

Towards a multi-scale, socio-technical view of the design and evaluation of  
water, sanitation, and hygiene infrastructure

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A dissertation  
submitted in partial fulfillment of the  
requirements for the degree of

Doctor of Philosophy

University of Washington  
2023

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**Abstract**

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Water, sanitation, and hygiene (WASH) are important prerequisites to human health, yet global investments in this infrastructure do not always deliver the expected benefits. The relationships between WASH and health are complex, and not fully accounting for these complexities in the design and evaluation of interventions may be limiting implementation success. In this dissertation I help the WASH sector reimagine how infrastructure can be engineered and its contributions to health and level of service measured. I propose greater implementation of a multi-scale, socio-technical perspective of infrastructure in the design and evaluation process. I present a diverse collection of research projects, each with a different scope, scale, and/or evaluation technique linked to evidence-based design suggestions. I conclude by reflecting on key conventions underlying WASH infrastructure development – namely, the use of the term *community* and the application of global technical WASH standards – to further demonstrate the value of a multi-scale, socio-technical approach.

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## **ACKNOWLEDGEMENTS**

It is undoubtedly a privilege to have so many people to thank. I praise God for my dear husband, brothers and sisters in Christ, family, friends, and colleagues who have given of themselves to help me during my graduate career. Without dismissing their contribution or my appreciation, I would like to take this opportunity to specifically acknowledge those who provided research support to this dissertation.

My deepest gratitude is for my advisor, Dr. Jessica Kaminsky. Over the past five years I have appreciated her trust, flexibility, easy-going attitude, and encouraging words. She offered me more research opportunities than I could accept and allowed me the freedom to work on a variety of projects, as evidenced by this eclectic dissertation. I am also indebted to her qualitative research expertise (especially for Chapter 4) and her knowledge of the field of water, sanitation, and hygiene that shaped the entirety of work herein.

I would also like to extend gratitude to my other committee members, Drs. Steve Muench, Jerry Herting, and Crystal Farh. A special thanks to Steve for his constructive advice during my General Exam about the big-picture idea of my dissertation. I am extremely grateful to Jerry for his unceasing stats support (especially for Chapters 2 and 3), patience, and good-humored, nurturing spirit. A heartfelt thank you to Crystal for being my Graduate Student Representative and her interest in my research.

I have also had the great pleasure of working with Dr. Suman Chakrabarti. His contribution to this dissertation and impact on my broader development as a graduate student are hard to overestimate. The genesis and methods of the first two projects of this dissertation are based on his ideas and ingenuity. His patience and availability around the clock were also remarkable, things that I do not take for granted. My time at the university was enriched immensely by our collaborations.

I would also like to acknowledge the chapter-specific assistance of the following persons and organizations.

**Chapter 2.** This work is based on the India Human Development Survey dataset provided by the University of Maryland and the National Council of Applied Economic Research, New Delhi.

Chapter 2 is based on work supported by the University of Washington Valle Scholarship, Scholar Award from the Seattle Chapter of the ARCS Foundation, and National Science Foundation Graduate Research Fellowship Program under Grant No. DGE-1762114. Any opinions, findings, and conclusions or recommendations expressed in this chapter are those of the authors and do not necessarily reflect the views of the University of Washington, ARCS Foundation, or National Science Foundation.

**Chapter 3.** This project benefited from the generous coding help provided by the Center for Social Science Computation and Research and methods suggestions offered by the Center for Statistics and the Social Sciences (especially Ms. Sara LaPlante) at the University of Washington.

This research used data from the China Health and Nutrition Survey (CHNS), which received funding from the National Institute for Health (NIH), the Eunice Kennedy Shriver National Institute of Child Health and Human Development (NICHD) for R01 HD30880 and R01 HD38700, National Institute on Aging (NIA) for R01 AG065357, National Institute of Diabetes and Digestive and Kidney Diseases (NIDDK) for R01 DK104371 and P30 DK056350, National Heart, Lung, and Blood Institute (NHLBI) for R01 HL108427, the NIH Fogarty grant D43 TW009077, the Carolina Population Center for P2 CHD050924 and P30 AG066615 since 1989, and the China-Japan Friendship Hospital, Ministry of Health for support for CHNS 2009, Chinese National Human Genome Center at Shanghai since 2009, and Beijing Municipal Center for Disease Prevention and Control since 2011. The CHNS also acknowledges the support of the National Institute for Nutrition and Health, China Center for Disease Control and Prevention, Beijing Municipal Center for Disease Control and Prevention, and the Chinese National Human Genome Center at Shanghai.

Chapter 3 is also based on work supported by the University of Washington Valle Scholarship, Scholar Award from the Seattle Chapter of the ARCS Foundation, P.E.O. International Scholar Award, and National Science Foundation Graduate Research Fellowship Program under Grant No.

DGE-1762114. Any opinions, findings, and conclusions or recommendations expressed in this chapter are those of the authors and do not necessarily reflect the views of the University of Washington, ARCS Foundation, P.E.O. International, or National Science Foundation.

**Chapter 4.** I would like to express my sincere thanks to the study's participants for sharing their time and experiences. This project would not have been possible without their willingness, nor without Chris Wilkerson and Seattle Public Utilities' partnership. I am grateful for the help of Graham Pruss, April Ballard, Karen Levy, and Rachel Fyall in designing the study and collecting the data. I am thankful to Rachel Fyall's Spring 2021 Housing Policy class and to her graduate student Lizzie Tong for the excellent assistance with data analysis. Thank you also to Urban@UW for their support.

Chapter 4 is based on work supported by the University of Washington Valle Scholarship, Scholar Award from the Seattle Chapter of the ARCS Foundation, P.E.O. International Scholar Award, and National Science Foundation Graduate Research Fellowship Program under Grant No. DGE-1762114. Any opinions, findings, and conclusions or recommendations expressed in this chapter are those of the authors and do not necessarily reflect the views of the University of Washington, ARCS Foundation, P.E.O. International, or National Science Foundation.

The wages of sin is death,  
but the free gift of God is eternal life  
in Christ Jesus our Lord.

Romans 6:23

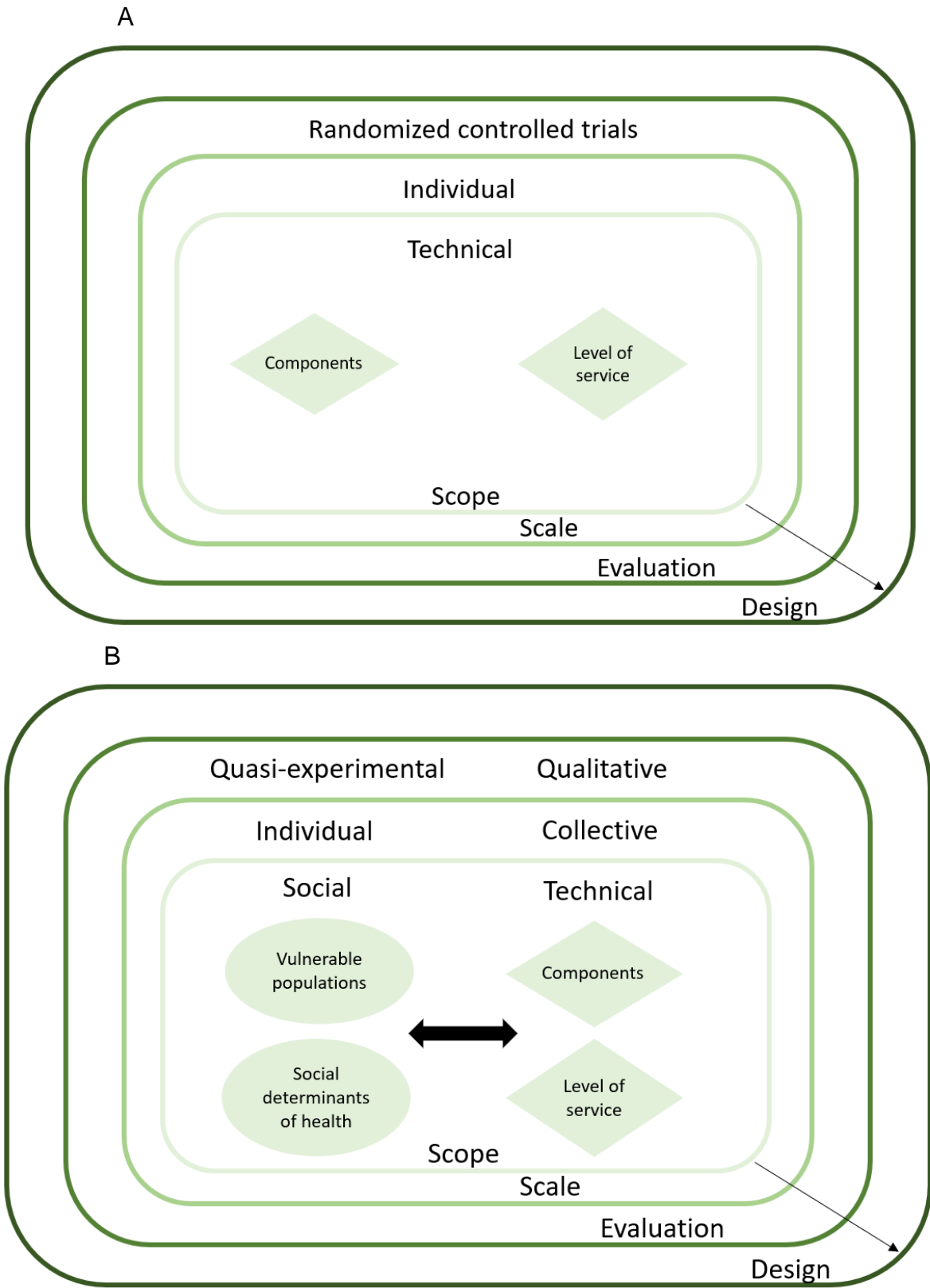
## CHAPTER 1 INTRODUCTION

Infrastructure that supports water, sanitation, and hygiene (WASH) is central to reducing the global burden of disease. According to the latest estimates, unsafe WASH contributed to 104.6 million disability-adjusted life years and 1.6 million deaths in 2016 alone.<sup>1</sup> Despite over five decades of programs and initiatives, improving WASH access and delivering the associated health benefits have been recurrent challenges for the sector. There has been a growing recognition in recent years that such uneven success may reflect the need for a re-examination of how WASH research and practice are done, namely how WASH infrastructure is designed and evaluated.<sup>2-6</sup> The sector may be too narrow in how it scopes, scales, and assesses its projects, and such reductionism may be limiting progress. This dissertation attempts to contribute to an expanded view of the design and evaluation process, including the measurement of WASH infrastructure's level of service and contributions to health. I aim to develop the sector's understanding of how to study and engineer WASH infrastructure as a socio-technical and multi-scale<sup>7,8</sup> phenomenon. I draw on both qualitative and quasi-experimental methods and a wide range of contexts to demonstrate the implementation of this perspective and its value in WASH infrastructure development.

### 1.1 Dissertation summary

#### 1.1.1 Conceptual overview

This section presents the integration of a multi-scale, socio-technical perspective into the design and evaluation of WASH infrastructure and connects it to the research in this dissertation. These prefatory remarks are meant to tie subsequent chapters together and are centered around the conceptual frameworks depicted in Figure 1.1. In brief, Figure 1.1 Panels A and B are comprised of four concentric rings of *scope*, *scale*, *evaluation*, and *design*. The embeddedness of the rings implies both information conveyance and chronological sequencing; that is, information is seen as moving outward, with initial decisions about research project scope ultimately informing an end infrastructure design. I envision a WASH infrastructure project's scope and scale phases directly informing its evaluation technique and design and the findings from the evaluation phase guiding future design decisions. Panel A outlines the reductionistic approach the WASH sector is currently questioning, and Panel B shows the socio-technical, multi-scale framework I am proposing.



**Figure 1.1 Design and evaluation of WASH infrastructure.** *Panel A:* Traditional approach; *Panel B:* Socio-technical, multi-scale approach

As Figure 1.1 suggests, adopting the view of infrastructure as socio-technical should influence a project's scope. In simple terms scope can be thought of as the "what" and "who" pieces of a project, including study outcomes, exposures, and target populations. Considering how the social and technical interact with one another (the bi-directional arrow in Panel B) and with health can help define these inputs and outputs. This dissertation focuses on the social dimensions of education and homelessness, two social determinants of health,<sup>9</sup> and socio-demographic characteristics such as age and sex that define certain populations as more vulnerable to technically determined WASH risks. The technical refers to the physical hardware, such as a water tap, and level of service it provides, such as water that is free from contaminants, on-premises, and available when needed.<sup>10</sup> The technical is often the main focus within conventional WASH research and practice (Panel A). Though social factors are not completely absent from the sector's current approach, I did not include them in Panel A to keep the figure simple and make the distinction between the two panels clearer. I would argue that the sector to some extent understands the socio-technical nature of infrastructure but does not always apply this knowledge to WASH infrastructure development.<sup>7</sup> This dissertation demonstrates putting that knowledge into practice.

Next, acknowledging infrastructure as multi-scale means realizing it can operate at and influence both the individual and collective. Scale is concerned with matters of "how much" and to "what extent." Traditionally, WASH interventions are implemented at the individual or household level, which inherently limits their ability to address extra-household risks (Panel A). This narrow view may be preventing conventional WASH from sufficiently improving an environment so as to produce the expected health benefits. The sector is calling for more community-level interventions (Panel B), though it is currently unclear what they should entail.<sup>2,4-6</sup> This dissertation seeks to clarify the conceptualization of community interventions.

Overcoming reductionism in the WASH sector may also be aided by more diverse evaluation methods. The sector's reliance on randomized controlled trials (RCTs) to assess intervention outcomes may be limiting the evidence base, both in terms of scale and scope (Panel A). RCTs are difficult to employ for multi-scale community interventions due to the time and resources needed to implement large-scale interventions experimentally.<sup>11</sup> Furthermore, RCTs do not typically employ

qualitative methods,<sup>12</sup> which can make it challenging to study human-infrastructure interactions. This dissertation demonstrates the value of rigorous quasi-experimental and qualitative designs for the evaluation of WASH interventions (Panel B).

Ultimately, the scope, scale, and evaluation technique will inform the design of WASH infrastructure to be researched or implemented in practice. The scope and scale immediately determine a project's design, while the results of a project's evaluation will typically inform future designs. Each research project in this dissertation offers WASH infrastructure design considerations. The dissertation's conclusion, rather than simply amassing these suggestions, focuses on two key conventions underlying Figure 1.1 Panel A and examines them from the proposed multi-scale, socio-technical perspective.

### *1.1.2 Research overview*

The research in this dissertation is divided into three chapters (Chapters 2 through 4), each chapter addressing, to varying degrees and with some overlap, the different scope, scale, and evaluation pieces and linking them to infrastructure design considerations for WASH research and practice.

To begin, Chapter 2 presents a quasi-experimental study using instrumental variable two-stage least squares estimation (*evaluation*) to quantify the association between primary school children's education and household drinking water access (*scale*) and examine the heterogeneous effects across socio-demographic groups and water infrastructure types in India (*scope*). To my knowledge, this study is the first to establish a plausibly causal link between children's water collection responsibilities and their learning achievement and offers the sector a rigorous statistical approach for estimating the social impact of infrastructure. One of the design recommendations from the study is for the construction of off-premises piped taps as opposed to other off-premises water infrastructure in the absence of piped-to-premises water in water-insecure contexts (*design*).

Chapter 3 is also a quasi-experimental study that uses generalized estimating equations (*evaluation*) to estimate the relationships between changes in household- and community-level water, sanitation, and air pollution (*scale*) and changes in both child and adolescent linear growth faltering in China from

1989 to 2011. To my knowledge, this study is one of the first among the WASH literature to examine growth faltering among both children and adolescents and analyze the effects of household and community air pollution from cooking fuel (*scope*). Based on the results, I recommend the sector prioritize improving community-wide sanitation coverage and household indoor air quality as interventions aimed at reducing growth faltering (*design*).

Chapter 4 is a qualitative study that uses content analysis of semi-structured interview data (*evaluation*) to describe the WASH conditions (*scale*) of people living in recreational vehicles (RVs) in Seattle, WA USA (*scope*). This project was conducted in partnership with the City of Seattle's RV wastewater pump-out pilot program and provides some of the earliest evidence of RV residents' WASH experiences, an understudied high-income country WASH issue. Though this study is primarily descriptive, we offer modest *design* considerations informed by the results and interviews with service providers involved in outreach or environmental health work in Seattle. The recommendations include advice against a mobile RV water-tank filling service and suggestions for more educational components on the topics of maintenance, safe water storage, and greywater management in tandem with infrastructure services.

## **1.2 Dissertation format**

The research presented in each chapter follows a peer-reviewed journal publication format. At the time this dissertation was compiled, Chapter 2 was published, Chapter 3 was accepted, and Chapter 4 was under preparation. Due to the requirements of the publishing journal, Chapter 2's format is slightly different than that of Chapters 3 and 4 in that it combines the Results and Discussion into one section. Any references to the work herein should be made to the published articles rather than to this document. The supplementary information for the three chapters is compiled at the end into Appendices 1 through 3.

**CHAPTER 2 REDUCED WATER COLLECTION TIME IMPROVES LEARNING ACHIEVEMENT  
AMONG PRIMARY SCHOOL CHILDREN IN INDIA**

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## 2.1 Abstract

In low- and middle-income countries, the provisioning of safe drinking water is a challenge that will likely worsen with climate change. Securing water will require more work and time, burdening women and children the most. Currently, the consequences of this time burden to children's development remain understudied. To address this gap, we examine the tradeoff between children's household water collection responsibilities and learning achievement. Using nationally representative data from India, we measure the effect of daily fetching time on primary school children's learning achievement in a two-stage regression model, with rainfall as the instrument. Our analyses indicate that higher fetching times predict lower mathematics (-1.23 standard deviations, 95CI[-2.32, -0.14]), reading (-1.13 standard deviations, 95CI[-2.07, -0.19]), and writing (-1.21 standard deviations, 95CI[-1.89, -0.51]) test scores. These effects are heterogeneous across sex and infrastructure type. For example, we find girls' mathematical and reading skills profit more from reductions in fetching time than boys' (score less affected for boys by  $\beta$  amount: mathematics:  $\beta = 0.26$  points, 95CI[0.095, 0.42]; reading:  $\beta = 0.27$  points, 95CI[0.054, 0.49]). Children using hand pumps, open wells, or tube wells are hurt more academically in mathematics and writing by increases in fetching time than children with mostly off-premises piped access (e.g., writing scores more affected by  $\beta$  amount: hand pump:  $\beta = -0.18$ , 95CI[-0.29, -0.081]; open well:  $\beta = -0.18$ , 95CI[-0.33, -0.040]; tube well:  $\beta = -0.14$ , 95CI[-0.29, -0.00072]). Given these results, we recommend off-premises piped infrastructure in the absence of piped-to-premises water in water-insecure contexts and offer guidance for targeting infrastructure investments in India.

## 2.2 Keywords

Education; instrumental variable analysis; piped water; water security

### 2.3 Introduction

Water is foundational for health and development. Currently, in low- and middle-income settings, over 780 million people lack access to safe drinking water.<sup>13</sup> As water insecurity worsens due to climate change,<sup>14</sup> securing water will require more work and time. While the health effects of poor access to water on childhood illness and mortality<sup>15–17</sup> are well-documented, the broader social implications of the time burden of collection are comparatively understudied.<sup>18</sup> Given that women and children, particularly young girls, are often responsible for water collection,<sup>19</sup> this time burden may be costly for children's development.

