesses on this subject.
> In all the books of replies which have yet arrived from India, I have been struck with this, viz., that we make ''caste'' an excuse for doing next to nothing for the native troops… (I allude especially to sanitary measures for the native lines and bazaars.) (Vallée 2006: 112)

As soon as the "Report" was signed, Nightingale declared it "the dawn of a new day for India," bringing "sanitary civilization not only to our [European] men in India but to the native cities" (Vallée 2006: 129). Motivated by past epidemics and by the potential for future ones, Nightingale strongly pushed for new visions of sanitation in India overall. She considered India "a place where plague and pestilence were 'the ordinary state of things'" (Arnold 1993: 97-98) and where unsanitary conditions of "native bazaars" could lead to "poisoning us [Europeans] round our own stations" (Vallée 2006: 111). Due to the borderless nature of epidemics, Nightingale did not exclude "native" spaces. She advocated for improvements in the sanitary conditions of Indian troops and civilians.

The 1864 follow up document, "Suggestions in Regard to Sanitary Works Required for Improving Indian Stations" (hereafter "Suggestions"), emphasizes the practical implementation of the "Report." Though her name is not officially on the "Report" nor "Suggestions," it is understood that Nightingale wrote the bulk of both authoritative documents (Vallée 2006). "Suggestions" targets the sanitary improvement of European soldier barracks, but it also includes instruction for "native" public spaces.

"Suggestions" pays special attention to the public sanitation of bazaars, calling them a "common cause of unhealthiness" (Vallée 2006: 361). Included in the recommendations for bazaars are that:

> "a plan be prepared by the local authority,"
> "streets be drained in such manner as to remove readily all rainfall,"
> "public latrines be provided,"
> "provision be made for… sanitary inspection and cleansing," and
> "the local authority draw up by-laws." (Vallée 2006: 361)

There were, however, contradictions in Nightingale's approach. First, it should be acknowledged that "Suggestions" recommends removing some bazaars altogether (Vallée 2006). Demolition of informal areas can, in fact, further disenfranchise marginalized groups (Spodeck 2013). Second, Nightingale advocated for imperial knowledge and power as the conduit for sanitation reform in India while ignoring the detrimental effects of imperialism (Godden 2009)—a contradiction and colonial legacy that Indian cities and international development organizations continue to wrestle with today (Chaplin 2011, Ranganathan 2018).

While Nightingale's engagement on this issue reflects certain imperialist assumptions and her practical influence on India's sanitation infrastructure remains unclear (Arnold 1993), her ardent advocacy for India's sanitation cannot be denied. We see this through the official reports she ghost-wrote and numerous letters she sent to head administrators and viceroys from 1857 until her death.[20] Her vision reminds us that in order to improve sanitation for one community (e.g., European soldiers in India) it must be improved for all communities, and that we must make public spaces a priority. Decades later, such sentiments were reflected in Mahatma Gandhi's own advocacy.

3. Gandhi: sanitation for the "lower" class

At the turn of the twentieth century, Gandhi used his rise to eminence in India to counter colonialism and casteism, as well as classism, by thrusting into sharp light the taboo challenge of sanitation. Contrary to Nightingale's stance, Gandhi saw colonialism as ultimately counterproductive to the cause of Indian sanitation. In his notes on municipalities, he wrote that "the peoples of the West have evolved a science of corporate sanitation and hygiene from which we have much to learn," but added that "[w]e must modify Western methods of sanitation to suit our requirements" (CWMG Vol 25 1967: 461). Gandhi promoted a two-pit system—an on-site decentralized approach addressing the entire sanitation service chain—that he believed would not require "vast sums of money" for "sanitary reform." Such technological systems would be untethered from the political economy of imperialism and the "horror of Western materialism." Gandhi was not opposed to science, technology, and Western ideas per se, but he was against "the power structures that are reproduced within these categories" (Joshi and Khattri 2019).