The time burden of water fetching can be understood in terms of tradeoffs. This burden is often referred to as time poverty and is a result of “competing claims on individuals’ time that reduce their ability to make unconstrained choices on how they allocate their time.”<sup>20(p16)</sup> While no choice is completely unconstrained,<sup>21</sup> this definition is helpful as it highlights the finite nature of time. In the short-term, with each day limited to twenty-four hours, individuals must decide between daily activities. The tradeoff for many children is between school, market work, and household chores such as water collection. Their levels of engagement across these categories are determined by other household members’ tradeoffs,<sup>20</sup> both of which are products of sociocultural conditions surrounding the division of labor and importance of education, among other norms.<sup>22</sup> Depending on these norms and households’ resources, displacing children’s education may be necessary for families to meet basic needs. In households facing severe time constraints, children may drop out of school<sup>20,23</sup>; in households that are less time-poor, children may not regularly attend school or may be expected to work rather than study outside of school hours.<sup>24</sup> Improving households’ access to water infrastructure in either situation may help promote children’s education by reducing the time burden of domestic labor and lessening the necessity of tradeoffs with schooling.<sup>25</sup>

Children’s involvement in water collection, as with all child labor, can prejudice their participation in school.<sup>24,26–28</sup> Nankhuni and Findeis (2004) illustrate this tradeoff clearly. They found that among urban and rural households in Malawi the more hours children (aged six to fourteen) dedicated to fetching water, the less likely they were to attend school, with a lower likelihood for those with piped water access.<sup>29</sup> Similarly, Haile and Haile (2012) showed that among rural Ethiopian children (aged

seven to fifteen) girls were more likely to fetch water than boys, and increasing the distance to a water source – a proxy for collection time – reduced the likelihood of attending school.<sup>30</sup> It is worth noting that these two studies represent the smaller body of research that focuses on children's school participation and their own water collection as opposed to other household members' water collection responsibilities (e.g., <sup>25,31,32</sup>).

Children's water collection responsibilities may also limit academic performance, though there is comparatively less evidence to support this link. The general consensus is that child labor in and outside of the household can adversely affect learning outcomes, albeit the latter is considered more harmful to children's development.<sup>23,26,33–35</sup> Illustratively, a study in Ghana showed that work outside of the household was statistically significantly associated with learning achievement in reading and mathematics among children aged nine to eighteen (e.g., associated with a ten-percent reduction in an elementary mathematics test score); the significance of the effect of work at home was unclear.<sup>36</sup> In a unique study focusing on children's water collection responsibilities and academic abilities among Tanzanian households, Akabayashi and Psacharopoulos (1999) estimated the effect of distance to water source on reading and mathematical skills. They found evidence of a relationship between distance to water source and number of hours worked and discovered that children (aged seven to fourteen) worked more if the water sources were farther away, which in turn was negatively related to the development of girls' reading skills and boys' mathematical skills.<sup>24</sup>

To our knowledge, there are no other studies analyzing the effect of children's water collection responsibilities on learning achievement, and Akabayashi and Psacharopoulos' (1999) study has several limitations. First, it likely underestimated the relationship between time and learning achievement given distance to source is only a proxy for the total time burden. Second, the reading and mathematical ability measures were vaguely defined and based on parental judgement rather than test scores.<sup>36</sup> Third, the analysis examined the correlation rather than plausibly causal relationship between water access and learning. A more complete and conclusive assessment of the total burden to children's learning achievement remains to be done.

Our paper addresses this gap by estimating the effect of decreasing the time burden of primary school children's water collection on their learning achievement using nationally representative data from India. Our study complements the accumulating literature examining the relationship between water and sanitation and children's cognition<sup>37-41</sup> by using rigorous methods that support causal inference<sup>42-45</sup> and by exploring heterogeneity in the effect of water fetching time on learning achievement across sex, community (caste or religion), economic status, and water infrastructure type. We discuss our results and their policy relevance in light of climate-related water security issues and government water priorities in India.<sup>46</sup>

## **2.4 Methods**

### *2.4.1 Data*

Our primary data source is the nationally representative India Human Development Survey (IHDS). This multi-topic panel survey was organized by the University of Maryland and the National Council of Applied Economic Research, New Delhi and administered in 2004-2005 and 2011-2012. The survey instruments were translated into thirteen different Indian languages. For each round, two one-hour interviews were administered by local interviewers and completed for approximately 42,000 households in 384 districts; most of the same households were surveyed in both rounds. Children in these households aged eight through eleven completed short mathematics, reading, and writing tests. Given the seven- to eight-year gap between survey rounds, these test scores are not panel data but instead represent the national learning achievement for students during those years. We also used IHDS measures of social and economic conditions to control for household characteristics such as education, income, and caste or religion (hereafter, caste/religion).<sup>47,48</sup>

In addition, we employed the highest-resolution available monthly rainfall data (in centimeters) at the district level for the years 1989 through 2014 from the India Meteorological Department.<sup>49</sup> At the time of the study, data on freshwater availability in India were limited at the appropriate level of granularity and over the 2004 through 2012 span of interest.

#### *2.4.2 Outcomes*

Our three primary outcomes of interest are the mathematics, reading, and writing test scores<sup>50</sup> collected by the IHDS for all children aged eight through eleven. The tests were modeled closely after the Annual Status of Education Report (ASER) survey cognitive tests.<sup>41</sup> The mathematics test was scored from zero to three, with the levels representing the inability to do mathematics (0) and the abilities to recognize a number (1), to subtract (2), and to divide (3). The reading test was scored from zero to four, with the levels representing the inability to read (0) and the abilities to read a letter (1), to read a word (2), to read a paragraph (3), and to read a story (4). The writing test was scored from zero to one, with the levels representing the inability to write (0) and the ability to write with two or fewer mistakes (1). Originally, the IHDS scored the writing test from zero to two in the 2011-2012 survey, with an extra level for writing with no mistakes (1). Prior to our analysis, we recoded the variable as binary to match the 2004-2005 survey in which the writing with no mistakes level was accounted for in the writing with two or fewer mistakes level. While these three tests only take integer values as scores, it is reasonable to assume that the observable test performances are underlain by unobservable, normal latent abilities.<sup>51</sup>

#### *2.4.3 Exposures*

Our primary exposures of interest are child fetching time and freshwater availability. Children's fetching times were reported by their mothers as the total time daily spent collecting water by boys and/or girls aged eight through eleven in the season during which the survey was completed. This time included traveling, collecting, and waiting in line at sources such as open wells, hand pumps, or tube wells. Freshwater availability is measured as the district-level two-year mean rainfall in centimeters (years 2004-2005 inclusive for households in the first round, and years 2010-2011 inclusive for households in the second round). We constructed a two-year annual mean to capture the previous year's precipitation, which is an important determinant of the subsequent year's freshwater availability.<sup>52</sup>

## 2.5 Empirical framework

### 2.5.1 Covariates

At the individual level, we adjusted for the age (in years) and sex (dummy variable for male or female) of the test-taking child. At the household level, we included the usual drinking water source (categorical variable) and its location (dummy variable for on- or off-premises) (Appendix 1 Table A.1 for relevant survey questions). We also constructed the leave-out cluster mean of the location variable (mean for household  $h$  over all households in a village other than  $h$ ) to represent village-level access to water, which may influence household-level availability.<sup>53,54</sup>

We also adjusted for household monthly consumption per capita (natural logarithm of monthly consumption per capita in rupees; sum of monthly expenditures incurred by the household divided by the number of persons living in the household); highest level of adult education (in years); residence location (dummy variable for urban or rural); and community (caste/religion; categorical variable). While there is no universally acknowledged caste hierarchy,<sup>55</sup> based on previous literature we defined the Scheduled Castes/Dalits, Scheduled Tribes/Adivasis, and Muslims as the most underprivileged castes and religious groups, and Forward Castes and Brahmins as being among the most privileged. We assigned Other Backward Castes (the official term for disadvantaged castes other than Scheduled Castes in India) a status in between.<sup>56</sup>

### 2.5.2 Base specification (naïve model)

The base specification, or naïve model, for each of the three tests for child  $i$  at time  $t$  is of the form:

$$(1) Y_{i,t} = \alpha + \beta T_{i,t} + \gamma X_{i,t} + \varepsilon_{i,t},$$

where  $Y_{i,t}$  is the test score of interest (mathematics, reading, or writing);  $T_{i,t}$  is the child's total daily fetching time in minutes; and  $X_{i,t}$  is a vector of individual- and household-level covariates, time (month and year of survey), and district fixed effects. We adjusted for seasonality with month dummy variables and controlled for national-level trends in the outcomes with a year dummy. With district fixed effects we accounted for all time-invariant unobserved factors operating at the district level and forced identification of within-district coefficients. The naïve model used ordinary least-squares estimation and serves as a point of reference for the instrumental variable model.<sup>26</sup>

### 2.5.3 Instrumental variable model

Estimates from the naïve model are likely to be biased by omitted variables that are associated with test scores and fetching times.<sup>42</sup> The conventional approach for dealing with confounding in social experiments is to randomly assign the exposure of interest to a treatment group. Random assignment ensures that omitted variables are not associated with the exposure and outcome. Our freshwater availability variable (precipitation is a quasi-random process) solves the omitted variables problem by using variation in fetching times that is not associated with omitted variables. In other words, to make plausibly causal inferences about the relationship between learning achievement and water fetching time, we employed the instrumental variable two-stage least squares estimation method<sup>16</sup> to parse out the relationship that is independent of their endogeneity to other variables,<sup>57,58(pp512-530)</sup> particularly to household and institutional characteristics. The instrumental variable method ensures that parameter estimates are consistent, implying that they converge to the population parameters in asymptotically large samples.

### 2.5.4 Instrument validity

We verified that rainfall satisfies the three assumptions for a valid instrument and claim that it is relevant, exogenous, and excluded.<sup>59</sup> Specifically, we verified that (1) there is a true association between rainfall and water fetching (relevance); (2) rainfall is not associated with confounders of the fetching time-test score relationship (exogeneity); and (3) the effect of the rainfall on test scores is exclusively mediated by fetching time (exclusion). Details of assumption validity diagnostic tests and supporting literature are available in Appendix 1 Table A.9 and the Appendix 1 Supplementary methods section. While we are interested in the direct effect of children's water collection time on their own schooling, we recognize that there may be additional mechanisms tied to other household members' fetching responsibilities that affect children's learning achievement. We consider one of these potential mechanisms in section 2.6.5.

### 2.5.5 Econometric specification

The econometric specification is of the form:

$$(2) T_{i,t} = a + bZ_{i,t} + cX_{i,t} + v_{i,t},$$

$$(3) Y_{i,t} = \alpha + \beta\widehat{T}_{i,t} + \gamma X_{i,t} + \varepsilon_{i,t},$$

where  $Z_{i,t}$  is the instrumental variable of freshwater availability, and  $\widehat{T}_{i,t}$  is the predicted total daily fetching time of children in minutes.

The first-stage model (equation 2) estimates children's daily fetching time using  $Z_{i,t}$  (rainfall) and  $X_{i,t}$  as predictors; this step purges fetching time of its correlation with the test score outcomes. The second stage (equation 3) estimates the effect on test score ( $Y_{i,t}$ ) with the predicted fetching times from the first stage ( $\widehat{T}_{i,t}$ ). Two stages of linear regressions estimated by ordinary least squares is the standard approach for instrumental variable analyses.<sup>60</sup> We present these estimates as our main results (outputted by the *ivreg* function in the AER package (version 1.2.9)<sup>61</sup>) with cluster-robust standard errors at the village level (computed using the *cluster.robust.se* function in the *ivpack* package (version 1.2)<sup>62</sup>), as the IHDS randomly selects households from each sampled village.<sup>47,48</sup> When the two stages were manually and separately estimated (using R's *lm* function), we computed cluster bootstrapped standard errors with the *lm.cluster* function in the *miceadds* package (version 3.9.14).<sup>63</sup>

All data cleaning and analysis was done in RStudio (version 1.2.1335).<sup>64</sup> All figures in the main text were made with the *ggplot2* package (version 3.4.2)<sup>65</sup> unless otherwise noted.

## 2.6. Results and discussion

### 2.6.1 Summary statistics

Table 2.1 provides an overview of the households surveyed by the IHDS. All children who were tested were included in the calculation of the descriptive statistics. The variables shown were used as controls in our analyses. Given that most of the same households were surveyed twice, the descriptive statistics are similar across rounds, except for household expenditure per capita which increased from an average 715 to 1599 rupees. In addition to economic growth, the increase in household expenditure per capita can be largely attributed to our choice of using nominal values as opposed to real values adjusted for inflation. We accounted for inflation with a year fixed effect. Nearly one-half of the sample is girls. The mean age is young (approximately 9.5 years), and the mean education is low (approximately 7 years). Approximately 70 percent of households were located in rural areas at the times of the surveys, and approximately 35 to 40 percent of households

belonged to Dalit or Muslim communities. The water delivery mechanisms across India were found to be heterogeneous, with various non-networked water supplies collectively accounting for 60 to 70 percent of households' usual supplies; the rest of the households relied on piped water (approximately 38 percent) (Appendix 1 Table A.2 for the distribution across all IHDS water infrastructure types). Hand pumps were the most common type of infrastructure among children who fetched water, except for urban children who typically collected from piped taps (Appendix 1 Table A.3).

**Table 2.1 Demographic and socioeconomic covariates used in regressions**

	2004-2005 (n = 10,981)		2011-2012 (n = 10,450)	
<i>Categorical covariates</i>	%		%	
Female	47.0		47.7	
Urban residence	29.4		28.7	
<i>Community</i>				
Other Backward Class	35.4		35.0	
Dalits	22.2		23.1	
Forward caste	14.4		12.1	
Muslim	13.8		15.6	
Brahmin + SJC	7.9		6.0	
Adivasis	6.3		8.1	
<i>Water infrastructure usual</i>				
Piped	38.1		37.3	
Hand pump	36.8		37.8	
Open well	11.3		9.0	
Tube well	10.2		10.8	
<i>Location of water infrastructure</i>				
On-premises, dummy	50.8		48.6	
<i>Interval covariates</i>	<b>Mean</b>	<b>SD</b>	<b>Mean</b>	<b>SD</b>
Age (8-11, years)	9.5	1.1	9.5	1.1
Household expenditure per capita (rupees)	714.7	589.5	1599.0	1324.5
Highest adult (21+) education in household (years)	6.8	4.9	7.4	4.9

Notes: SD is the abbreviation for standard deviation. We grouped the most privileged caste (Brahmins) with the most privileged religious groups (Sikhs, Jains, and Christians). The four most common water infrastructure types are listed. Hand pumps and open wells are manually operated, while tube wells and piped water are pressurized sources. n = 21,431 children tested

Table 2.1 displays the test scores for children aged eight through eleven. Comparing the second round to the first, students' average reading and mathematical skills were slightly lower, and their writing skills were higher, though the standard deviations were similar across both rounds. For the mathematics test the more advanced skills such as division declined the most (approximately 23.0 to

17.6 percent of students achieving the highest score of three), while the ability to identify a number improved across rounds (32.2 to 36.5 percent). More students were non-readers in the second round than in the first round (11.4 versus 9.5 percent). The average test scores of students from wealthier households or more privileged castes/religions were higher; however, the high heterogeneity in scores within each income and caste/religion stratum makes the differences between strata less pronounced and meaningful. The differences in average scores across sex are negligible (Appendix 1 Figures A.1.1-A.1.3). Most children self-reported that they were attending school at the times of the surveys (Appendix 1 Table A.4).

**Table 2.2 Characterization of average test scores among Indian children (aged 8-11)**

	<b>2004-2005</b> <b>(n = 10,981)</b>		<b>2011-2012</b> <b>(n = 10,450)</b>	
<i>Distribution of test scores</i>	<b>%</b>		<b>%</b>	
<i>Mathematics</i>				
0 (Cannot recognize number)	17.6		16.4	
1 (Number)	32.2		36.5	
2 (Subtraction)	27.2		29.6	
3 (Division)	23.0		17.6	
<i>Reading</i>				
0 (Cannot read)	9.5		11.4	
1 (Letter)	13.3		14.2	
2 (Word)	20.4		20.2	
3 (Paragraph)	21.6		18.6	
4 (Story)	35.3		35.6	
<i>Writing</i>				
0 (Cannot write)	31.5		25.8	
1 (Writes with two or fewer mistakes)	68.5		74.2	
<i>Average scores</i>	<b>Mean</b>	<b>SD</b>	<b>Mean</b>	<b>SD</b>
Mathematics	1.6	1.0	1.5	0.96
Reading	2.6	1.3	2.5	1.4
Writing	0.68	0.46	0.74	0.44

Notes: SD is the abbreviation for standard deviation. n = 21,431 children tested

Table 2.3 shows children's average daily fetching times across the different categories of sex, caste/religion, residence location, income quartile, and primary water source infrastructure. In general, fetching times were lower in 2011-2012 than in 2004-2005; however, across the two rounds the percentage of children fetching water increased for all subgroups. Across all years, on average girls had higher fetching times than boys (13-minute and 6-minute differences in the means across sex for 2004-2005 and 2011-2012, respectively). Children from most socially advantaged groups

(Brahmins, Sikhs, Jains, and Christians) had the lowest average fetching times (approximately 31 and 28 minutes for 2004-2005 and 2011-2012, respectively). The average fetching time was higher for children in rural households (approximately 57 and 35 minutes in 2004-2005 and 2011-2012, respectively) than for children in urban households (approximately 43 and 32 minutes in 2004-2005 and 2011-2012, respectively). Comparing across income quartiles, the proportion of children fetching shows evidence of a trend: the highest income quartile had the fewest children fetching (e.g., in 2004-2005, approximately 9 percent versus 25 percent for the lowest quartile). Similarly, the proportion of children collecting water differs across infrastructure types, with households using piped water having the smallest proportion of children fetching (e.g., in 2011-2012, approximately 16 percent of children from households with piped water fetched versus 40 percent of children from households using hand pumps). Among the 10 to 16 percent of children who fetched from piped sources, over 90 percent had access to off-premises taps in both rounds (Appendix 1 Table A.5). Children with on-premises access may have still fetched water if, for example, the tap was located on a distant part of the compound and/or was shared by several households and required waiting. Given that the majority of children did not fetch water and had on-premises piped water (Appendix 1 Table A.5), references to piped water throughout the paper mainly refer to on-premises piped. We label it as “mostly on-premises” or “MONP” for clarity. However, given the prevalence of off-premises water among children who fetch from piped water sources, our discussions on the effects of fetching time on learning achievement refer to “mostly off-premises” piped water, which is denoted as “MOFP.” Regardless of the location of the piped source from which children fetch, our rainfall instrument remains relevant given that in India piped water is often supplied by rainfall-fed reservoirs<sup>66</sup> or rainfall-recharged groundwater.<sup>67</sup>

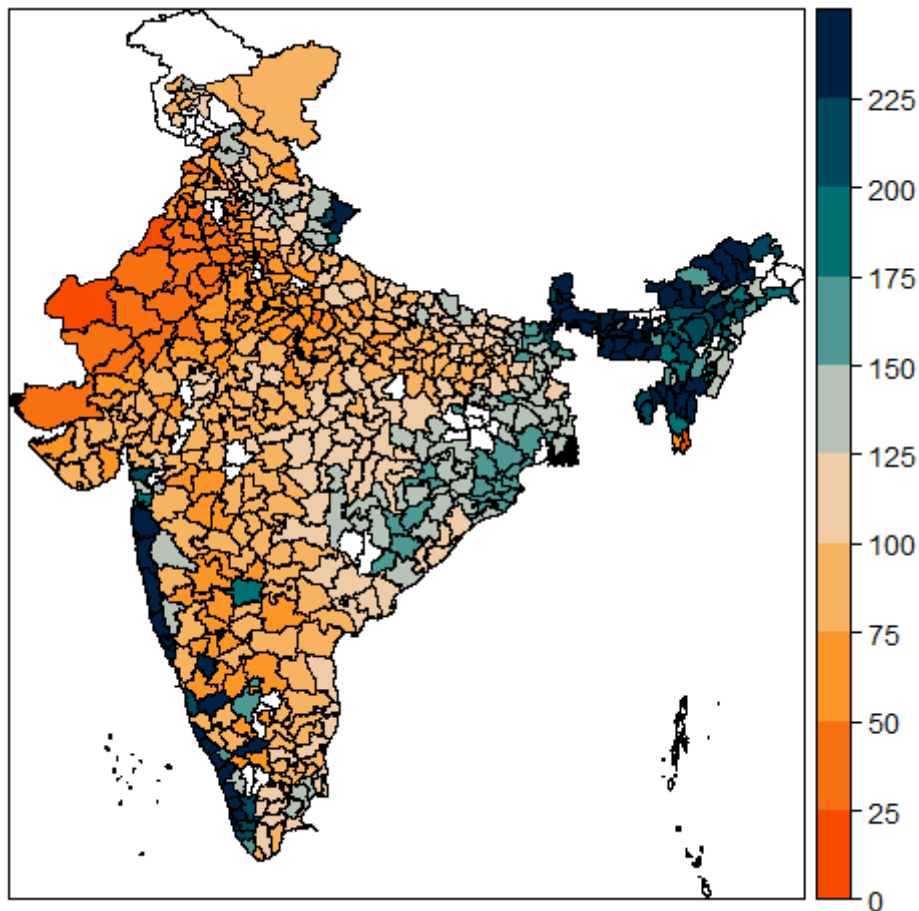
**Table 2.3 Daily fetching times in minutes among children who fetch (aged 8-11), by category**

Category	2004-2005 (n = 10,981)			2011-2012 (n = 10,450)		
	Children who fetch	Mean among children who fetch	SD among children who fetch	Children who fetch	Mean among children who fetch	SD among children who fetch
	%	Min	Min	%	Min	Min
<i>Sex</i>						
Girl	22.4	59.8	61.5	32.2	37.6	36.1
Boy	12.3	46.0	48.9	23.6	31.5	32.0
<i>Community</i>						
Other Backward Class	17.9	54.5	53.7	29.0	34.0	36.8
Dalit	20.5	56.5	61.6	30.1	35.1	31.9
Forward Caste	12.4	50.2	55.9	19.5	39.9	41.6
Muslim	15.0	60.5	69.1	21.2	34.4	34.5
Brahmin + SJC	8.7	30.9	21.7	17.3	28.3	28.9
Adivasis	25.3	56.1	52.8	48.3	34.1	28.1
<i>Residence</i>						
Rural	19.5	57.2	58.4	33.4	35.2	35.5
Urban	11.0	43.2	51.8	13.5	32.7	26.5
<i>Income quartile</i>						
0-25	25.2	56.0	55.3	37.6	32.5	31.5
25-50	19.2	53.1	57.7	32.3	33.4	30.3
50-75	14.4	55.8	60.7	24.0	39.2	36.7
75-100	9.3	51.2	57.5	17.0	37.1	43.1
<i>Infrastructure</i>						
Piped	10.4	58.9	66.9	15.7	38.7	35.6
Hand pump	22.6	48.9	50.7	39.8	31.8	31.5
Open well	22.6	65.3	60.7	33.2	35.1	28.2
Tube well	16.7	57.5	60.2	23.9	42.5	47.4

Notes: Fetching time (minutes) represents the summation of the mother's estimations of her children's total time (including waiting time, for all trips) spent collecting water each day during the survey season. SD is the abbreviation for standard deviation. We grouped the most privileged caste (Brahmins) with the most privileged religious groups (Sikhs, Jains, and Christians). The income quartiles were constructed such that 0-25 represents the lowest 25<sup>th</sup> percentile. The four most common water infrastructure types are listed. As shown in the last four rows of the table, based on the Joint Monitoring Programme (JMP) drinking water ladder the majority of children are from households where they fetch water from limited sources (i.e., drinking water from an improved source such as piped water, hand pumps, or tube wells for which collection time exceeds thirty minutes roundtrip, including queuing).<sup>68</sup> However, given children's fetching times are reported as daily total minutes, the comparison to the JMP ladder roundtrip definition is imprecise. Example interpretation for the "Piped" row near the bottom of the table: In 2004-2005, approximately 10.4 percent of children from households with piped water are children who fetched water, with a mean fetching time of 58.9 min (SD = 66.9 min). n = 21,431 children tested

Appendix 1 Table A.6 provides more information on fetching times by state. With a few exceptions, across India's states the percentage of children who fetched water is less than 30 percent. However,

for all states, there is high variation within states and between years, reflective of the high temporal and spatial variability in freshwater availability (Figure 2.1).

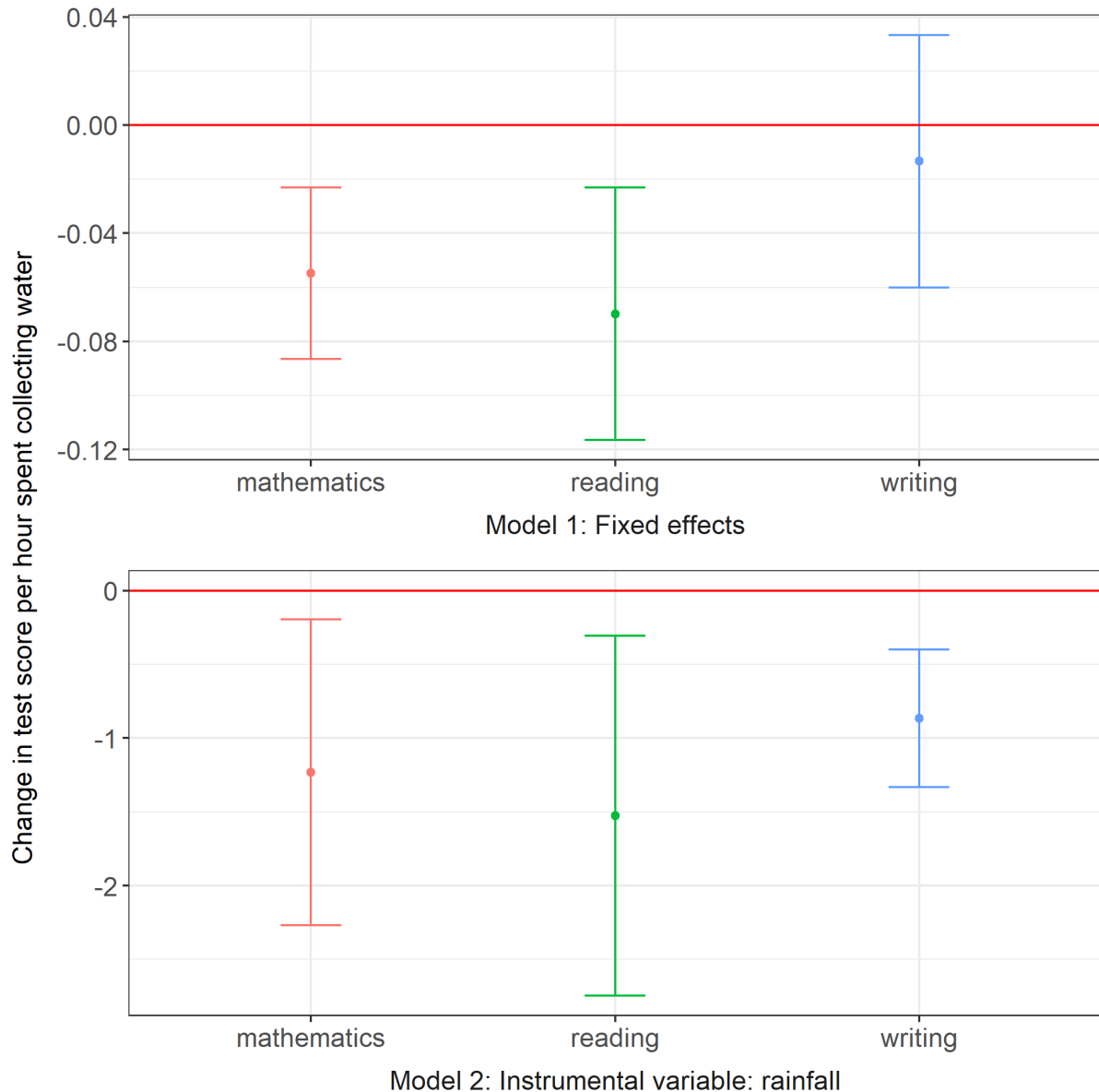


**Figure 2.1 2000-2012 average annual rainfall (centimeters): Data for instrument.** District-level rainfall measurements from the India Meteorological Department<sup>49</sup> are objectively measured and exhibit heterogeneity across India. The scale represents the average annual precipitation in centimeters. Average annual rainfall is not our instrumental variable but rather the precursor of the two-year average rainfall instrument. White areas indicate where data are unavailable. The map was created using freely available GADM data<sup>69</sup> and R packages `rgdal` (version 1.5.12),<sup>70</sup> `sp` (version 1.4.2),<sup>71,72</sup> and `colorRamps` (version 2.3).<sup>73</sup>

### 2.6.2 The relationship between fetching time and learning achievement

To ground the findings from our preferred, more complex instrumental variable model, we compare them with the evidence from the simpler, naïve model (Figure 2.2). We present all results in terms of one-hour changes in fetching time as opposed to one-minute changes given the orders of magnitude in Table 2.3. Broadly, the naïve model results in the top panel suggest that, controlling for all else in the model, there is statistical evidence that an increase children's water collection time is associated with a decrease in their mathematical and reading skills. The effect on writing is negative but

insignificant (Appendix 1 Table A.7). These model estimates are downward-biased, or biased toward the null, which may be attributed to omitted variable bias in the OLS estimator.<sup>26</sup>



**Figure 2.2 Effect of water fetching time on test scores of children aged 8-11.** Each test has its own grading scheme, and no meaning can be attached to comparisons of scores between tests. Standard errors represented by the whiskers are cluster-robust at the village level. Model 1: Mathematics: -0.055, 95CI[-0.087, -0.023]; reading: -0.070, 95CI[-0.12, -0.023]; writing: -0.013, 95CI[-0.060, 0.033]; Model 2: Mathematics: -1.23, 95CI[-2.32, -0.14]; reading: -1.53, 95CI[-2.80, -0.26]; writing: -0.87, 95CI[-1.36, -0.37]. n = 21,431 children tested

Our instrumental variable model (Figure 2.2, bottom panel) exhibits a similar story in terms of the relative magnitudes of the associations (Appendix 1 Tables A.8 and A.9). All else equal, for a one-hour increase in fetching time children’s average mathematics test score would decrease by approximately -1.23 points on a three-point scale (equivalent to approximately 1.3 standard

deviations). For every additional hour of fetching time, the average reading score would decrease in a statistically significant way by approximately -1.53 points on a four-point scale (equivalent to approximately 1.1 standard deviations). The average writing score would also decline significantly by approximately -0.87 points for a one-hour increase in water fetching time on a one-point scale (equivalent to approximately 1.9 standard deviations).

### *2.6.3 Heterogeneity across subgroups and water source*

To strengthen the policy-relevance of our research, we identified the conditional average effects of changes in daily fetching time on learning achievement among different subpopulations of children. We measured effect heterogeneity across income, community (caste/religion), and sex by building regression models with interaction terms between these categories and our fetching time variable. The models were run using R's *lm* function, and cluster robust standard errors were manually computed.<sup>74</sup>

Table 2.4 presents the heterogeneity analysis results. At the 95 percent confidence level, the only significant results are across sex: boys' mathematics and readings scores are less affected than girls' by approximately 0.26 and 0.27 points, respectively, for one-hour reductions in fetching time. The lack of statistical significance across community and income quartile does not imply that there are no real, substantive differences in the effects of changes in water collection time on test scores across those categories; rather, in our dataset and with our methods, we are unable to confidently say that these differences are statistically different from zero. We offer two potential explanations for these findings. First, unlike for caste, different sexes can more readily be found living in the same households or communities. Thus, in our heterogeneity analyses we were more easily able to isolate the effect across sex than across caste. Second, any household-level gender norms such as son preference vary widely by state,<sup>75</sup> while caste divisions are pervasive<sup>56</sup> and may have been more difficult to eliminate statistically.

**Table 2.4 Interaction effects of predicted fetching times across different social statuses on test scores**

Category	Mathematics		Reading		Writing	
	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
<i>Sex</i>						
Main effect	-1.94	[-3.04, -0.84]	-1.67	[-2.95, -0.40]	-0.89	[-1.38, -0.39]
<i>Interaction effect</i>						
<i>Girl</i>						
<i>Referent</i>						
Boy	0.26	[0.095, 0.42]	0.27	[0.054, 0.49]	0.036	[-0.030, 0.11]
<i>Community</i>						
Main effect	-1.31	[-2.41, -0.20]	-1.62	[-2.90, -0.35]	-0.86	[-1.07, -0.64]
<i>Interaction effect</i>						
<i>OBC</i>						
OBC	0.043	[-0.19, 0.28]	0.18	[-0.14, 0.50]	-0.031	[-0.14, 0.077]
<i>Dalit</i>						
<i>Referent</i>						
FC	0.11	[-0.19, 0.40]	0.34	[-0.031, 0.70]	0.080	[-0.057, 0.22]
Muslim	0.17	[-0.13, 0.48]	-0.12	[-0.57, 0.34]	-0.037	[-0.20, 0.12]
Brahmin + SJC	-0.090	[-0.44, 0.26]	0.24	[-0.24, 0.71]	0.052	[-0.11, 0.21]
Adivasis	0.14	[-0.26, 0.53]	-0.026	[-0.63, 0.58]	-0.14	[-0.35, 0.066]
<i>Income quartile</i>						
Main effect	-1.70	[-2.82, -0.58]	-1.65	[-2.97, -0.34]	-0.98	[-1.47, -0.48]
<i>Interaction effect</i>						
<i>0-25</i>						
<i>Referent</i>						
25-50	0.053	[-0.18, 0.28]	0.16	[-0.19, 0.51]	0.10	[-0.011, 0.22]
50-75	0.0026	[-0.25, 0.25]	-0.030	[-0.39, 0.33]	0.088	[-0.035, 0.21]
75-100	-0.072	[-0.33, 0.19]	0.13	[-0.23, 0.49]	0.13	[0.0049, 0.25]

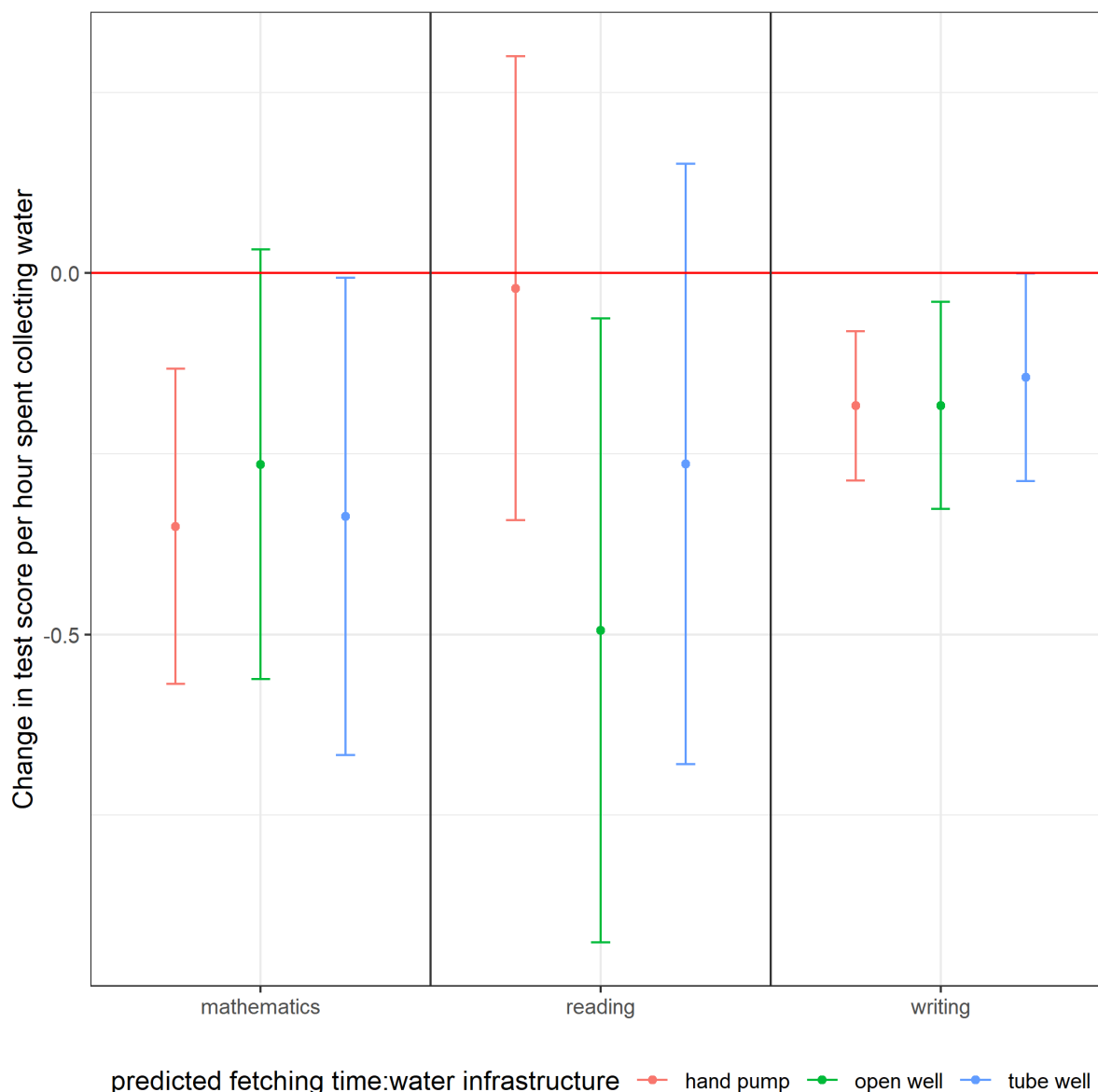
Notes: These estimates are the interaction terms of predicted fetching times and community, sex, or income from separate executions of the (manually coded, not *ivreg*) two-stage least squares model with rainfall as the instrument (Model 2 in Figure 2.2). The 95 percent confidence intervals (CIs) were constructed from cluster bootstrapped standard errors at the village level (1000 replications).

Reference groups are marked by the *referent* rows and include girls, Dalits, and the 0-25<sup>th</sup> percentile. We grouped the most privileged caste (Brahmins) with the most privileged religious groups (Sikhs, Jains, and Christians). FC and OBC are abbreviations for Forward Caste and Other Backward Caste. The mathematics, reading, and writing tests have their own grading schemes, and no meaning can be attached to comparisons of scores between tests. Positive estimates suggest that the category experiences a relatively smaller change in score for a one-hour increase in fetching time compared to the referent, while negative estimates suggest that the category experiences a relatively larger change in score compared to the referent. n = 21,431 children tested

Our results suggest that beyond the average benefit that better water access affords to all students, if Indian girls are given more time, they can accomplish more academically than boys. The disproportionate effect to girls may be a consequence of fetching time being more relevant to girls than boys; existing evidence suggests and our data support (Table 2.3) the claim that among children who fetch, there are more girls than boys.<sup>76,77</sup> Furthermore, this gendered effect on girls' education is

not unique to water infrastructure. Previous research has found that Indian girls can profit educationally more than boys from investments in other basic infrastructure. For example, improving access to electricity in rural India has been shown to increase enrolment, study time, and attainment among all children (aged seven to fifteen), with girls benefiting more than boys.<sup>78</sup> Though biofuel collection among girls is less common than water collection,<sup>79</sup> the link between improved energy infrastructure and education can still be understood in terms of tradeoffs: just as with water, so better access to electricity can reduce the labor-intensity of girls' household responsibilities and enable them to spend more time attending school and/or studying.<sup>78</sup>

Our results provide insight into the type of water infrastructure that should be constructed to promote children's academic success. The mathematics and writing scores of children who collect water from hand pumps, open wells, or tube wells are more affected by increases in fetching time than those of children with access to MOFP piped water (Figure 2.3). Specifically, their mathematics scores are approximately 0.27 to 0.35 points more affected and their writing scores approximately 0.14 to 0.18 points more affected by water collection compared to the scores of children in households with MOFP piped water access. These results may be due to the fact that most children with piped access spend little to no time collecting water; in our dataset 85 to 90 percent of children with piped water did not fetch (see Appendix 1 Table A.5). This result may also be explained by differences in physical exertion required to operate each type of infrastructure. Unlike pressurized piped water, hand pumps and open wells are manually operated and therefore more labor-intensive. Repeated laborious tasks may exhaust or injure children, degrading the quality (e.g., inability to focus) and/or quantity (e.g., need more rest) of their study time. It is important to consider these potential costs and risks given that among those children who fetched water in our dataset, the majority used hand pumps.



**Figure 2.3 Interaction effects of predicted fetching times across different water infrastructure types on test scores.** Each test has its own grading scheme, and no meaning can be attached to comparisons of scores between tests. These predominantly negative interaction terms suggest that the three infrastructure types are associated with relatively larger changes in scores for a one-hour change in fetching time compared to the referent of MOFP water. Main effects: Mathematics: -1.05, 95CI[-2.13, 0.043]; reading: -1.22, 95CI[-2.49, 0.055]; writing: -0.74, 95CI[-1.22, -0.25]. n = 21,431 children tested

#### 2.6.4 Climate-related water insecurity

Across several regions of India in nearly two-thirds of the districts,<sup>46</sup> climate change is heightening water insecurity.<sup>80</sup> In recent decades, over the span of the IHDS surveys, the country has experienced climate extremes.<sup>80</sup> We found evidence of the consequences of climate-related water insecurity in our dataset. For all subgroups examined in our analyses, the percentage of children

fetching water increased across survey rounds (Table 2.3). Poor, rural, and Scheduled Tribes/Adivasis subpopulations experienced the largest increases. In addition, average mathematics and reading scores decreased slightly for most subgroups across rounds (Appendix 1 Figures A.1.1-A.1.3). Since these surveys, water insecurity in India has been linked to worse educational outcomes. In 2016, severe drought across ten states was associated with a 22-percent increase in the number of children dropping out of school to help with water collection.<sup>76,80</sup> Our results are becoming increasingly relevant for more of India's children.