Gandhi recognized that such power structures could be reproduced in sanitation systems, especially through labor and the continuation of caste-based practices. One of Gandhi's most radical acts was that of cleaning his own latrine and disposing of his own waste. He also encouraged others to do the same. While Nightingale observed that British officials used caste barriers as an excuse to ignore poor sanitation, Gandhi used sanitation to radically confront caste hierarchies. By cleaning his own waste and advocating for others to do the same, Gandhi defied the entitlement and casteism that he believed undermined the nation's capacity for swaraj, or home rule (CWMG Vol 14 1965). For him, improving Indian sanitation was on par with and a part of the fight for swaraj. For cities, he advocated that "the municipalities of India should take part in the national movement [for swaraj], but not at the sacrifice of their primary duties, cleanliness and sanitation" (CWMG Vol 25 1967: 449). Moreover, based on Gandhi's initiation of multiple manual scavenging campaigns (e.g., Bhangi

[20] Nightingale closely interacted with the viceroys of India. Even before Lord Ripon became a viceroy, "[o]ften he [Ripon] was her [Nightingale's] voice in Parliament" (Vallée 2007: 11).

Mukti Andolan and Bhangi Kasta Mukti), integral to a city's "primary duty" of sanitation would be the de-stigmatization, liberation, and physical protection of oppressed caste groups (Alok 2010).[21]

Along with swaraj and casteism, Gandhi strove to break down class divides in access to public sanitation, in particular the sanitation of trains and railway stations. Looming plagues and epidemics motivated Gandhi's vision for improved sanitation across the railway system. He wrote:

> [Railway stations] are discreditable-looking places where there is no order, no cleanliness but utter confusion and horrible din and noise. ... The closets attached to these places defy description. ... Is it any wonder that plague has become endemic in India? Any other result is impossible where passengers always leave some dirt where they go and take more on leaving. (CWMG Vol 13 1964: 549-550)

Proper sanitation on trains was a matter of social justice for Gandhi. Though the ticket fare for first class was five times that of third class, Gandhi was indignant that third class passengers did not receive one-fifth or "even one-tenth of the comforts" of those in first class. He thus claimed that the third class subsidized the luxuries of the upper classes. Additionally, he believed in the potential of proper train sanitation as an "object lesson" in "decency and cleanliness" to ordinary passengers. He regarded providing such "bare necessities" to third class passengers as "simple justice" (CWMG Vol 13 1964: 550).

Gandhi's solution to the problem of poor sanitation in public places, such as trains and stations, was to have those in power regularly experience such conditions:

> Let the people in high places, the Viceroy, the Commander-in-chief, the Rajas, Maharajas, the Imperial Councillors and others, who generally travel in superior classes, without previous warning, go through the experiences now and then of 3rd class travelling. We would then soon see a remarkable change in the conditions of the 3rd class travelling... (CWMG Vol 13 1964: 550-551)

Even Gandhi, however, stopped travelling in third class by 1925. He then emphasized that the whole system of governance was the problem, and that swaraj was "the only remedy" for the hardships that railway passengers faced (CWMG Vol 28 1968: 449-450). Over seventy years after gaining independence however, India still faces sanitation challenges on railways and in public spaces, including running thousands of trains that daily discharge human waste directly onto railway tracks (Burt et al 2016), essentially an often-unrecognized form of open defecation. This exposes a number of marginalized groups to unsafe waste,

[21] Gandhi's writings and actions pertaining to the relationship between sanitation, swaraj, and caste are multi-faceted, dynamic, and not without contradiction, for example see Joshi and Khattri (2019).

including sanitation workers, communities living and working near railways, and internal migrants.

4. Surat City: sanitation for migrants

Spanning the decades since India's Independence, there have been major attempts to fulfill Gandhi's vision for public sanitation across India. One example motivated by a plague is in Gandhi's home state, Gujarat, in the city of Surat. Surat (population 4.4 million, Census 2011) went through major sanitation reforms after becoming the epicenter of a plague in 1994. In response, the city made improvements in drainage, increased sanitation and hygiene regulation, and initiated regular health inspections (Swamy et al 1997), reaching similar conclusions as expressed in the planning and engineering recommendations of Nightingale's "Suggestions" document. These impressive reforms had continued from then on and gave government officials and health workers confidence in their preparedness for future epidemics (Chatterjee 2015).