In recent years the Indian government has focused on providing on-premises piped water to all rural households to meet the heightened water needs associated with increased toilet coverage facilitated by the Swachh Bharat Mission.<sup>81</sup> Since 2019, through the Jal Jeevan Mission the number of households with functioning piped tap connections increased from approximately 17 to 41 percent.<sup>82</sup> Remarkably, Bihar, one of the poorest states in India,<sup>83</sup> experienced an increase in coverage from 2 to 86 percent of households. This progress was likely aided by Bihar's relatively high freshwater availability,<sup>80,84</sup> which may indicate that other states in east and northeast India with similar resources could support reliable on-premises piped infrastructure. In contrast, coverage in the wealthy state of Tamil Nadu<sup>83</sup> improved from 17 to 34 percent; this slower progress may have been hindered by recent drought conditions<sup>85</sup> and ensuing freshwater deficits. In south as well as northwest India, with existing and increasing water insecurity concerns,<sup>80</sup> shared village-level off-premises supplies may be more sustainable than universal household connections. For off-premises water supplies, based on our findings we recommend the construction of piped taps as opposed to other types of infrastructure such as hand pumps or open wells. Off-premises piped networks have the added benefit of being infrastructure that helps to advance the Jal Jeevan Mission. Households may be able to gain access to on-premises piped water more readily in the future if the distribution systems already exist.

One potential targeting strategy for off-premises piped water construction is to prioritize low-income rural areas where girls are lagging behind educationally. In our dataset, among several of the lowest-income states<sup>83</sup> we found evidence of a co-occurrence of hand pump use and high gender gaps in learning achievement across all subjects, notably in Uttar Pradesh and Madhya Pradesh. Both states have less on-premises coverage than Tamil Nadu. While improvements in off-premises piped

supplies may be more pressing in Madhya Pradesh due to its current low freshwater availability,<sup>84</sup> further research on hydrological and climate modeling as well as measurements of household-based water insecurity<sup>14</sup> may aid targeting strategy decision-making. Sufficient planning will be needed to ensure that existing issues such as groundwater source depletion<sup>67,86</sup> and piped water supply intermittency<sup>76,87</sup> do not rapidly engender defunct piped systems with unpredictable water delivery that could counter-productively demand more time spent on collection.

#### *2.6.5 Extension: Mechanism through caregivers' fetching time*

This paper has assessed at length the immediate tradeoff that children themselves make between fetching water and their education. We now consider a different mechanism via caregivers' water collection responsibilities by which fetching time might affect children's education (i.e., same exclusion restriction criterion, different theoretical underpinnings). Children whose caregivers fetch water may be required to complete tasks instead of their schoolwork that these adults would have otherwise performed. Alternatively, children may lack supervision while studying at home if their caregivers need to allocate that time to water collection or other domestic responsibilities. We explored these types of tradeoffs, performing our main two-stage least squares model with men and women's fetching times instead of children's fetching times among the adults living in the same households as the children who were tested. The results suggest that one-hour reductions in women and men's fetching times are associated with improvements in children's mathematics (women: -0.37, 95CI[-0.66, -0.076]; men: -0.94, 95CI[-1.72, -0.16]), reading (women: -0.46, 95CI[-0.79, -0.12]; men: -1.17, 95CI[-2.06, -0.27]), and writing (women: -0.26, 95CI[-0.38, -0.14]; men: -0.66, 95CI[-1.02, -0.30]) abilities (Appendix 1 Table A.10). Comparing our caregiver and main model results shows that children's fetching responsibilities may have larger educational ramifications than their caregivers', which supports our main hypothesized mechanism through children's own fetching time. A recent study also examined the implications of mothers' water collection on their children's education and found that children (aged six to fourteen) whose mothers spent less time fetching water had higher predicted probabilities of being able to perform elementary arithmetic.<sup>38</sup> While our results are not directly comparable due to scaling differences, our conclusions are the same: the less time women spend fetching water, the better the academic performance of the children in their households.

### *2.6.6 Robustness to potential confounders or variables on the causal pathway*

Our paper rests on the assumption that freshwater availability is primarily associated with learning achievement through children's fetching time, a premise further supported by the preceding section. However, it is conceivable that there are variables which mediate this relationship, variables that may exist on the hypothesized causal pathway linking rainfall to fetching time, fetching time to effort, and effort to educational performance. One such variable is child labor.<sup>43</sup> We assumed that the effect of child labor on learning achievement is primarily mediated through time not spent in school or not studying outside of school.<sup>88</sup> We captured this effect with variables for days absent from school (over the past month, reported for children by an adult survey respondent) and days spent working on the farm (over the past year, reported for children by an adult survey respondent). A second potential confounder is child health. Rather than fetching time, freshwater availability may be associated with learning achievement through food security, a proximal determinant of children's nutritional status<sup>89,90</sup> and distal factor associated with cognitive abilities.<sup>91</sup> We captured this potential effect by adjusting for a household's diet diversity, computed as the sum of the unique food groups consumed by the household in the month prior to the survey.<sup>92</sup> We also controlled for child height (absolute, in centimeters), a well-researched proxy of child health.<sup>93</sup> We ran our main model with these additional covariates and found that the primary effects of fetching time on learning achievement held; the point estimates and confidence intervals remained similar to those of the main econometric specification in Figure 2.2. Furthermore, the effects of diet, days absent, and days farming were insignificant. The relationship between height and learning achievement was significant but relatively small compared to the relationship between fetching time and achievement (Appendix 1 Table A.11). These results support the exclusion restriction and allay concerns of confounding due to child labor or child health on our assumed pathways.

### *2.6.7 Robustness to test score measurement*

We treated test scores as interval scales in our main models under the assumption that the observable test performances were generated by unobservable, normal latent abilities captured by the scores.<sup>51</sup> However, we also acknowledge the long-standing concerns and complexities surrounding the treatment of ordinal scales as interval scales<sup>94</sup> and performed a robustness check to explore the implications of our interval-scale assumption. We estimated linear probability models for

which the dependent variables were dummy variables equal to one if the child achieved at least a certain level of mastery in mathematics, reading, or writing.<sup>50,95</sup> The results in Appendix 1 Table A.12 confirm our main findings that decreased fetching time is associated with improvements in mathematics, reading, and writing skills, though not associated with the highest mastery of these skills. For example, we found that the probability that children achieve at least the basic mathematical skill of number recognition or subtraction is associated with approximately 0.53- and 0.82-point decreases, respectively, for one-hour increases in predicted fetching times. While we did not perform our heterogeneity analyses using linear probability models, we recognize that comparisons across groups (e.g., sex, caste/religion, or income) may be sensitive to the choice of scale.<sup>94</sup> Despite the robustness of our main conclusions and the confidence this check lends, we recommend careful interpretation of the heterogeneity results (Table 2.4).

#### *2.6.8 Sensitivity to assumptions about the data-generating process*

For our main models, the first and second stages were linear regressions estimated using ordinary least squares, which is standard for two-stage least squares.<sup>60</sup> However, there are limitations to this approach. Using linear regression in the first stage not only allowed for predicted fetching times to be negative, but also may not have adequately handled the preponderance of zero fetching times in the sample; recall that fewer than 30 percent of children fetch across either survey, per Appendix 1 Table A.5. We addressed these limitations by re-estimating our main models using Heckit (sampleSelection package (version 1.2-12)<sup>96</sup>), Tobit (AER package (version 1.2-9)<sup>61</sup>), and Tweedie (statmod package (version 1.4-34)<sup>97</sup>) models as the first stages. We present detailed methods and findings in the Appendix (Appendix 1 Table A.13 and its legend), including a figure (Appendix 1 Figure A.2) comparing the predictive fits across all models. We generally found that the three different models yielded similar conclusions to our main results in terms of direction and significance of the relationship between children's fetching time and learning achievement across all subjects. The effect sizes across the three models were smaller than those from our main model (e.g., for the Tobit model, a one-hour reduction in fetching time was associated with a decrease of 0.080 standard deviations in the average mathematics test score), which is to be expected; models designed to account for zeros should have less variation to model relative to common-response-distribution models. While we

report the results from the standard linear two-stage least squares approach as our main findings, we consider the results from these alternate specification as lower-bound estimates.

### *2.6.9 Strengths and limitations*

This paper has several strengths. First, we evaluated the relationship between fetching time and learning achievement using an instrumental variable approach that supports causal inferences. Second, we employed a large nationally representative dataset, which lends confidence and broad relevance to our estimates. Third, we answered novel questions about learning achievement to contribute to the limited evidence base on the social implications of poor water access. However, this paper is not without limitations. First, while the data follow the same households over time, different children were measured in the first and second waves. Not being able to track the same children over time meant we could not assess the cumulative effects of water access conditions on learning achievement. Second, fetching times of all household members were reported by mothers rather than measured in situ by an IHDS enumerator, meaning there is the possibility of recall bias.<sup>98</sup> However, using instrumental variable analysis with a large sample size addressed this problem, given that rainfall as an objectively measured quantity is prone to less measurement error.<sup>42</sup> Third, while we used the standard two-stage least squares approach for our main models that is designed to produce first-stage residuals that are uncorrelated with fitted values and covariates<sup>60</sup> – an important feature for establishing plausible causality – we also encountered a lack of fit due to the disproportionately large frequency of fetching times equal to zero. We addressed the semi-continuous nature of the data by re-estimating our models using three alternate first stages; however, the lack of literature limited our ability to identify potential implications of these non-standard two-stage least squares modeling approaches. Notwithstanding, the findings were consistent with the conclusions from our main model, lending confidence to our claims.

**CHAPTER 3 ENVIRONMENTAL SANITATION AND UNDERNUTRITION: EVIDENCE FROM  
CHINA'S CHILDREN AND ADOLESCENTS, 1989-2011**

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### **3.1 Abstract**

Research on the benefits of basic water and sanitation interventions for child linear growth faltering has had mixed success, which may mean more environmentally transformative interventions are needed. To help guide these efforts, we used panel data from China (1989 to 2011) to estimate the relationships between changes in household- and community-level water, sanitation, and air pollution and changes in both child and adolescent height-for-age difference. Our regression analysis revealed community excreta levels as having an additional effect ( $\beta = -0.87$  cm) beyond households' own toilet facilities ( $\beta = -0.28$  cm), the latter involving risks of exposure to both human and animal feces. We did not detect a threshold effect for excreta density. In communities with high levels of excreta, having high piped water coverage and a household toilet offered little protection. Polluting cooking fuel was the most influential exposure at the household level ( $\beta = -0.45$  cm). According to our decomposition analysis, improvements in these four exposures collectively explain 15 percent of the decline in growth faltering in China during the study period.

### **3.2 Keywords**

Air pollution; externalities; height; panel data; sanitation; water

### 3.3 Introduction

Linear growth faltering – when children fail to reach their growth potential and have low height for their age – is an indicator of chronic undernutrition and a major global health concern.<sup>93,99,100</sup> In addition to threatening children's development, growth faltering can have long-term, even intergenerational, consequences on human capital and economic productivity.<sup>101–104</sup> Growth faltering from undernutrition is a complex and multifactorial process, associated with proximal factors such as genetics<sup>102</sup> and diet and with distal factors such as access to education and urbanization.<sup>93</sup> Water and sanitation, part of the focus of this paper, are interconnected with many of the underlying determinants<sup>105</sup> and are also thought to directly support child growth by disrupting exposure to fecal pathogens<sup>6,106</sup> and reducing the reoccurrence of infection, namely diarrhea, soil-transmitted helminthiasis, and environmental enteropathy,<sup>107</sup> the latter being the least understood<sup>108</sup> but potentially most prevalent pathway.<sup>93,109,110</sup>

Despite several plausible biological mechanisms, the evidence surrounding the role of water and sanitation in child undernutrition is considerably mixed.<sup>111</sup> Though many observational studies and randomized controlled trials have reported significant effects of improved water and/or sanitation on linear growth,<sup>112–117</sup> others have not observed such outcomes.<sup>118</sup> Most recently, trials in Bangladesh, Kenya, and Zimbabwe introduced household-level water treatment, basic latrines, and handwashing facilities and found no effect on child growth.<sup>6,119–121</sup> Of the several explanations offered for these null results,<sup>3,4,11</sup> many researchers view them as an indication of the need for more holistic, or transformative, interventions.<sup>6,7,122</sup> Conventional strategies for improving water and sanitation services often entail low-cost household interventions aimed at reducing single transmission pathways,<sup>2</sup> which can leave numerous fecal exposure risks<sup>4</sup> within the broad etiological framework of undernutrition unaddressed. While more dramatic reductions in fecal contamination is the goal, it is unclear what exactly transformative interventions will require<sup>2</sup> to achieve such reductions and meaningfully influence child growth.

As a starting point for operationalizing transformative water and sanitation, a group of leading scholars have proposed a return to the notion of environmental sanitation.<sup>2</sup> The concept was presented by the World Health Organization in 1949 as the management of all factors in the natural

and built environments that may harm human health, development, and survival.<sup>123</sup> Compared to the current perspective, environmental sanitation is a vastly expanded view on disease control. It goes beyond fecal pathogens in the household to account for external sources (e.g., neighboring households) of any pathogens or pollutants that might affect immune ontogeny; these sources are typically referred to as negative externalities. In practice, environmental sanitation would likely involve integrated, primarily community-level interventions delivered at scale that attend to a diversity of factors such as food safety, animal waste management, and air quality.<sup>2</sup>

Irrespective of the exact scope, evaluating the effects of transformative interventions rigorously will be challenging. It is impractical to rely solely on randomized controlled trials given the time and resources needed to implement large-scale interventions experimentally.<sup>11</sup> Especially in these early days, when there is still no consensus on what should constitute transformative programming,<sup>2</sup> continuing to draw on evidence from past large-scale interventions<sup>4,124,125</sup> is an efficient way forward. Historic lessons can then inform later trial designs. Though observational studies are inherently limited, panel-data as opposed to cross-sectional approaches can account for many of the concerns related to confounding.<sup>111,126</sup> It is standard practice, particularly among development institutions such as the World Bank, to assess scaled-up water and sanitation projects using quasi-experimental panel designs and quantify how changes in exposures lead to changes in child outcomes,<sup>127–131</sup> including undernutrition.<sup>111,132</sup>

In keeping with this approach and the broad conceptualization of environmental sanitation, this study uses a panel dataset from China over the period 1989 to 2011 to explore the associations between improvements in household and community water, sanitation, and air quality and reductions in undernutrition.<sup>133,134</sup> After China's economic reform, the 1980s marked a shift in the country's focus toward more rural public health projects involving centralized water<sup>135</sup> and modern energy infrastructure development (e.g., rural electrification); greater attention to rural toilet retrofitting began in the 1990s.<sup>136</sup> Piped water and sanitation coverage more than tripled among rural residents over the next thirty years,<sup>137,138</sup> and the fraction of electricity and clean fuels used for cooking increased by nearly 50 percent.<sup>139,140</sup>

Existing empirical evidence linking China's water, sanitation, and energy interventions to improvements in child height is limited. To our knowledge, most of the water and sanitation research has involved cross-sectional data and/or concentrated on household-level exposures, and the findings have been inconsistent.<sup>141–144</sup> Two panel-data articles that considered the community level mainly reported on the benefits of water infrastructure investments to child height.<sup>145,146</sup> We only know of two studies examining household solid fuel use and stunting in China, one of which was longitudinal, and both of which found statistically significantly negative associations.<sup>147,148</sup> Consequently, there remains an opportunity to glean additional insights from China's history of scaled-up public health projects to inform the future of transformative programming.

Toward this end, with all nine rounds of the China Health and Nutrition Survey (CHNS) we answer the question: How were improvements in water, sanitation, and air quality (collectively termed environmental sanitation) associated with reductions in height-for-age difference (HAD) among Chinese children and adolescents aged 0 through 228 months (n = 12,045 person-year observations)? We include data on adolescents given they are in an important phase in which future patterns of adult and intergenerational health are established,<sup>149</sup> and a phase in which growth has been shown to benefit from improved water and sanitation.<sup>150</sup> We estimate the separate effects of changes in water, sanitation, and air pollution and distinguish the community influence from that of the household, and we report the associations in negative terms to convey the magnitude of the burden borne in the absence of these changes. After adjusting for key confounders, we find that growth faltering was associated with both community and household sanitation conditions, in addition to being associated with household air quality and possibly community piped water coverage. We discuss these findings in light of the existing literature to show how our results can inform the design and analysis of transformative interventions.

### **3.4 Methods**

#### *3.4.1 Data*

We employed data from the China Health and Nutrition Survey (CHNS) published by the University of North Carolina at Chapel Hill and the Chinese Center for Disease Control and Prevention.<sup>151</sup> This survey was designed to monitor China's social and economic transformations after the country's

reformation in 1979 and focuses on the health, nutrition, and family planning policies and programs implemented by the national and local governments. The CHNS uses a multistage, cluster sample design to survey individuals from twelve provinces in which over half of the population resides. Across the nine rounds of surveys from 1989 to 2011, approximately 8500 households with a prospective cohort of 33,000 individuals from over 300 communities were interviewed (Appendix 2 Tables A16 and A17), with attrition supplemented with new individuals to maintain power.<sup>152</sup> Note that a community is identified by the CHNS as a unique set of numbers indicating the province, urban/rural status, city/county, and neighborhood/village. The strengths of the dataset include its panel structure, which supports (1) high internal validity (i.e., serial correlation can be addressed) and (2) causal inference (i.e., many of the same individuals were measured over time). The dataset's diverse set of variables also enables us to (3) reduce the risk of bias due to confounding. In addition to the freely available individual and household survey data, we received permission from the University of North Carolina at Chapel Hill to analyze the community data (see Appendix 2 for the University of Washington Institutional Review Board approval for STUDY00013590 with MOD00010383 and the data-use agreement). We also accessed the World Bank Open Data to construct a national wealth variable.<sup>153</sup> Please see the Appendix 2 Methods section for more data details.

### *3.4.2 Outcome*

Our main outcome variable is height-for-age difference (HAD), which represents the difference in the measured height and the age- and sex-specific growth standards median.<sup>154</sup> We focused on linear growth faltering and changes in absolute height deficits over time as opposed to stunting and changes in the proportion of children and adolescents stunted over time. Examining only the relative difference in stunting prevalence would have potentially underestimated the magnitude of change, as children and adolescents who are stunted are only the subset of those suffering from linear growth faltering with height-for-age z-scores (HAZ) greater than two standard deviations below the growth standards median.<sup>100,155</sup>

We computed HAD for children and adolescents with valid height measurements, defined as heights within  $\pm 6$  standard deviations of the World Health Organization (WHO) Growth Standards median.<sup>155</sup> We performed the calculations using age in months, height in centimeters, and the WHO Growth

Standards with the anthro package in R<sup>156</sup> for children under five (which converted recumbent length to standing height for children under three years of age) and the who2007 package<sup>157</sup> for children and adolescents ages five through nineteen. HAD as opposed to HAZ is recommended for studying population-level changes in height over time (i.e., across ages), given it does not rely on standard deviations derived from cross-sectional data.<sup>154</sup> We also provide the main analysis in terms of HAZ (Appendix 2 Table A3).

### *3.4.3 Household-level exposures*

We created five exposure variables in an effort to comprehensively represent household-level environmental sanitation. We extracted data on (1) drinking water infrastructure (in-house tap, in-yard tap, in-yard well, other); (2) drinking water quality (groundwater, open well, surface, ice/snow, treatment plant, other, unknown); (3) toilet type (no facility, flush inside, no-flush inside, public flush, public no-flush, cement or earth open pit, other); (4) excreta observed by the surveyor around the household (none, very little, some, much); and (5) type of fuel normally used for cooking (coal, electricity, kerosene, liquified petroleum gas, natural gas, wood, charcoal, other). Please see Appendix 2 Table A18 for the corresponding survey items. We removed individuals with the “unknown” category for water treatment and the “other” category for cooking fuel. We created five binary exposure variables in which the category of one represents the highest health risk: (1) no on-premises piped water (no in-house or in-yard tap);<sup>158</sup> (2) no treated water; (3) an open pit or no toilet,<sup>159</sup> hereafter abbreviated as open pit/no toilet; (4) excreta present near dwelling; and (5) polluting cooking fuel (coal, wood, charcoal, or kerosene).

### *3.4.4 Community-level exposures*

We calculated two sets of community-level variables indicating the prevalence of each household exposure in a given survey year. The first set of five variables represents the proportions of households exposed. These average rates range from 0 percent, which indicates no surveyed households were exposed in the community that year, to 100 percent, which indicates all households in the community were exposed that year. The second set of variables are within-community densities, each computed as the product of the community’s proportion exposed and population density (density expressed as the natural logarithm of (density plus 1)) in a given year.

### 3.4.5 Covariates

We included a number of individual-, household-, and community-level controls in our main analyses (Table 3.1). At the individual level, we included an age spline variable that models the non-linear relationship between age and height over time using a natural spline with knots at ages two, five, twelve, and sixteen based on Figure 3.1 Panel A. We included an interaction term between the age spline and sex to account for the sex-specific age-patterning of height. Sex was also included as a separate variable.<sup>133</sup> At the household level, we controlled for mother and father's years of education and heights<sup>102</sup>; the total number of children and adolescents in the household<sup>160</sup>; whether the household had electricity; household income (natural logarithm of the (real gross income per capita in 2015 USD plus 0.001)); and nationality. At the community level, we controlled for the median household income (household income was on the natural-logarithmic scale); the population density (natural logarithm of (density plus one)); the proportion of households with access to electricity; and the level of public goods and services offered by the government represented as index quintiles created using principal components analysis on binary variables for paved roads, postal, telephone, and bus services. We also controlled for national wealth expressed as the natural logarithm of real gross domestic product per capita in 2015 USD. Please see the Appendix 2 Supplementary methods section for more covariate details.

### 3.4.6 Econometric specification

As our data have repeated measures on approximately 59 percent of the individuals (Appendix 2 Table A19), we based our regression analysis on generalized estimating equations (GEE) with fixed effects. This approach is a semiparametric technique for correlated data that focuses on estimating the population-average as opposed to subject-specific effects.<sup>161</sup>

As our main marginal model, for child/adolescent  $i$  from household  $h$ , nested in community  $c$ , and survey year  $t$ , the econometric specification is of the form:

$$HAD_{i,h,c,t} = HHEXP_{h,c,t}\alpha + COMEXP_{c,t}\beta + X_{i,h,c,t}\theta + U_{c,t}\gamma + N_t\Gamma + v_c + w_t + \varepsilon_{i,h,c,t}$$
$$cor(\varepsilon_{i,h,c,t}; \varepsilon_{i,h,c,t'}) = \rho \text{ for } t \neq t'$$

$HAD_{i,h,c,t}$  is the individual's height-for-age difference;  $HHEXP_{h,c,t}$  is an array of household-level exposures;  $COMEXP_{c,t}$  is an array of community-level average exposures;  $X_{i,h,c,t}$  is an array of individual- and household-level controls;  $U_{c,t}$  is an array of community-level controls;  $N_t$  is the national-level wealth variable;  $v_c$  is a vector of community dummy variables (i.e., community fixed effects); and  $w_t$  is a linear time trend variable accounting for the secular trend in HAD. Including community fixed effects forced identification of within-community effects and removed large biases from all time-invariant unobserved factors at that level.<sup>60</sup> We specified an exchangeable correlation structure  $\rho$  for all pairs of observations on the same individual as opposed to an autoregressive structure, as 41 percent of the individuals are observed only once in the dataset.<sup>162</sup> Standard error estimates are clustered by individual and robust to heteroskedasticity.

In our main model, we controlled for an individual's private household-level exposures to better isolate the negative externality of his/her community's environmental sanitation.<sup>163</sup> To distinguish between the contributions of private and external effects on HAD, we reran our main models separately for the household- and community-level exposures. Given our hypothesis is primarily that of negative externalities controlling for individual-level exposure, we focus our interpretations on the adjusted community and unadjusted household effects. We label these as the "community + household" and "household" models, respectively.

All models were run in R with the *geepack* `geeglm` function.<sup>64,164–166</sup> All plots were made with the *ggplot2* package (version 3.4.2)<sup>65</sup> or the *dotwhisker* package (version 0.7.4)<sup>167</sup> with the assistance of the *egg* package extension<sup>168</sup> unless otherwise noted.

### 3.4.7 Predictive linear decomposition

To predict the relative contributions of different undernutrition- and development-related factors toward explaining the decrease in HAD from 1991 to 2011, the period with a clear secular trend in height, we used the following equation:

$$\text{Percent contribution of factor } F = \left[ \frac{\beta * (F_{1991} - F_{2011})}{HAD_{1991} - HAD_{2011}} \right] * 100 \dots$$

Here  $\beta$  is the estimated regression coefficient on the factor  $F$  from the main GEE model which controls for community and household exposures,  $F_{1991} - F_{2011}$  represents the mean change in the factor, and  $HAD_{1991} - HAD_{2011}$  represents the mean change in HAD. We bootstrapped the  $F$ ,  $HAD$ , and  $\beta$  values (200 replicates) to account for the uncertainty around the sample means and regression coefficients. We computed errors bars at the 2.5<sup>th</sup> and 97.5<sup>th</sup> percentiles of the 200 bootstrap *Percent contribution of factor F* for each factor  $F$ , with the 50<sup>th</sup> percentiles as the mean estimates.

#### 3.4.8 Community sanitation threshold effects

We considered the potential for nonlinear relationships between community-level sanitation and  $HAD^{169}$  and for diminishing or increasing returns to a child or adolescent's health as sanitation risk approaches zero. We first visualized the nonlinearity of the relationships by graphing the local polynomial regression fittings of community-level log excreta density and open pit/no toilet density. We then estimated the marginal effects across their observed ranges, using natural splines to model the densities and holding other covariates at their means.

### 3.5 Results

Preliminary inspection of the data shows that there were notable improvements in both children and adolescent's heights and environmental sanitation in China from 1989 to 2011. As illustrated in Figure 3.1 Panel A, the height deficit across birth cohorts decreased over time by approximately 8 cm, with individuals born in the most recent cohort (2000 to 2010) averaging close to the international growth standards (Appendix 2 Figure A1 for HAZ by birth cohort). Concurrently, individuals born in China were growing up in progressively healthier homes and communities (Figure 3.1 Panel B), as well as taller, wealthier, and smaller families (Table 3.1). From 1991 to 2011 the percentage of individuals living in environmentally sanitary households (i.e., households without: untreated piped water, an open pit/no toilet, excreta observed around their dwelling, and polluting cooking fuel (solid fuel or kerosene)) increased from 10 percent to 48 percent. Except for energy, the rates of change of these exposures were similar to one another across the study period (30 percent to 50 percent reductions; 70 percent for energy), although baseline coverages were different and likely reflected government priorities prior to 1989 (Figure 3.1 Panel C). The positive trends in height and environmental sanitation were also geographically widespread. Among the areas surveyed, the co-

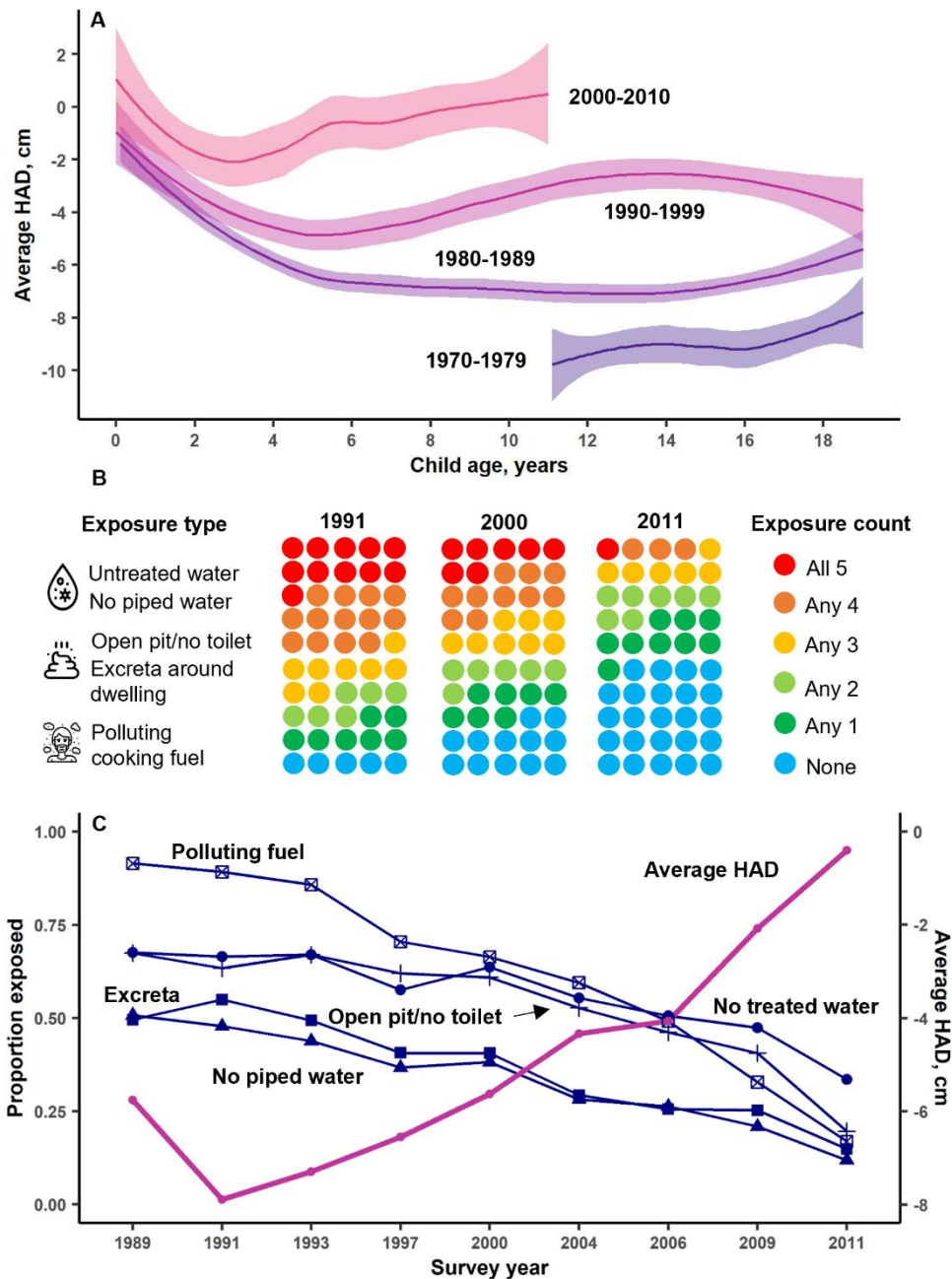
occurrence of such improvements is detectable at the province level (Figure 3.2 Panels A-F). For example, Hunan province had both one of the highest reductions in average household exposure level (approximately 2.0 out of 5 exposures) and the largest improvement in the proportion of children and adolescents stunted (approximately 40 percent reduction) (Figure 3.2 Panel E).

**Table 3.1 Summary statistics for children and adolescents across aggregated survey years**

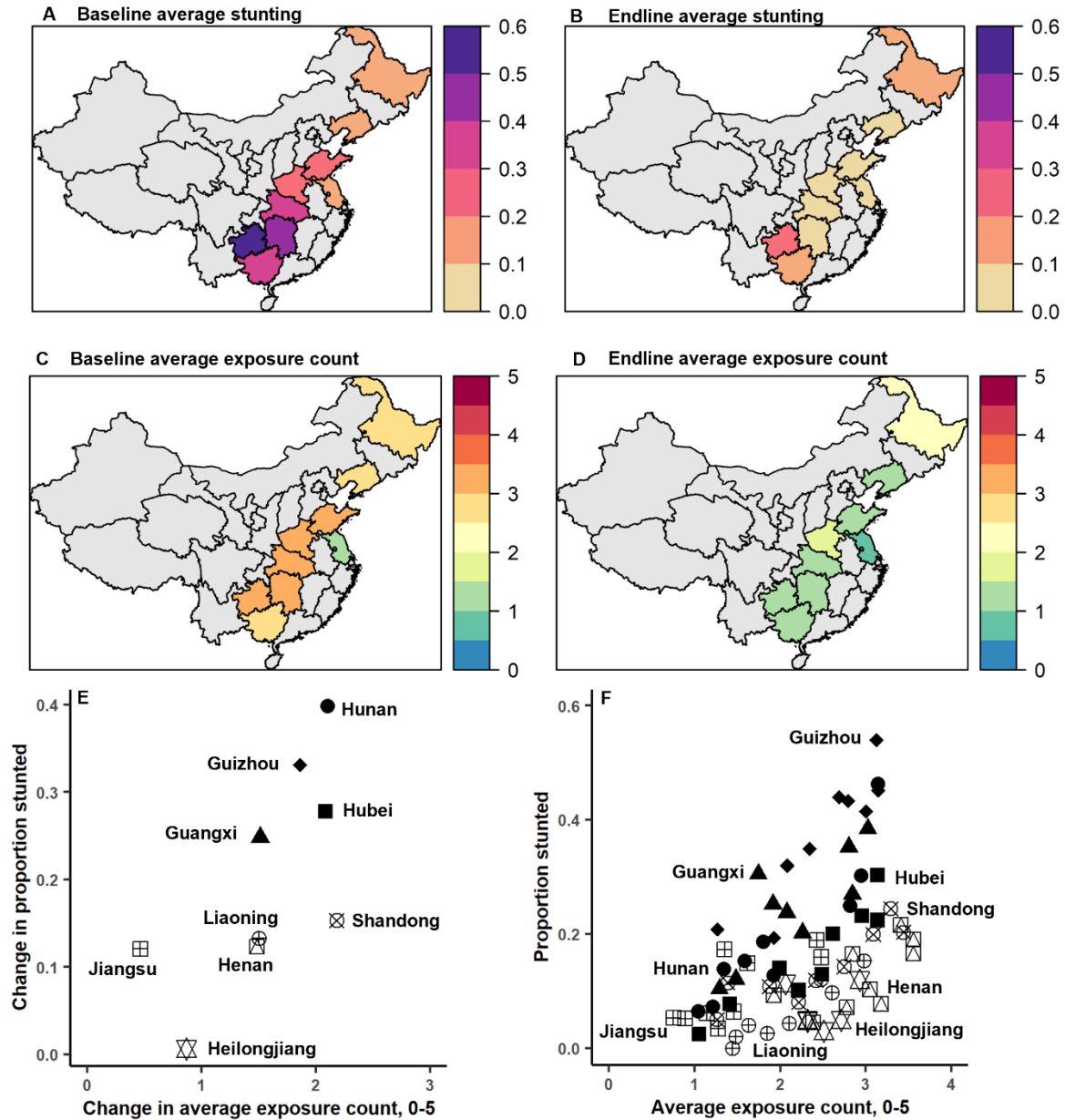
	1989, 1991, 1993 (n = 5355 obs)		1997, 2000, 2004 (n = 4168 obs)		2006, 2009, 2011 (n = 2522 obs)	
	Mean	95% CI	Mean	95% CI	Mean	95% CI
<b>Environmental sanitation exposures</b>						
<i>Household level</i>						
No treatment plant water, %	66.9	[65.98, 67.8]	59.2	[58.2, 60.2]	42.1	[41.1, 43.1]
No piped water, %	46.5	[45.5, 47.5]	35.2	[34.3, 36.1]	18.4	[17.6, 19.2]
Open pit or no toilet, %	65.4	[64.5, 66.3]	59.5	[58.5, 60.5]	32.8	[31.9, 33.7]
Excreta outside, %	51.9	[50.9, 52.9]	38.0	[37.0, 39.0]	20.7	[19.9, 21.5]
Cooks with polluting fuel, %	88.0	[87.4, 88.6]	66.5	[65.6, 67.4]	30.4	[29.5, 31.3]
<i>Community level</i>						
No treatment plant water, %	66.9	[66.1, 67.7]	59.1	[58.2, 60.0]	41.6	[40.8, 42.5]
No piped water, %	46.5	[45.6, 47.4]	35.6	[34.8, 36.4]	18.0	[17.4, 18.6]
Open pit or no toilet, %	65.8	[65.1, 66.5]	60.2	[59.4, 61.0]	33.3	[32.6, 34.1]
Excreta outside, %	52.6	[51.9, 53.3]	38.4	[37.8, 39.0]	20.9	[20.4, 21.4]
Cooks with polluting fuel, %	88.2	[87.7, 88.7]	68.6	[67.9, 69.3]	31.9	[31.3, 32.5]
Log no treatment plant water density	4.1	[-1.3, 9.5]	3.6	[-2.2, 9.4]	2.7	[-2.9, 8.2]
Log no piped water density	2.7	[-2.5, 8.0]	2.0	[-2.8, 6.9]	1.0	[2.5, 4.6]
Log open pit or no toilet density	4.0	[-0.8, 8.7]	3.6	[-1.4, 8.7]	2.1	[-2.7, 6.8]
Log excreta outside density	3.2	[-1.4, 7.7]	2.3	[-1.6, 6.3]	1.4	[-2.1, 4.8]
Log cooks with polluting fuel density	5.5	[1.3, 9.7]	4.3	[-0.2, 8.8]	2.0	[-1.97, 6.0]
<b>Outcome</b>						
Height-for-age difference, cm	-7.4	[-20.6, 5.9]	-5.7	[-20.4, 9.0]	-1.9	[-16.7, 12.9]
<b>National-level covariate</b>						
Log real gross domestic product per capita, 2015 USD	6.97	[6.7, 7.2]	7.7	[7.3, 8.1]	8.5	[8.1, 8.9]
<b>Other community-level covariates</b>						
Log real gross income per capita, per thousand 2015 USD	-0.7	[-1.5, 0.1]	-0.3	[-1.2, 0.7]	0.4	[-0.7, 1.6]
Electricity, %	97.3	[97.08, 97.52]	99.6	[99.56, 99.64]	99.8	[99.78, 99.82]

Log pop density (ind per sq. km)	6.4	[2.8, 9.99]	6.5	[2.5, 10.5]	7.3	[3.4, 11.1]
Public goods/services, 1-5	3.4	[0.3, 6.4]	2.5	[-0.4, 5.4]	2.3	[-0.6, 5.3]
<b>Individual-level covariates</b>						
Female, %	47.6	[46.6, 48.6]	45.9	[44.9, 46.9]	45.8	[44.8, 46.8]
Age, years	9.4	[-0.6, 19.5]	11.6	[2.5, 20.7]	9.7	[-0.4, 19.7]
Han, %	81.3	[80.5, 82.1]	84.5	[83.8, 85.2]	86.0	[85.3, 86.7]
Mother's height, cm	155	[143.9, 166.1]	156	[145.1, 166.9]	157	[145.5, 168.5]
Father's height, cm	165	[152.7, 177.3]	166	[153.8, 178.2]	167	[151.1, 182.9]
Mother's education, years	6.9	[-0.5, 14.3]	8.0	[1.1, 14.8]	9.6	[3.4, 15.8]
Father's education, years	8.7	[2.5, 14.8]	9.3	[3.8, 14.8]	10.3	[4.7, 15.9]
Household log real gross income per capita, per thousand 2015 USD	-0.8	[-2.2, 0.6]	-0.3	[-2.1, 1.4]	0.2	[-2.3, 2.7]
Household electricity, %	97.0	[96.67, 97.33]	99.7	[99.59, 99.81]	99.9	[99.83, 99.97]
Number of children in household < 20 years old	1.9	[0.3, 3.6]	1.7	[0.2, 3.2]	1.4	[0.2, 2.6]
Urban, %	26.5	[25.6, 27.4]	28.9	[28.0, 29.8]	35.4	[34.5, 36.3]
<i>Individual-level covariates with n = 10,381 obs</i>						
Medical insurance, %	15.8	[15.1, 16.5]	22.2	[21.4, 23.0]	89.5	[88.9, 90.1]
Energy intake, per 1000 kcal per day	2.0	[0.5, 3.4]	1.8	[0.5, 3.1]	1.5	[0.4, 2.7]
Protein intake, per 10 g per day	5.8	[0.2, 11.3]	5.5	[0.9, 10.1]	5.2	[0.8, 9.6]