The city of Surat, however, was not prepared for how migrant workers responded to sanctions during the COVID-19 pandemic, when hundreds began protesting and overwhelming transit systems. In terms of public sanitation for low-income communities, the 2011 Surat City Resilience Strategy acknowledged the city's limitations regarding internal migration:

> The Urban community development department (SMC) is active and monitors delivery of essential service in slums. In comparison to [the] rest of India, slums in Surat have better access to water supply, drainage and sewerage facilities. But, very high in-migration of semiskilled workers from across the country poses a continuous challenge to the efforts of SMC. (ACCCRN 2011)

This continues to be a concern in Surat's strategy from 2017, where growing internal migration rates are blamed for increasing "stress on the city's management [and] existing infrastructure" (TARU 2017). The COVID-19 pandemic has exposed the utter lack of services for migrant workers and their families. After the 24 March 2020 national lockdown announcement, transportation was prohibited, and migrants moved into lockdown shelters. Two weeks later, the state director general of police allegedly warned the Gujarat home department that the lack of basic facilities in shelters could lead to clashes; and a day later on 10 April, hundreds of migrant workers assembled in the streets of Surat demanding food and permission to go back to their hometowns and villages (Jha 2020). Protests in the streets and crowding at transit hubs sprung up in and around Surat for months (Langa 2020a, Langa 2020b, Sharma 2020), as well as in other cities across India.

Due to COVID-19 sanctions, states shut down their borders, leaving many migrants stuck with nowhere to go and nowhere to safely defecate or manage their hand, menstrual, and other hygiene needs (Chandrashekhar 2020). Back

when Gandhi fought for sanitation on the train system, he emphasized the need for passengers to be able to complain to railway authorities, stating that "some grievances have their origin in the entire system of Government being evil… suppress[ing] any revolt that we may arise" (CWMG Vol 28 1968: 450). Almost a century later, during COVID-19, migrant workers in his home state would in fact revolt in the streets and at transit hubs, exposing current limitations not only in public sanitation but arguably in the broader governance system itself.

Surat is a case of a city that has actively worked toward improving sanitation in low-income areas. Under extreme pressure, however, the city could not accommodate its migrant workers. My point here is not to attribute causes to particular protests but to underscore that pandemics and their related flash points uncover persistent gaps in clean, accessible sanitation for migrant workers, their families, and other marginalized groups—communities we should pay close attention to during COVID-19.

5. SBM: it's time for 100% sanitation for the poor

What the history of epidemics and plagues teaches us and what we are clearly experiencing during COVID-19 is that rich, middle-class, and low-income communities are dependent on each other in cities and therefore interact in a way that the health of each community depends on the health of others. Since 2014, the Government of India's Ministry of Housing and Urban Affairs (MoHUA) has made numerous efforts to increase access to sanitation through Swachh Bharat Mission-Urban (SBM-U).[22] There have been limitations, however, in providing public sanitation for low-income groups.

Starting in 2014, SBM-U aimed to declare all urban local bodies open defecation free (ODF) by October 2019. Like Nightingale's "Suggestions," the necessary conditions to achieve ODF status include public sanitation, for instance "[a]ll commercial areas [must] have public toilets within a distance of 1 kilometer" (GoI 2020c: 7). The target was to construct 2,56,000 public toilet seats by 2 October 2019 (GoI 2020e)—a significant but small number compared to the millions of unhoused individuals and migrants in India (Census 2011). By the start of 2020, approximately 2,38,000 public toilets were constructed, 18,000 less than the target (GoI 2020a). Even after cities were declared ODF, there have been reports of insufficient numbers of public toilets (e.g., UNICEF 2020).