Notes: For clarity, more than one decimal place was retained if averages were near the boundaries of the 95 percent confidence intervals (CIs). Variables included in the table are those used in the main models and sensitivity analyses. Missing values for log population density were imputed using a linear model with a linear trend for survey year, as well as province and community fixed effects and their interactions with survey year. In the same way, the four variables that comprise public goods/services were imputed and then combined using principal components analysis. These variables included binary indications of the presence of paved roads, postal, telephone, and bus services. Declines in per capita energy and protein intake over time may be due to measurement error,<sup>170</sup> lower levels of physical activity, and/or improvements in growth environments.<sup>171</sup> Relatedly, the average body mass index also increased from 17.1 to 18.0 across the three aggregated periods (estimated with n = 10,289 person-year observations).<sup>129</sup> Based on dataset with n = 12,045 person-year observations except for the last three rows for which n = 10,381 person-year observations

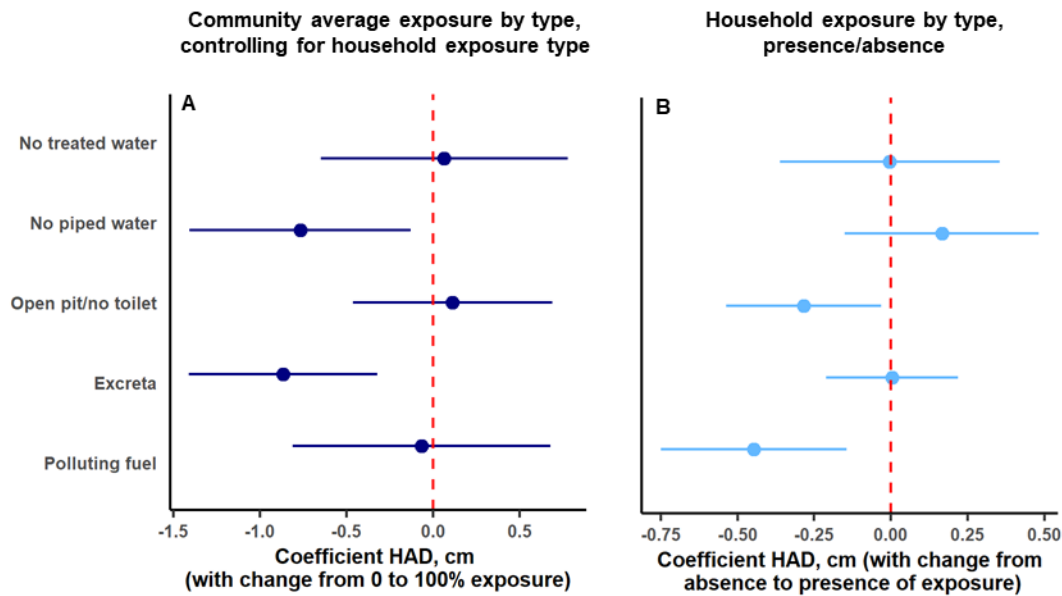


**Figure 3.1 Co-occurring changes in height and environmental sanitation.** *Panel A:* Height-for-age difference (HAD) in centimeters of children and adolescents aged 0-228 months, by birth cohort ( $n = 12,045$  person-year observations). WHO Growth Standards were used to calculate HAD. Curves fitted by locally estimated scatterplot smoothing (loess) represent mean HAD by cohort with 95 percent confidence intervals. Birth cohort 1970-1979 consists of individuals who at the time of the first survey in 1989 were at minimum 10 years of age. Birth cohort 2000-2010 excludes children born in 2011 and consists of individuals who at the time of the last survey in 2011 were at maximum 11 years of age. *Panel B:* Changes in household-level environmental sanitation from 1991 to 2011 ( $n = 97,770$  person-year observations). This panel shows the changes in the proportions of individuals at each summed exposure level (0-5) across surveys. For the survey years shown, the number of dots of each color is proportional to the fraction of the total sample at each of the five exposure levels. *Panel C:* Proportion of individuals in each survey year exposed to a particular exposure (left y-axis) and mean HAD trend (right y-axis).



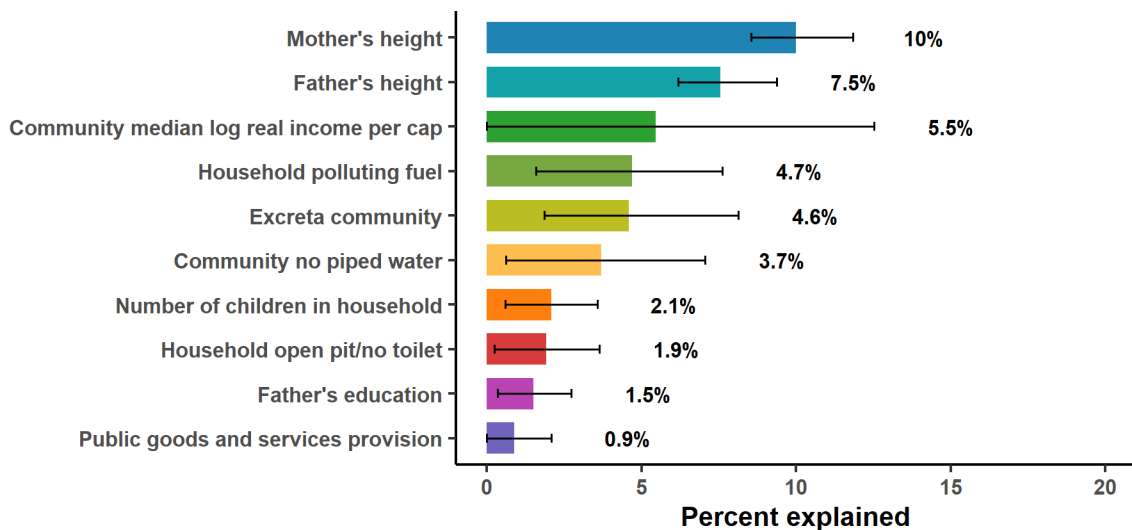
**Figure 3.2 Province-level average stunting and household environmental sanitation.** *Panel A:* Baseline map of the province-level proportion of children and adolescents who were stunted (height-for-age z-score < -2). *Panel B:* Endline map of the province-level proportion of children and adolescents who were stunted. *Panel C:* Baseline map of the province-level average household environmental sanitation level (i.e., the average number of household-level exposures, 0-5). *Panel D:* Endline map of the province-level average household environmental sanitation level. For Panels A-D, grey indicates provinces that were either not surveyed or in the case of Beijing, Shanghai, and Chongqing only had 2011 data. *Panel E:* Scatterplot of the positive relationship between the absolute value of the difference in the proportion of individuals stunted (y-axis) and the absolute value of the difference in average household-level environmental sanitation level (x-axis) in each province between baseline and endline. *Panel F:* Scatterplot exhibiting the cross-sectional relationship between stunting prevalence (y-axis) and household-level average environmental sanitation level (x-axis) in each province across all survey years in which a province was surveyed. For Panels A-D: Maps created using freely available GADM data<sup>69</sup> and R packages *rgdal* (version 1.5.12),<sup>70</sup> *sp* (version 1.4.2),<sup>71,72</sup> *rcartocolor* (version 2.0.0),<sup>172</sup> *cowplot* (version 1.0.0),<sup>173</sup> and *colorRamps* (version 2.3).<sup>73</sup> For all six panels, baseline refers to the first survey wave of 1989 except for Heilongjiang whose baseline is year 1997, and endline refers to the 2011 survey. Province-level averages are based on the dataset with  $n = 104,091$  person-year observations

Figure 3.3 reports our main results. The effect sizes of the significant community-level estimates (Panel A) are larger than those at the household level (Panel B). Community-level prevalence of no on-premises piped water and excreta are the highest significant predictors of growth faltering: on average, children and adolescents in communities with 0 percent piped water coverage or with excreta around 100 percent of the surveyed dwellings were 0.77 cm (95CI[-1.40, -0.13]; Appendix 2 Table A3 HAZ: -0.17, 95CI[-0.27, -0.060]) or 0.87 cm (95CI[-1.41, -0.32], HAZ: -0.094, 95CI[-0.19, 0.0017]) shorter than individuals in communities with 100 percent piped water coverage or no excreta, all else being equal. Increasing a community's exposure to untreated water, open pits/no toilets, or polluting cooking fuels was not significantly associated with worsening HAD. We find a similar story when we substitute community exposure densities for proportions (Appendix 2 Figure A2). At the household level, Panel B shows that on average having an open pit/no toilet compared to having access to any other type of toilet was associated with a 0.28-cm HAD deficit (95CI[-0.54, -0.033]; HAZ: -0.039, 95CI[-0.081, 0.0042]). In addition, on average children and adolescents from households using polluting cooking fuels compared to those living in households with clean fuels (electricity or gas) were 0.45 cm shorter, all else equal (95CI[-0.75, -0.14], HAZ: -0.051, 95CI[-0.10, 0.0025]). A household's exposure to untreated water, non-piped water, or excreta was not significantly associated with increasing HAD.



**Figure 3.3 Community and household exposure effects.** All models had the full set of covariates, linear time trend, and community fixed effects. Confidence intervals are reported at the 95 percent confidence level. Standard errors are clustered by individual and are robust to heteroskedasticity. *Panel A:* Effects of community average exposures by type, controlling for household exposure type, mutually adjusted exposures (i.e., one model). No piped water: -0.77, 95CI[-1.40, -0.13]; excreta: -0.87, 95CI[-1.41, -0.32]. *Panel B:* Effects of household exposures by type (comparing presence versus absence of exposure), mutually adjusted exposures. Open pit/no toilet: -0.28, 95CI[-0.54, -0.033]; polluting fuel: -0.45, 95CI[-0.75, -0.14]. n = 12,045 person-year observations

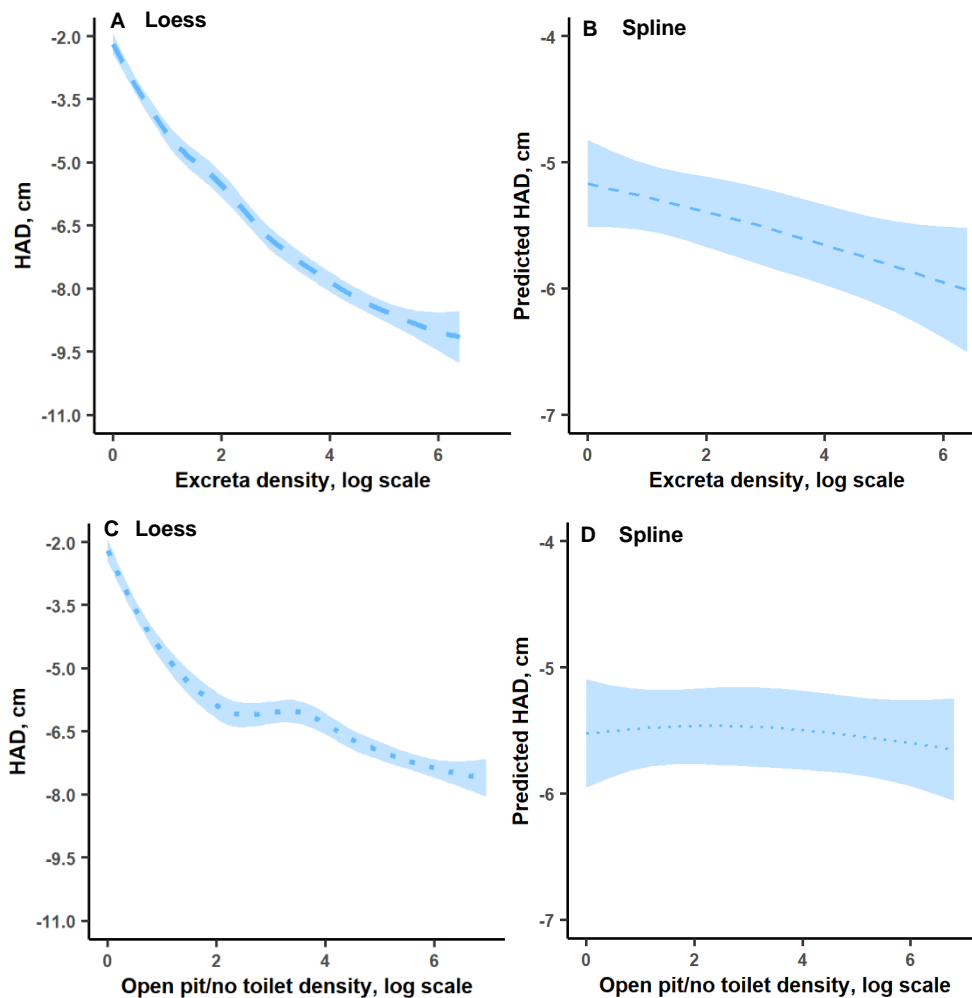
In Figure 3.4 we display the results of our decomposition analysis, comparing the relative contributions of different undernutrition- and development-related factors on the observed decline in average HAD across 1991 to 2011. Collectively, the ten variables explain 43 percent of the observed change in population-level HAD (see <sup>174</sup> for a comparable percent explained). Parental height alone accounts for 17.5 percent. Approximately 15 percent of the variation in HAD was due to improvements in environmental sanitation, primarily with respect to household polluting fuel and community excreta. Changes in the average income level may explain 5.5 percent of the improvement in mean HAD, though this estimate is highly uncertain. Changes in the number of children and adolescents in the household, paternal education, and community-level public goods and services each explains less than 3 percent of the decrease in population-level HAD. The reversal of the relative importance of community no piped water and household polluting fuel is likely a consequence of the polluting fuel estimate having a tighter confidence interval during the decomposition analysis bootstrapping procedure.



**Figure 3.4 Decomposition analysis: Explaining the changes in height-for-age difference from 1991 to 2011.** We estimated the share of the variation in height-for-age difference (HAD) attributed to certain variables of interest in our community + household GEE model, most of which had statistically significant associations with HAD. Other variables in our model that not shown, as well as possible omitted variables, may explain the remaining 57 percent, 95CI[47.7, 67.8] of the variation in HAD. Bar heights correspond to the 50<sup>th</sup> percentiles (averages) of the bootstrap coefficients from 200 regressions (i.e., randomly sampled with replacement). Errors bars (truncated at theoretical minimum of 0) are the 2.5<sup>th</sup> and 97.5<sup>th</sup> percentiles of the regression coefficients and capture the uncertainty of the estimates and sample means. We chose the period 1991 and 2011 due to its clear secular trend in height. Percent explained: Mother's height 10 percent, 95CI[8.5, 11.8]; father's height 7.5 percent, 95CI[6.2, 9.4]; community median log real income per capita 5.5 percent, 95CI[-1.6, 12.5]; household polluting fuel 4.7 percent, 95CI[1.6, 7.6]; community excreta 4.6 percent, 95CI[1.9, 8.1]; community no piped water 3.7 percent, 95CI[0.61, 7.1]; number of children in household 2.1 percent, 95CI[0.60, 3.6]; household open pit/no toilet 1.9 percent, 95CI[0.24, 3.6]; father's education 1.5 percent, 95CI[0.35, 2.7]; public goods and services provision 0.90 percent, 95CI[-0.42, 2.1]. Based on n = 12,045 person-year observations

Figure 3.5 demonstrates the relationship between HAD and community-level sanitation over a range of exposure density values. Previous studies have shown that sanitation can be a mechanism through which population density affects child growth.<sup>163,175</sup> Panels A and C show the direct links between the exposure densities and HAD, and Panels B and D display the marginal effects, which are adjusted predictions of HAD averaged across communities, holding all other non-factor covariates at their means. In comparing Panels A and B we see that while most of the association between community-level excreta density and HAD can be explained by other variables in our model, on average there remains a small but significant linear marginal effect. Within the range of densities observed in our data, excreta density has a negative linear relationship with HAD, and any decrease can be beneficial, even at low densities. In other words, we do not detect a threshold effect for excreta density. In terms of open pit/no toilet, while Panel C shows worse HAD at higher densities,

Panel D indicates that in reality HAD is likely independent of open pit/no toilet density after controlling for other variables.



**Figure 3.5 Community sanitation threshold effects on height-for-age difference.** All panels show 95 percent confidence intervals and truncated log density distributions at their 95<sup>th</sup> percentiles. Density is defined as the product of the fraction [0, 1] of households in a community in a given year who have either excreta observed or an open pit/no toilet and the natural logarithm of community population density + 1. *Panel A:* Plot of height-for-age difference (HAD) across the observed range of community excreta density levels (on the log scale) from the local polynomial regression fitting (loess) of community-level excreta density on HAD. *Panel B:* Adjusted predictions of HAD across the observed range of community excreta density levels. The community-level excreta density variable was modeled as a natural spline with a knot specified at 2.5 (on the log scale), given the slope change at that point in Panel A (joint significance test for the two natural spline components with the *linearhypothesis* function in the *car* package (version 3.0.8)<sup>176</sup> was insignificant at  $\alpha = 0.05$ ; coefficients of the two components: -0.85, 95CI[-1.64, -0.055] and -0.71, 95CI[-1.24, -0.18]). *Panel C:* Plot of HAD across the observed range of community open pit/no toilet density levels (on the log scale) from the local polynomial regression fitting (loess) of community-level open pit/no toilet density on HAD. *Panel D:* Adjusted predictions of HAD across the observed range of community open pit/no toilet density levels. The community-level open pit/no toilet density variable was modeled as a natural spline with a knot specified at 2 (on the log scale), given the slope change at that point in Panel C (joint significance test for the two natural spline components was insignificant at  $\alpha = 0.05$ ; coefficients of the two components: 0.036, 95CI[-0.90, 0.98] and -0.18, 95CI[-0.71, 0.35]). Additional notes on

Panels B and D: Marginal effects as defined here are effects that are marginalized, or averaged, across communities (holding all other non-factor covariates at their means) and measure the association between a change in the predictors and a change in HAD.<sup>177</sup> Predictions were calculated using the *effect* function in the effects package (version 4.2.0)<sup>176</sup> based on GEE models with the full set of controls and a linear time trend variable. The 95 percent confidence intervals were estimated using standard errors that are robust to heteroskedasticity and clustered at the individual level. n = 12,045 person-year observations

### 3.5.1 Robustness checks and sensitivity analyses

We demonstrated that our main effects (Figure 3.3) are quantitatively robust to model re-specifications, namely linear mixed-model<sup>161</sup> (Appendix 2 Table A2), first-difference estimator, and individual fixed effects (Appendix 2 Figure A3) specifications. We showed the results are reasonably robust to using HAZ in place of HAD as our dependent variable (Appendix 2 Table A3), though dissimilarities are also to be expected given the existing evidence of their differing abilities to measure changes in linear growth over time.<sup>154</sup>

We tested the robustness of our main household polluting fuel estimate with instrumental variable analysis, using coal and gas subsidies as our instruments (Appendix 2 Figure A4). Though the estimated effect of predicted household polluting fuel on HAD has a wide confidence interval – a possible consequence of the relatively small sample size (n = 2949 person-year observations) – its overlap with that of our main GEE estimate, which itself is more conservative ( $\beta = -0.45$  compared to  $\beta = -1.15$ ), together suggest that our finding for household polluting fuel is not unreasonable. We provide additional details in the Appendix 2 Supplementary methods section.

We explored the sensitivity of our main results to the introduction of additional key controls for nutrition<sup>178</sup> and medical care access<sup>179</sup> (Appendix 2 Table A4), as well as to our valid height measurement cutoff (within  $\pm 5$  rather than  $\pm 6$  standard deviations of the WHO Growth Standards median) (Appendix 2 Table A5). The sensitivity analyses yielded similar estimates to those from our main models, as judged by the overlapping confidence intervals.

### 3.5.2 Heterogeneity analyses

We investigated the heterogeneity of our main effects across age, sex, ethnicity, community wealth, community population density, and urban-rural classification (Appendix 2 Tables A6-A11). With

respect to the four significant exposures from our main models, we found that as children and adolescents aged, their growth faltering was higher – that is, they felt the negative effect of age on HAD more – if they lived in communities with full excreta coverage and in households using polluting cooking fuel rather than in communities and households without these exposures. We also discovered that the benefits of community income were attenuated in communities with 100 percent excreta coverage compared to 0 percent coverage, and high community no piped water and excreta coverage negatively affected Han more than non-Han individuals. The concentrated negative effect among ethnic Han is likely a consequence of the relatively small number of minorities in our sample, as the CHNS only surveys one of China’s five minority autonomous regions.

### *3.5.3 Falsification test*

We conducted a randomization inference test to assess the possibility that our main effects were obtained by chance. Our null hypothesis was that our household and community exposures had no effects on HAD. For each exposure we sampled independent Bernoulli  $p$  random variables for each household, assigning each household a value of 0 or 1 with the probability of success  $p$ . We conducted three series of tests, each with a different  $p$ , as we were unsure of the implications of their different assumptions: (1)  $p = 0.5$  (fair coin toss); (2)  $p =$  overall exposure mean (weighted by household size due to double-counting the exposure value for every individual within a household); or (3)  $p =$  exposure mean when each household was given the same weight independent of household size. All individuals within a household for a particular year were assigned the same random exposure value. We calculated the community-level exposures from the randomly assigned household exposures and re-estimated our community + household and household GEE models. We repeated this process 200 times for each of the three types of  $p$  values. We extracted the 2.5<sup>th</sup> (lower bound), 50<sup>th</sup> (mean), and 97.5<sup>th</sup> (upper bound) percentiles of the vector of 200 coefficients for each exposure and plotted them in Appendix 2 Figure A5 Panels A and B; Panels C through F show the distributions of the 200 estimates for the four main significant exposures (community excreta, community no piped water, household open pit/no toilet, and household polluting fuel). Across the different probability parameters, both the community and household estimates were centered at zero. For our four main significant exposures, the point estimates did not overlap the randomly obtained confidence intervals, though for community no piped water the randomization test did produce

coefficients as large as our GEE model coefficients. While there is a small possibility that our community no piped water finding is random, this series of tests provides reasonably convincing evidence that our results were not obtained by chance.

#### *3.5.4 Water and sanitation mechanisms*

In response to the call for transformative public health programming, there has been renewed emphasis on addressing animal fecal contamination,<sup>122</sup> which may impair linear growth<sup>180</sup> though it is not certain.<sup>181</sup> We characterized the excreta exposure in our main analyses by predicting household and community excreta as linear combinations of log community population density, animal ownership, and open pit/no toilet prevalence. Based on this model, we would expect that for a household that owned animals and had an open pit/no toilet, approximately 54 percent of the excreta around the dwelling was from animals, with the remainder being human feces (Appendix 2 Table A12). Excreta from neighbors and neighbors' animals were not significant contributors to household-level excreta. At the community level, the prevalence of open pits/open defecators was the only significant predictor in the model of the proportion of the community with excreta around its dwellings.

In a similar fashion, we considered the relationships between on-premises piped water and the regularity of household cleaning practices and average cleaning frequency across a community, a proxy for a community's hygiene level. We found that community-level no piped water was negatively associated with community hygiene, and household-level hygiene was negatively associated with no piped water at the household level, though neither association was statistically significant (Appendix 2 Table A13). A larger sample and/or a different hygiene indicator may have provided more insight into the piped-water mechanism.

We sought to understand the associations between exposure combinations and HAD. We first partitioned the full sample into subsamples based on piped water and excreta coverage, with "low" coverage meaning individuals living in communities with coverage at or below the 25<sup>th</sup> percentile, and "high" indicating coverage at or above the 75<sup>th</sup> percentile. We then further segmented the subsamples by household toilet status (yes/no). At each division we reported the mean HAD and 95 percent confidence intervals to track how the outcome changed. We depict this process graphically in

Appendix 2 Figures A6a-A6c. We discovered that across the different combinations of exposures the key to low HAD was low excreta prevalence. Having a toilet and piped water offered little protection to individuals living in high-excreta environments. While the mean HAD deficits were often smaller, the confidence intervals overlapped those of individuals living in high-excreta communities with low piped water coverage and no toilet.

### *3.5.5 Project placement*

As with most large-scale projects, China's water, sanitation, and energy programs were not randomly assigned, and the government may have prioritized investments to certain communities based on characteristics that are also determinants of child and adolescent HAD.<sup>182</sup> To explore the potential for such systematic bias, we examined the associations between predicted changes in community-averaged income, education, electricity, and roads and given changes in averaged community-level exposures across survey years, as well as associations between baseline (1989) levels of these four characteristics and observed changes in the averaged community-level exposures or averaged HAD across survey years. We found evidence of potential government targeting by community characteristics, especially by roads and baseline water<sup>182</sup> and sanitation conditions (Appendix 2 Tables A14a and A14b, Figure A7). The relationships exhibited wide variability such that targeting policies were likely not uniform across time or space,<sup>113</sup> which makes it challenging to ascertain the effects of selection bias. We also recognize that changes in the exposures may have corresponded to baseline characteristics due to the least-developed communities naturally having the most room for improvement. Though we accounted for much of the potential confounding by adjusting for these dynamic community characteristics and community fixed effects, we acknowledge that there may be time-varying omitted variables that influenced project placement and caution against drawing overly strong causal inferences from our study.<sup>111</sup>

### *3.5.6 Regression to the mean and attrition bias*

In addition, we assessed the effect of regression to the mean and found no cause for concern, as the effect appears to bias our results toward the null and lead us to more conservative conclusions (Appendix 2 Figure A8). Controlling for parental height<sup>183</sup> in our regression models also protects against this bias. Finally, we considered selection bias due to loss to follow-up and found that while

the effects of some of our exposures (community polluting fuel, household open pit/no toilet, and household polluting fuel) on the probability of loss to follow-up were statistically significant (Appendix 2 Table A15a), there was little actual difference in how the sample sorted across the household levels of the exposures for those observed once as opposed to multiple times in the dataset (Appendix 2 Table A15b). Therefore, the threat of selection bias is minimal.

### **3.6 Discussion**

Based on our findings, how can China's experience inform the future of transformative programming? Broadly speaking, these results can guide decision-making on the scale and composition of water, sanitation, and clean energy interventions aimed at reducing child and adolescent linear growth faltering. Principally, our results suggest that interventions should prioritize improving community sanitation in addition to increasing household sanitation provision. Our findings also encourage greater attention to community-level piped water coverage and further scholarship on its associated externalities. Finally, our results indicate that focusing on indoor air quality over water or sanitation may be the most effective household-level strategy. We focus the discussion on summarizing and interpreting these four significant exposures, beginning with community excreta. To compare our findings to those in the existing literature, we are often required to use our HAZ instead of main HAD coefficients, as the former is more common. However, as previously alluded to, HAZ may be inappropriate to measure changes in linear growth over time due to it being constructed from standard deviations from cross-sectional data,<sup>154</sup> and we recommend that the comparisons be interpreted with particular caution. We conclude the discussion by compiling the implications of the findings for transformative programming practice and research.

#### *3.6.1 Community level*

We found that community excreta prevalence was statistically significantly associated with linear growth faltering. On average, living in a community with excreta outside every household compared to a community with no excreta was associated with a HAD deficit of 0.87 cm or HAZ of 0.094 standard deviations. For individuals living in communities with high excreta prevalence, having high coverage of community piped water and/or a household toilet offered minimal protection from excreta-related risks. In our decomposition analysis we estimated that reductions in community excreta

across rural China from 1991 to 2011 accounted for an estimated 4.6 percent of the change in population-level HAD. We also found that the increasing HAD deficit with age was higher among individuals living in communities with 100 percent excreta coverage compared to those in communities with no excreta. Our main regression estimate is more conservative than some published effect sizes for sanitation externalities (e.g., Cameron et al. (2021) and (2022) with magnitudes between 0.4 and 0.5<sup>37,184</sup>); however, it is important to note that other studies have found no effect of village sanitation on undernutrition.<sup>111,185,186</sup> Our estimate is closer to the coefficients reported for community sanitation in Shrestha et al. (2020) (0.28)<sup>187</sup> and Cunningham et al. (2017) (0.14).<sup>188</sup> Differences in study contexts, especially in open defecation rates (only 1.3 percent of our sample within each survey round) and differences in exposure measurement (e.g., excreta observed versus self-reported toileting practice)<sup>189</sup> may partially explain the range of effect sizes across the literature (see also <sup>169,174,190–192</sup>).

In contrast to community excreta, we did not find community prevalence of open pits/no toilets to be significantly related to HAD. Our excreta mechanism extension analysis results may help to explain this finding. We found a positive association between community open pit/no toilet prevalence and community excreta coverage, and logically speaking we would expect the former to determine the latter. That is, community excreta prevalence is an indicator of the extent to which households contain their human and animal feces in toilets. This relationship between excreta and toilets may suggest that the effect of community open pit/no toilet coverage on HAD passed through and was subsumed by community excreta coverage. Any effect of improved toilet coverage on HAD was therefore accounted for in the effect of improved excreta management on HAD. There may also have been insufficient improvement in community open pit/no toilet coverage to affect child and adolescent growth. Between 1989 to 2004, the period with the most observations in our sample, community open pit/no toilet coverage decreased from approximately 65 percent to 60 percent, while community excreta coverage decreased from 52 percent to 38 percent. The relatively minimal variation in open pit/no toilet coverage over time may also explain the absence of a community open pit/no toilet density threshold effect. The evidence on community sanitation threshold effects in the literature is limited, though recently Cameron et al. (2022) found increases in child height were realized only after a community reached 50 percent to 75 percent private toilet coverage.<sup>184</sup> Yet, Harris et al. (2017)

report no threshold effect associated with community latrine coverage,<sup>169</sup> which is similar to what we discovered for excreta density. Continued research on threshold effects is needed to help clarify community sanitation coverage targets.

In addition to community excreta prevalence, we discovered that the proportion of a community with no on-premises piped water was a significant predictor of HAD, though our falsification test imputes some uncertainty into this finding. On average, living in a community with no piped water compared to a community with full coverage was associated with a HAD deficit of 0.77 cm or HAZ of 0.17 standard deviations. For individuals living in communities with high excreta prevalence, having high piped water coverage offered small compensation for the excreta-related risks. Approximately 3.7 percent of the observed change in population HAD was attributable to improvements in community piped water. Unlike sanitation, neighbors' water access is not always viewed as generating externalities<sup>37,193,194</sup> or as having a direct effect on height<sup>195</sup>; however, some studies have shown clean water coverage can influence child health.<sup>127,196–198</sup> Given the infectious nature of many water-related diseases,<sup>199</sup> it is not unreasonable to conceive of the greatest risks being captured more accurately on an aggregate community level as opposed to household level.

We consider several ways through which these piped water externalities might arise. First, households in rural China, which constitute most of our sample, often share in-yard water supplies with other households.<sup>197</sup> If a household were to gain access to a private tap while its immediate neighbors still used the common water source, the household and its disease environment could still be affected by the neighbors. Second, community coverage may matter more than private access due to the nature of some small-scale utilities in rural Chinese villages.<sup>200</sup> For such systems, the share of community members with piped water may determine, in part, the price of water and reliability of operations, and any benefits to linear growth may only be realized once a sufficient percentage of households are connected and supporting the system. Third, in our sample the improvements in community piped water access may have increased overall water availability<sup>201,202</sup> and enabled increased community-level hygiene; we found some evidence of this relationship. However, past research suggests that this interpretation may only hold in the case of continuous water supply, which is uncommon in many parts of rural China.<sup>203,204</sup> Furthermore, though the

evidence on the relative importance of piped versus treated water in China is mixed,<sup>146</sup> our results suggest that piped water is more important for growth faltering. Additional research is needed to clarify the pathways through which water quality and quantity might relate to linear growth faltering at the community and household levels (see <sup>15,118,205–207</sup>).

### *3.6.2 Household level*

In contrast to the community level, our regression analysis revealed that household toilet type rather than excreta presence was a significant predictor of HAD. On average, having an open pit or not having a toilet compared to having a non-open-pit toilet was associated with a HAD deficit of 0.28 cm or HAZ of 0.039 standard deviations. For individuals living in communities with high levels of excreta, irrespective of the community's piped water access, having a household toilet provided minimal protection from excreta-related risks. Improvements in household toilets were associated with 1.9 percent of the observed change in the population HAD from 1991 to 2011. Our regression result is similar in magnitude to Aguayo et al.'s (2016) estimate (0.029)<sup>208</sup> and below that of Reese et al. (2019) (0.16).<sup>195</sup> Many other publications, however, report no effect of household sanitation on child growth.<sup>119–121,169,191,193</sup> In our study, having a household open pit/no toilet may have been associated with growth faltering due to the multiple risks it represents. Having an open pit/no toilet not only increases the likelihood of a household being exposed to its members' or animals' feces per our excreta mechanism extension analysis, but also means household members are less protected from their community's excreta when defecating. Having a toilet may provide households a secure place to defecate, which may account for the small amount of protection we found toilets offered to households living in communities with high excreta coverage. An open pit/no toilet may also indicate that households are being exposed to fecal pathogens through the collection and reuse of human and animal excreta, a common practice in rural China.<sup>146,209–212</sup> Having a toilet may help households improve their waste management by containing and treating excreta that would otherwise be used directly to fertilize backyard farms. Compared to the presence of excreta, which could have been a one-off occurrence for a household the day it was surveyed, an open pit/no toilet is more fixed and therefore a more accurate indicator of a household's waste management practices. Interestingly, though, our analysis of growth trends across age suggested the patterns depended on household

excreta rather than open pit/no toilet exposure, and we recommend further research on exposure-specific age patterning through adolescence.

Finally, we found household polluting cooking fuel to be statistically significantly related to growth faltering. Specifically, we discovered that using polluting cooking fuel compared to clean fuel was associated on average with a HAD deficit of 0.45 cm or HAZ of 0.05 standard deviations.

Approximately 4.7 percent of the observed variation in mean HAD across the study period was due to improvements in cooking fuels, improvements representing an almost 70-percent reduction in the proportion of the population exposed, which was the largest change across the four exposures. We also detected an increasing HAD deficit with age that was accentuated for individuals living in households that used polluting cooking fuel. In a similar study among Chinese children aged six to seventeen, the effect of solid fuel use was estimated to be 0.21 standard deviations.<sup>147</sup> Though our finding is more conservative, it nevertheless contributes to the growing literature on the importance of indoor air quality for linear growth<sup>205,213</sup> and emphasizes the benefits of prioritizing household-level improvements in clean cooking fuel over household-level improvements in water and sanitation. Though our study only involved cooking fuel, we suggest transformative interventions aim to reduce other sources of indoor air pollution such as building materials, ventilation, and fuels used for lighting and heating.

### *3.6.3 Recommendations*

In accordance with the vision of environmental sanitation, based on our results we recommend transformative interventions aimed at reducing growth faltering prioritize improving community excreta management, household toilet access and use, household air quality, and potentially community piped water coverage. Of these four factors, the focus should be community excreta management. The exact design of transformative interventions will depend on the context and likely involve other elements not examined in this study. For example, in China we would recommend at minimum community-wide coverage of household toilets that enable on-site treatment and safe reuse of human and animal excreta, clean cook stoves, and possibly continuous piped water supply. Other contexts with higher open defecation rates may benefit from community-led total sanitation campaigns<sup>214</sup> that integrate animal feces management,<sup>181</sup> especially where animal feces are used as cooking fuel.

Regardless of the design, we recommend researchers assess community sanitation interventions differently from those at the household level given intra- and inter-household fecal transmission pathways affecting undernutrition may not be equally captured by the same indicators. For example, researchers may consider mapping a community's open defecation sites and documenting households' waste reuse behaviors in addition to surveying toilet conditions at both levels.

Among the research suggestions offered throughout the discussion, we encourage community water externalities be a priority research topic, as our findings indicate they may be an important determinant of growth faltering. We also recommend researchers interested in transformative programming aim to clarify how water, sanitation, and air quality interventions affect patterns of growth faltering across children and adolescents. Maximizing the benefits from environmental sanitation interventions requires knowing which age groups to target with which components.

#### *3.6.4 Limitations*

As with any research, this paper has important limitations. First, we were unable to model the more proximal determinants of linear growth faltering (i.e., pathogens, pollutants), having data only on distal community and household interventions. Future research on environmental sanitation and linear growth should collect data on indicators such as fecal markers and fine particulate matter levels. Second, given the rapid economic growth in China from 1989 to 2011,<sup>133</sup> it is unlikely that we were able to account for all of the potential time-varying confounders at the community level, as our community fixed effects did not account for such confounders. As previously mentioned, we caution against drawing definitively causal conclusions from our findings. Third, though the CHNS dataset is not nationally representative, by spanning multiple provinces it supports the external validity of our results. Even still, we acknowledge that China is hugely diverse in development and culture, and the results of this study cannot be easily generalized to all communities countrywide.

**CHAPTER 4 WATER, SANITATION, AND HYGIENE AMONG URBAN RECREATIONAL VEHICLE  
RESIDENTS IN SEATTLE, WA USA**

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#### **4.1 Abstract**

The growing number of people living in vehicles in the urban United States (US) in recent years has made their water, sanitation, and hygiene (WASH) situation an increasingly relevant public health issue. To our knowledge there has been no research focused on WASH among vehicle residents, including people living in recreational vehicles (RVs) who have unique access to onboard WASH facilities. This descriptive, exploratory study investigates WASH conditions among RV residents in Seattle, WA participating in the city's mobile RV wastewater pump-out program. We conducted semi-structured interviews with 31 of the program's clients and analyzed the data using qualitative content analysis. We found several similarities between RV residents and other previously researched unhoused populations with respect to water and hygiene resources, barriers, and behaviors. Differences in sanitation conditions were largely attributable to the pump-out program, though RV residents reported a low prevalence of open defecation even in its absence. Limited RV mobility (with the associated issues of the distance to RV facilities and cost of gas), parking, and maintenance were among the main barriers to participants using their onboard WASH facilities. We also observed a lack of knowledge of safe onboard water storage and greywater disposal that could pose potential health risks to residents and the public. Without being overly normative, we discuss the results and their implications for research and practice in relation to the experiences of 10 service providers involved in outreach or environmental health work in Seattle.

#### **4.2 Keywords**

Content analysis; homelessness; qualitative; vehicles

### 4.3 Introduction

For the estimated 342,400 unhoused persons in the urban United States (US),<sup>215</sup> accessing water, sanitation, and hygiene (WASH) can be challenging. The lack of a “fixed, regular, and adequate nighttime residence”<sup>215(p2)</sup> means these individuals are regularly disconnected from buildings,<sup>216</sup> where WASH infrastructure is typically located. Physical and mental health issues, which are common among people experiencing homelessness in high-income settings,<sup>217</sup> can also make it difficult to use facilities and maintain healthy WASH behaviors.<sup>218–221</sup> WASH-related issues can exacerbate such pre-existing health conditions and increase the risk of infectious and skin diseases.<sup>217,221,222</sup> While these relationships between health, homelessness, and WASH are not new discoveries,<sup>221,223</sup> the topic had received little research attention until recently. The growing interest in studying WASH among the urban unhoused has started generating evidence on the scope of the problem,<sup>218,221,224</sup> the population’s qualitative experiences,<sup>225,226</sup> and the heterogeneity of access and needs across different subpopulations.<sup>227–230</sup> Most of this literature has focused on people living in shelters, encampments, and on the streets, and to our knowledge the experiences of people living in vehicles have yet to be studied. As the number of vehicle residents in some US cities has increased in the last few years,<sup>231,232</sup> the knowledge gap has become more pronounced and their WASH situation more relevant for public health.

Vehicular homelessness is a relatively new urban phenomenon and one that likely grew during the COVID-19 pandemic, though no official statistics yet exist.<sup>233,234</sup> Broadly speaking, vehicular homelessness or vehicle residency refers to the habitation of a vehicle for shelter.<sup>235</sup> Officially, the US government defines vehicles as unfit for occupancy due to their construction properties, codes, mobility, and space limitations<sup>236–238</sup> and therefore considers vehicle residents as unsheltered homeless,<sup>215</sup> although not all residents agree with the label.<sup>235</sup> To vehicle residents, it is a form of affordable housing that allows them to avoid sleeping in shelters and on the streets<sup>239</sup> and to have more privacy, independence, and mobility. Sustaining this lifestyle requires residents to continually relocate or camouflage with other parked vehicles<sup>233,235</sup> to evade city parking citations and towing. The resulting hiddenness of people living in their vehicles<sup>234</sup> makes it complicated to conduct research on the population. Illustratively, there is no published estimate on the total number of vehicle residents in the urban US.