Though constructing hundreds of thousands of public toilets is laudable, a major challenge is the quality of public toilets. This is a worry with a long history. Concerned about plagues, the quality of public sanitation also troubled Gandhi. This has continued to be a major public health problem in 2020, when a number

[22] Swachh Bharat Mission has two components: Swachh Bharat Mission-Gramin (SBM-G), which is the rural program overseen by the Ministry of Drinking Water and Sanitation, and Swachh Bharat Mission-Urban (SBM-U). This article focuses on SBM-U, which is overseen by MoHUA.

of reports claimed that public toilets were not only insufficient, but those that had been provided were unusable (e.g., Upadhyay 2020, Mishra and Baishali 2020, GoI 2020b). This is especially unsettling during the COVID-19 pandemic, when water and sanitation experts recommend frequent deep cleaning of public toilet facilities and adequate water availability (Howard et al 2020), as public facilities may be the only means of adequately washing hands for migrants and other low-income individuals.

SBM-U's follow up protocols, ODF+ and ODF++, address both the quantity and quality of toilets.[23] They increase the number of public toilets, requiring that "[a]ll public areas" must have functional toilets within one kilometer, including parks, gardens, and transit hubs (GoI 2020c: 8). They also require quality evaluations of public and community toilets: Every 12 months, MoHUA must select a third-party assessor to conduct surprise evaluations in order to achieve and maintain ODF+ or ODF++ status (GoI 2020c).[24] MoHUA also launched the mobile app, Swachhata-MoHUA, to crowdsource complaints related to sanitation, including public toilets. Finally, the annual award program, Swachh Survekshan, provides an incentive for cities to follow SBM-U's public sanitation quantity and quality protocols.

MoHUA's efforts for ODF+ and ODF++, however, are constrained by time and finances. As of March 2020, SBM-U is not on track to reach its target of all cities declared ODF++ by 2024, according to the Standing Committee on Urban Development (Pandey 2020, GoI 2020b). Furthermore, MoHUA has stated that additional funds are required to sustain ODF and to ensure the complete fecal sludge management needed to ultimately achieve ODF++ (GoI 2020b: 99). With these limitations in mind, it would be prudent for MoHUA to more purposefully target low-income groups that greatly depend on public sanitation, in particular those without homes that can accommodate individual toilets.

MoHUA claims that one of the major challenges that SBM-U aims to overcome is restricted access to sanitary facilities due to increased urban migration, especially in areas of "economically weaker sections of society" (GoI 2020c: 6). Below, I suggest how MoHUA could streamline its SBM-U programming for this target group. First, in order for residents to use the Swachhata-MoHUA mobile app they must have access to smartphones. India has one of the most prominent digital divides in the world, with lower-income households and women having significantly lower access to mobile phones in general. Although ownership is rapidly increasing, a large proportion of Indian citizens report that they cannot properly use smartphones due to limited technological or general literacy (Pew

[23] The certification protocols of SBM-U include ODF, ODF+, ODF++, and Water Plus. There is also the annual Swachh Survekshan survey and ranking program.
[24] SBM-U defines "public toilets" as those for the floating population and general public. In contrast, "community toilets" are for "a group of residents or an entire settlement," particularly in low-income and informal areas (GoI 2017: 9).

Research Center 2019). Low-income communities then face a higher barrier to filing complaints about the public facilities they highly depend on.

This means that low-income users rely more heavily on MoHUA to monitor the quality of public facilities; therefore MoHUA should focus its time and finances on pro-poor efforts. Currently, ODF+ and ODF++ protocols require that MoHUA approved third-party assessors evaluate a total of 14 to 40 locations (depending on the size of the city) across 8 to 9 different location types, which include slums, schools, roads, public areas, commercial areas, residential areas, transport hubs, and water bodies (see Table 1). Since higher income groups have various means to report on the cleanliness of areas that they live and work in, it would behoove MoHUA to explicitly mandate in the protocols that all of these location types must be in low-income areas, especially those frequented by marginalized groups in terms of caste, religion, disability, and gender. In this way, MoHUA can use their limited time and finances on the communities that most depend on public facilities but have the least means of making sure those facilities are usable.

In order to assure that public facilities are being evaluated properly, the quality of assessments themselves must be verified. ODF+ and ODF++ protocols add that a "Quality Audit on the work of the assessor would be conducted," but include no details on who would conduct such an audit, nor when or how it would be conducted (GoI 2020c: 15 and 23). Such details are necessary since SBM-U assessments have been shown to be wanting. The Center for Science and Environment (CSE) found loopholes in MoHUA's Swachh Survekshan 2019 survey implementation, especially related to assessors who had too little time to conduct proper evaluations and who may have never even shown up to their designated locations (CSE 2019).

As with ODF+ and ODF++ protocols, Swachh Survekshan surveys should also streamline efforts by focusing on low-income and marginalized groups. Other than a singular mention of slum beautification, the Swachh Survekshan 2021 Toolkit makes no direct mention of sanitation access for low-income groups (GoI 2020f).[25] The survey could make sure that sample populations are primarily low-income. For example: For those performance categories that rely on ward-level data, more—if not the entire—weight could be designated to the poorest wards. To cut costs, only half of a city's wards could be included in the survey, all in the lowest income brackets. The structured interviews (i.e. surveys) for public toilets could all be conducted in low-income areas and results could be disaggregated by income level.

[25] The Swachh Survekshan 2021 Toolkit does provide indicators for the needs of sanitation workers and informal waste pickers. Plus, any assessment of community toilets indirectly implies that they are in low-income areas.

The improvements above are only a few recommendations to make SBM-U more pro-poor and inclusive. The suggestions summarized in Table 1 assist in establishing more focused public toilet assessments. Improvements, however, should also be made across all of SBM-U programming, including for community toilets. The Central Public Health and Environmental Engineering Organisation and MoHUA have developed impressive guidelines for public and community toilets (GoI 2018), but their design, management, and planning could be more inclusive and pro-poor (see for example GIZ 2016). As cities increasingly aim to meet ODF++ and Water Plus standards, the assessment of the rest of the sanitation service chain—beyond toilets—will require greater specificity and pro-poor focus, especially since the storage, conveyance, and treatment requirements of community and public facilities differ significantly from household toilets (GoI 2020d). Guidelines and official assessments must also be clear and streamlined so that city officials can more easily adhere to them. The SBM-U protocols and assessments have been a powerful tool to stimulate cities to provide sanitation, but in order to make them more sustainable, MoHUA should work to streamline implementation by focusing its policy on the underprivileged.[26]

Table 1 | Pro-poor changes suggested for SBM-U assessment protocols

	CURRENT	PRO-POOR CHANGES
ODF+ and ODF++ location types inspected by mohua approved third-party assessors	Slum School (not in ODF++) Roads and streets Public area Commercial area Residential area Transport hub Barren area (not in ODF+) Water bodies	All location types must be in wards and neighborhoods of the lowest income bracket, also consider caste, religion, disability, and gender representation (including transgender)
ODF+ and ODF++ audit of third-party assessors	"quality audit on the work of the assessor would be conducted"	Clarify who should do the audit, how, and by when
Swachh Survekshan performance categories	All wards calculated equally	Increase the weight of wards in the lowest income bracket, or only include 50% of all wards by selecting wards of the lowest incomes
Swachh Survekshan public toilet assessment	Conduct survey interviews near public toilets	Conduct surveys near public toilets in lowest income bracket neighborhoods, collect data on interviewees' stated income levels, and disaggregate results

Document sources: GoI 2020c, 2020f

[26] Some recommendations in this paragraph were borne from personal communication with R. Paul (24 August 2020) and A. Y. Kumar (26 August 2020).

6. Conclusion

What pandemic history reveals is that one of the key roles of government institutions and programs, such as MoHUA and SBM-U, should be to ensure that public services are reaching the most vulnerable and marginalized communities. Nightingale advocated that the British Raj not only care for European soldiers but also build and maintain public infrastructure for Indians. Gandhi pushed for the nation to invest in quality sanitation not just for citizens who could afford first class, but also for those who only had the means to travel third class. Even after the laudable efforts of the ODF campaign, COVID-19 has shown us the current limits of public sanitation, especially for low-income migrants.

As India continues toward ODF+, ODF++, and now Water Plus, we must ensure that those who depend on public sanitation the most are not only recognized but are also prioritized in practice. The practical changes I outline above focus on helping low-income groups, but economic disadvantages are further compounded by hurdles related to caste, religion, migration status, disability, and gender identity—including transgender (Boyce et al 2018). Cities that commit to providing and maintaining public sanitation for these marginalized groups also secure the health of everyone—rich or poor.

The necessity of this commitment is perhaps best conveyed by Gandhi. By 1917, India had one of the largest volunteer armies in World War I (over a million strong by the end of the war), yet Gandhi felt passionately enough about India's need to invest in infrastructure for public sanitation to write:

> The existence of the awful war cannot be allowed to stand in the way of removal of this gigantic evil. War can be no warrant for tolerating dirt and overcrowding. One could understand an entire stoppage of passenger traffic in a crisis like this, but never a continuation or accentuation of insanitation and conditions that must undermine health and morality. (CWMG Vol 13 1964: 550)

Plagues and pandemics expose the far-reaching consequences of the lack of public sanitation for the poor. If war should not stop us from improving sanitation, then a pandemic obligates us to do all that we can to make public sanitation for everyone a reality—a history lesson which the world should have heeded long ago.

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Conclusion | Shit, now what?

If you think someone is missing, the first piece of advice given is: Do not panic. In the case of my research, 844 million people are missing from basic drinking water services and more than four billion people are missing from safely managed sanitation. Should this not be cause for panic? This advice is not that we should be unconcerned, but that we should be in a state of mind to do something about it. In fact, further advice includes:

- Do not wait, especially if your missing person is vulnerable… .
- Do not delay in searching; time can be of the essence.
- Do not keep their disappearance a secret. The more people you tell, the more people you have looking on your behalf and the speedier the results might be. ...
- Do not give up, keep appealing and searching. Remember that people want to help. ... Your missing person is important.[27]

My dissertation in a variety of ways has heeded these suggestions. My main concern has been for vulnerable populations. Be they low-wage frontline water valvemen, communities from low-income regions, or migrants trapped in a pandemic lockdown, my colleagues and I have not hesitated to make their needs the focus of research. With each chapter of this dissertation, I have appealed to different influential audiences: technological innovators, development engineers, public administrators, government officials, policy makers, and those of my ilk—academic researchers. The underlying plea has been to make vulnerable people less missing (i.e. render them more visible) in technological innovation and infrastructural expansion for greater access to water and sanitation.

In the Introduction, I proposed that one way to understand how to do this is through the invisible infrastructure framework. It is not difficult to perceive the valvemen of Bangalore as extensions of both the municipal water system and NextDrop's digital water monitoring system. NextDrop often called them, "human sensors." In this way, valvemen are an ideal example of invisible infrastructure. My field research revealed how both the material environment (e.g. roads, trees, etc.) and the social environment (e.g. community income characteristics and their own individual characteristics, such as family situation) correlated with technological performance of the water system and NextDrop's intervention. The potential effects of overarching social challenges, such as the dowry system, were not clear to the utility nor NextDrop; and the privatization

[27] As listed on the Michigan State Police website, retrieved on November 8, 2020: https://web.archive.org/web/20201108111602/www.michigan.gov/msp/0,4643,7-123-1878_32000-299532--,00.html

of their jobs drastically lowered their pay, making them even more invisible to the state through de-prioritization of their work.

For "Clean latrines now—a pandemic history lesson," it took me a while to figure out what was missing from history and sanitation policy in India. It seemed that, though flawed, Nightingale, Gandhi, and Swachh Bharat Mission were at least trying their best to advocate for vulnerable communities. Then when COVID-19 reached the subcontinent and India went on lockdown, it was apparent that poor internal migrants had no access to sanitation. In other words, they had been invisible in sanitation planning and policy. This inspired me to dig further into what was happening in the city of Surat and how the Government of India could improve public sanitation for the poor. This is a case when exploring regimes of truth (i.e. asking who knows what) led me to see how the state could more clearly represent poor communities in the data they were already collecting in order to render them more visible.

The invisible infrastructure framework is fundamentally the same as our review's augmented sanitation service chain in Chapter 2, but it is further abstracted. I have even used similar colors. The argument in our review is that research is siloed and therefore social aspects of sanitation systems can become invisible, people go missing. This clearly speaks to regimes of truth in academia. My co-authors and I, in a sense, experimented with reorganizing this regime during our literature review process. My colleague, Sharada Prasad, convened a multidisciplinary group of scholars, and I helped coordinate regular sessions to discuss sanitation from various disciplinary perspectives. We then had to figure out how to rethink sanitation scholarship when we decided to write a review. We had questions: What is sanitation? Which journals count? Who are the scholars? What is a discipline? It was confusing, messy, and, of course, political (in the sense that most things are political). After the review was published, a scholar approached me and asked why their publication was not included. There were a number of viable reasons for this, but ultimately all I could do was shrug.

Regimes of truth are embedded in regimes of rule (i.e. who controls what) which are related to regimes of accumulation (i.e. who gets what).[28] I became more sensitized to these regimes when it was apparent that I would manage the review writing process for what is now Chapter 2. I questioned if we were the "right" people to conduct this review, which journals would be appropriate for the review, and who should have access to the review. Essentially, I situated our research team and myself into the social environment of the invisible infrastructure framework; and fundamentally, I questioned in what ways it was just or unjust for me to be part of this process.

Returning to the initial advice for missing persons, I write this dissertation not only to earn a degree but also to find the people who want to help. One of those

[28] See Watts and Peluso (2013) and Scoones (2016) as referred to in the Introduction.

people is you. Hopefully you found something in this dissertation useful. Maybe it was the invisible infrastructure framework I describe in the Introduction. You are reading this dissertation, so I assume you are directly or indirectly involved in water and sanitation work. You are probably not a top decision maker, but you're somewhere in a network of influencers (i.e. an intermediary, like the valvemen). You may be unclear or even fully unaware of your role (i.e. invisible) in tech-led transformation. The aim of this dissertation is help situate you, other stakeholders, and technology back into their social environments to consider who may be missing in the process of getting water and sanitation to all and why.[29]

Often at the end of "policy relevant" dissertations like this one, there are recommendations for future research and decision making. I have already given a number of them at the end of each of the previous chapters. As a final recommendation, I recall a quote I heard a week before writing this paragraph at the end of a symposium.[30] It is a quote that Martin Luther King, Jr. had paraphrased from the American abolitionist, Theodore Parker. Here it is in full:

> I do not pretend to understand the moral universe, the arc is a long one, my eye reaches but little ways. I cannot calculate the curve and complete the figure by the experience of sight; I can divine it by conscience. But from what I see I am sure it bends towards justice.[31]

I predict that many dissertations from 2020 will in some way attempt to address justice. In fact, they may use this same damn quote. But even if I am a product of history, it does not deter from the fact that, as I said at the start of this dissertation, there are millions, if not billions, of people around us without access to adequate water and sanitation, and I am sure that you sense there is something wrong, something quite unjust about that. Your mission, then, is to ensure that we connect the material flows of infrastructure to the invisible flows of social power, to include dignity and the realization of human rights as functions of an optimal technological system, and to continually calculate how to make social justice the purpose, aim, outcome of whatever we do to provide water and sanitation to everyone.

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[29] Here, I invoke the work of Donna Haraway on situating knowledge, Sheila Jasanoff's discussions on co-production, and Khalid Kadir's "Can Experts Solve Poverty?" video produced by UC Berkeley's Blum Center (youtu.be/8jqEj8XUPlk).

[30] The symposium was on the food, energy, and water nexus hosted by the Berkeley Energy and Resource Collaborative in November 2020. The speaker who shared this quote was Dr. Peter Gleick.

[31] Parker, T. (1853). Ten sermons of religion. Boston: Crosby, Nichols, and Company.

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Introduction

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Chapter 3

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