Among vehicle residents, people living in recreational vehicles (RVs) have the most unique WASH situation. Living in an RV such as a motorhome, camper, or fifth-wheel can in theory provide convenient access to a shower, sink, and toilet. However, maintaining functioning onboard infrastructure, especially with respect to wastewater management, can be demanding, especially for those with older vehicles and limited resources. City sanitation systems are also not designed to service vehicle residences. RV residents are entirely responsible for managing their own wastewater and may need to travel outside of a city to access waste disposal or “dump” stations (e.g., at highway rest areas or state parks). This combination of factors can lead to unsafe management of RV wastewater, which increases the risk of fecal pathogen transmission.

This study is set in the context of one US city’s response to this public health concern. In 2020 Seattle, WA began to pilot an RV wastewater pump-out program after observing a five-fold increase in reported wastewater spill incidents from 2015 to 2019,<sup>240</sup> which it attributed to the absence of a safe and legal means to dispose of RV wastewater within city limits. The program led by Seattle Public Utilities (SPU) offers a door-to-door service to collect RV wastewater free of charge and partners with community outreach workers who provide social services while waste is being pumped. Briefly, the service involves SPU visiting different areas of the city three to four times a week on a six-week rotating schedule. SPU targets areas with histories of RV wastewater spills and areas known by parking enforcement and outreach partners as having high concentrations of RVs. SPU hires a private vendor to drive a vacuum septic truck and perform the pump-outs, each of which takes approximately fifteen minutes, including traffic control and a brief survey on clients’ waste management and water access. SPU communicates about its services and schedule with the RV resident population via text messaging and flyers. In its first year, the program spent approximately \$291,000 servicing a total of 1118 RV tanks and reducing wastewater dumping from 94 reported spills in 2019 to 27.<sup>241</sup> Though there is no estimate for RV residents in particular, at that time the number of people living in vehicles in Seattle and the surrounding county had increased by approximately 28 percent, from 2147 to 2748 individuals.<sup>231</sup> In 2021, SPU also piloted a stationary pump-out service that allowed RV residents to dispose of their waste directly into the sanitary sewer. This model was not as successful as the mobile program as judged by the low attendance.

We leverage the opportunity created by this program to investigate how RV residents normally manage their wastewater and meet their other WASH needs. As an entry point into an understudied topic, we use qualitative methods to answer the question: What are the WASH experiences of people living in RVs who participate in Seattle's pump-out pilot program? We focus on documenting WASH service levels and highlighting RV-specific factors. The purpose of the study is primarily descriptive, and we avoid being overly normative in our discussion of the results. Our aim is also not to evaluate the pump-out program. We offer modest recommendations to cities interested in engaging with their RV residents and to researchers looking to study the population's WASH situation further. We base these suggestions on our findings and information from service providers involved in outreach or environmental health efforts in Seattle.

#### **4.4 Methods**

##### *4.4.1 Data collection: RV residents*

The project received approval from the University of Washington Institutional Review Board (STUDY00012853, MOD00010424) prior to data collection (Appendix 3). Data were collected through semi-structured interviews with RV residents who were primarily recruited via convenience sampling. Residents were introduced to the interviewer by SPU typically on the day their neighborhood was being serviced by the pump-out program (Figure 4.1 for the locations of the interviews across the city). Participants were individuals who had lived in a vehicle in Seattle for at least one month, were 18 years or older, and spoke English.

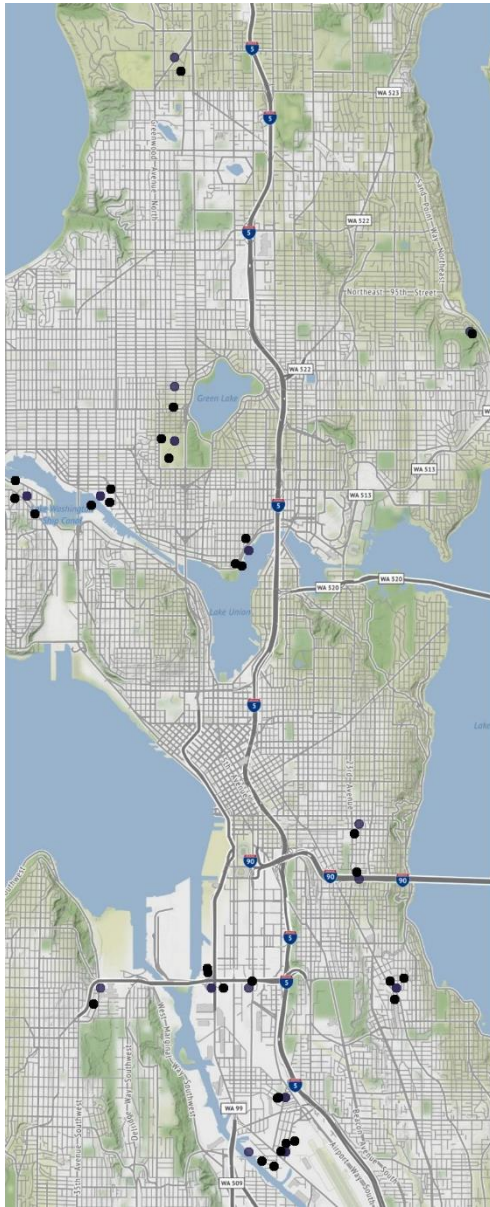
The interview protocol included questions about demographics, general information about RV living (e.g., how long they had been vehicle residents); RV wastewater dumping knowledge and practices (e.g., what they knew about where to dump and how to dump); other factors that may impact RV dumping practices; and individuals' WASH access and behaviors (e.g., where they obtain their drinking water, where they wash their hands). The protocol was developed with input from an RV resident. The full interview guide is in Appendix 3. Participants were offered a copy of a consent form outlining the study aims and were asked to give verbal consent before the interview began.

Consenting individuals were offered a small payment in exchange for their participation. Though non-

participation was not monitored, most residents who were asked agreed to participate. With the exception of one phone interview, interviews were typically 20-60-minute in-person, private conversations outside of residents' RVs. The first author audio-recorded and took notes during the discussions. A total of 31 eligible residents were interviewed from April to July 2021, which was deemed sufficient for reaching code and meaning saturation.<sup>242,243</sup>

#### *4.4.2 Data collection: Service providers*

Service providers were identified first by the authors and also later recruited based on recommendations from interviewed service providers. We recruited a wide range of individuals with diverse experiences working with people experiencing homelessness, environmental engagement including wastewater management, and other outreach activities. The participants were contacted by the first author via email, with a maximum of three contact attempts per participant. The interview protocol was more generally about vehicle residents as opposed to RV residents and included questions about the current position of interviewee; work involving vehicle residents, if any; anticipated benefits or challenges of and desired improvements to this work, if applicable; suggestions for WASH services for vehicle residents; and advice for cities with vehicle residents. Prior to the interviews, participants were read the consent form and asked to give their verbal consent. A copy of the consent form was emailed to each participant after the interview was complete. The interviews were typically 30-60-minute private conversations done through video conferencing. The first author audio-recorded and took notes during the discussions. The first author conducted 10 interviews from June to August 2021, which was considered sufficient for the purpose of guiding study recommendations. The participation rate was 10/15, or 66 percent.



**Figure 4.1. Map of Seattle marked with approximate locations of participants' RVs**

#### 4.4.3 Data processing

All interview audio was automatically transcribed with Otter.ai software.<sup>244</sup> The first author checked the quality of the automatic transcriptions by listening to the interviews and editing as needed. Transcription quality checks were selective in that the first author focused on reviewing parts of the interviews that pertained to the research question.<sup>245</sup>

For RV resident interviews only, transcripts were segmented such that a single unit of analysis was a complete answer to an interview question and its related probes. Divisions were also made when the topic changed noticeably but no new interview question had been asked.

Transcripts from service providers were not partitioned into units of analysis as we were not formally analyzing them.

We instead uploaded the interviews into qualitative analysis software,<sup>246</sup> read through each interview at least twice (once for a quality check), and selected excerpts that were related to the results of the analysis of the RV resident

interviews.

#### 4.4.4 Codebook creation

All de-identified RV resident interview transcripts were uploaded into qualitative analysis software<sup>246</sup> for codebook, or coding dictionary, creation. The first author divided the codebook into three separate categories for water, sanitation, and hygiene. Sub-categories and their operational definitions were derived from the WASH literature, primarily based on level-of-service criteria.<sup>14,247,248</sup> The criteria were combined into the five sub-categories of Accessibility, Adequacy, Reliability, Quality, and Acceptability. Each of these sub-categories was then assigned parent (super-ordinate level) codes

and typically one or more child (sub-ordinate level) codes; these codes were derived both deductively from the literature and inductively from a preliminary scan of the interview data. Parent codes were given positive and negative attributes to help differentiate between barriers and facilitators to WASH.

The first author coded all interviews at least three times using a directed content analysis approach<sup>249</sup> to refine codebook definitions, examples, and to develop the RV-specific child codes. We define a directed content analysis as a deductive content analysis with additional inductive coding that allows new child codes to emerge.<sup>250</sup> The additional subcategories of Access to information, Timescale, Energy, and participants' Suggestions also arose during this process. These multiple iterations helped familiarize the first author with the data and were also necessary given the ongoing changes being made to the coding rules. Coding rules included standards about simultaneous coding, (non)overlap between WASH categories, and assigning RV-related child codes, among other directions.

#### *4.4.5 Intercoder reliability check*

An intercoder reliability (ICR) check<sup>251–254</sup> was performed after the dictionary was refined. The purpose of the ICR check was to improve data analysis quality and comprehensibility; the focus was on consistency in the application of the codebook and not on transcript segmentation. The intercoder was a first-year public policy doctoral student at the authors' institution. This student did not have experience in qualitative coding but had almost four years of quantitative research experience. The first author chose four transcripts (13 percent of the dataset) for the ICR check based on interview quality and RV onboard WASH situation. This selection process involved organizing the thirty-two interviews into a three-by-three matrix representing the different combinations of (1) clarity and informativeness of the interview (high, medium, or low quality) and (2) participant's use of onboard WASH facilities (uses often, sparingly, or not at all/does not have). Four interviews were then chosen from the matrix entries with the highest number of interviews.

The first author trained the intercoder by reviewing the coding dictionary and rules prior to beginning the ICR check. The ICR check was an iterative process of coding and discussion. For each interview, the first author and intercoder independently applied the codebook to the four interviews

and met online to discuss coding decisions. Disagreements in coding decisions were resolved during the discussions. Disagreements were often due to one coder's inattention or to imprecise code definitions. Resolving disagreements due to imprecise code definitions involved the first author explaining what was intended by a particular code's definition and usually adding clarification to the definition of the code in a way that satisfied the intercoder.

After each round of coding the first author calculated a two-coder modified Mezzich's kappa for the ICR check summary statistic. This statistic allows more than one code to be assigned to a single unit of analysis and accounts for chance agreement between coders.<sup>255</sup> This application of Mezzich's kappa as a two-coder ICR statistic for qualitative data is a valuable methodological contribution. Mezzich's kappa was originally an interrater reliability statistic used to assess agreements in diagnoses among clinicians.<sup>255</sup> Eccleston et al. (2001) claimed to be the first to apply Mezzich's kappa to qualitative data<sup>256</sup> but not do so in a way that accorded with the original paper's logic. We along with other qualitative researchers had not recognized the discrepancies between the two papers<sup>250,253,254</sup> until we reproduced Mezzich's original calculations.<sup>257</sup> We offer a new application of Mezzich's kappa for two independent coders and clarify the differences between Eccleston et al.'s (2001) paper and the original in Appendix 3.

The final kappa value after the ICR check for the fourth interview was 0.33, which suggests low agreement.<sup>252</sup> Low agreement was due in part to the intercoder often forgetting to code Quality, Hygienic safety (Table 4.1). This category is unique in that it is based on objective engineering criteria rather than participants' subjective evaluation of WASH. Furthermore, the original coding rules allowed for more overlap between WASH categories, which often required Quality to be coded under all WASH categories. For example, a unit of analysis in which a participant discussed "showering with untreated water/outside/using a solar shower" would be coded as a Water low Quality, Sanitation low Quality, and Hygiene low Quality. That the intercoder was not a WASH researcher and the complexity of the coding rules make the omissions understandable. The first author simplified this coding rule and others during the final analysis.

**Table 4.1 Final ICR check: Agreement rates across the five most common codes**

<b>Code description</b>	<b>Coding frequency (intercoder, primary coder)</b>	<b>Agreement rate</b>
Quality, hygienic safety, treatment	8 occurrences, 13 occurrences	Agreed on 7
Quality, hygienic safety, risk of disease	9, 12	7
Adequacy, diversification	3, 5	2
Energy	3, 1	0
Accessibility, economic, RV-related	2, 3	2

Note: Table adapted from Burla et al. 2008.<sup>253</sup>

### *Final analysis*

The first author applied the final coding dictionary to the data in a deductive content analysis. The final codebook with the latest coding rules (Appendix 3 Table A2) and an outline of the dictionary are in Appendix 3. Table 4.2 shows the high-level relationships between categories, sub-categories and parent codes in the final dictionary. Note that the subcategory Reliability is now Availability. As this and other changes to the codebook and coding rules were made after the final ICR check, another ICR check will be completed prior to the publication of this study. The intercoder will code another four transcripts, and Mezzich's kappa will be recalculated. While the paper's findings are unlikely to change substantially, we ask that any references to this work be made to the final publication rather than to this dissertation.

**Table 4.2 Level-of-service framework: Final coding dictionary**

<b>Subcategory</b>	<b>Definition</b>	<b>Parent code</b>	<b>Child code(s)</b>
Accessibility	Able to be accessed	Physical	Time or distance, energy expenditure, RV issues
		Economic	Non-RV costs, RV costs
		Social	Sharing, socially reciprocal behaviors, community service, status, illegal practices, RV issues
Adequacy	Sufficient amount	Amount of facilities	Non-RV facilities, RV facilities
		Diversification	Mentions diversification
		Consumption	Mentions preserving/minimizing consumption
		Storage	Non-RV issues, RV issues
Availability	Available when needed	Operation	Non-RV issues, RV issues
		Competition	Number of users, behavior of users, RV issues
		Hygienic safety	Treatment, risk of disease, cleanliness, RV issues
Quality	Fit-for-use, functions as designed, and does not pose health risks	Technical quality	Non-RV issues, RV issues
		Cultural perceptions	Gender norms, privacy norms, other social norms, RV issues
Acceptability	Culturally palatable and comfortable to the user	Personal preferences	Non-organoleptic experiences, organoleptic experiences, RV issues
Timescale	Influence of time period on WASH	Pandemic	Mentions influences of pandemic on WASH
Energy	Association between energy and WASH	Seasons	Mentions influence of seasons or weather on WASH
Access to information	Obtaining knowledge about WASH	Energy	Mentions energy
		Where	Mentions source
Suggestions	Recommendations on how to improve WASH situation or the interview	How much	Knowledgeable, not knowledgeable
		Suggestions	Mentions suggestion

Note: The contents of the table apply to each of the water, sanitation, and hygiene categories.

## 4.5 Results

This section details the findings from the deductive content analysis using the deductively and inductively derived WASH level-of-service framework. The results are presented in Tables 4.4-4.6 and described separately for water, sanitation, and hygiene, following the nonoverlapping nature of the analysis. We examine all nine subcategories for each of the three WASH categories, with the focus being on the child codes with the highest numbers of respondents (second columns in Tables 4.4-4.6). We foreground RV-specific WASH issues by only featuring quotations related to RV living.

Despite interpreting higher-frequency codes as representing the most prevalent experiences, we recognize that code frequencies are also a consequence of interview structure and coding decisions. For example, the relatively higher coding frequencies under sanitation compared to water and hygiene are due in part to the interview's focus on sanitation, namely on the residents' participation in the pump-out program. Similarly, the high frequencies under the Quality subcategory are largely a result of the decision to code Hygienic safety based on objective engineering criteria rather than on participants' subjective evaluations, meaning our labels of “safe” or “unsafe” may not always represent RV residents' perceptions of their WASH experiences. This decision also meant that units of analysis in which a WASH resource was simply identified could be coded under Quality but often not another subcategory unless a clear comment on or assessment of the resource was also provided. These sources of bias are characteristic of qualitative research, and given the exploratory nature of the research are not overly consequential. Nevertheless, we still try to view the frequencies as starting points and not limit our review of the results to only high-frequency codes. By highlighting less-common codes we also capture some of the heterogeneity of WASH conditions.

### 4.5.1 Demographics

**Table 4.3 Demographic characteristics**

<b>Demographic characteristic</b>	<b>Value(s)</b>
Age	Mean: 50 years, Range: 29 years to 76 years
Sex	19 males, 13 females
Ethnicity	19 White, 3 Hispanic, 4 Native or Pacific Island, 4 Black, 2 Other
Length of vehicle residency	Mean: 4.7 years, Range: 2 months to 41 years
Length of time in current RV	Mean: 2.4 years, Range: 1 month to 27 years
RV mobile?	14 no, 17 yes, 1 unknown

Note: One interview was with a co-habiting male-female couple (hence, there is demographic information for 32 individuals); other than for the demographic information, this couple is counted as “one participant.”

Table 4.3 displays the demographic information we collected from our participants. We conducted a total of 31 interviews with 32 participants who provided demographic information. The majority were middle-aged, White men who had lived in a vehicle for four to five years. The average length of residency in participants' current RVs was about half as long as the mean total length of vehicle residency (2.4 versus 4.7 years). Fourteen interviewees' RVs were immobile at the time of the interview, and seventeen were mobile (sixteen if the male-female couple is counted as one interview). No other demographic items were collected.

#### 4.5.2 Water

**Table 4.4 Frequencies of codebook elements for water**

Water	Number of participants	Number of occurrences
<i>Accessibility</i>	30	185
<b>Physical, convenient</b>	22	32
Energy, convenient	6	7
Time or distance, convenient	17	21
RV-related, convenient	4	4
<b>Physical, inconvenient</b>	15	27
Energy, inconvenient	11	13
Time or distance, inconvenient	6	7
RV-related, inconvenient	7	7
<b>Economic, expensive</b>	7	12
Non-RV-related costs, expensive	6	8
RV-related costs, expensive	2	4
<b>Economic, inexpensive</b>	4	4
Non-RV-related costs, inexpensive	3	3
RV-related costs, inexpensive	1	1
<b>Social, benefits from/participates in</b>	25	88
Community service, benefits from	11	14
Illegal practices, benefits from	19	40
Sharing, benefits from	16	24
Socially reciprocal behaviors, benefits from	2	3
RV facilities, benefits from	6	7
<b>Social, does not benefit from/participate in</b>	16	22
Community service, does not benefit from	2	3
Illegal practices, does not benefit from	8	8
Sharing, does not benefit from	7	8
Socially reciprocal behaviors, does not benefit	1	1
RV facilities, does not benefit from	1	2
<i>Adequacy</i>	30	69

<b>“Amount” of facilities, enough</b>	2	2
Non-RV-related facilities, enough	2	2
<b>“Amount” of facilities, not enough</b>	7	9
Non-RV-related facilities, not enough	3	4
RV-suitable facilities, not enough	4	5
<b>Consumption, moderates</b>	7	7
Non-RV-related issues, moderates	7	7
<b>Diversification, yes</b>	26	45
<b>Storage, enough</b>	3	3
Non-RV/non-tank-related issues, enough	3	3
<b>Storage, not enough</b>	4	4
Non-RV/non-tank-related issues, not enough	3	3
RV-related/tank-related issues, not enough	1	1
<i>Availability</i>	17	37
<b>Competition, does not exist</b>	3	3
Number of users, no competition	3	3
<b>Competition, exists</b>	9	15
Behavior of users, competition exists	5	6
Number of users, competition exists	5	6
RV-related issues, competition exists	2	3
<b>Operation, continuous</b>	6	7
Non-RV-related issues, continuous	5	6
RV-related issues, continuous	1	1
<b>Operation, discontinuous</b>	8	11
Non-RV-related issues, discontinuous	8	10
RV-related issues, discontinuous	1	1
<i>Quality</i>	31	273
<b>Hygienic safety, adequate</b>	31	152
Cleanliness, adequate	3	3
Risk of disease, adequate	30	76
Treatment, adequate	27	64
RV-related issues, adequate	7	9
<b>Hygienic safety, inadequate</b>	22	110
Cleanliness, inadequate	6	8
Risk of disease, inadequate	21	45
Treatment, inadequate	21	43
RV-related issues, inadequate	8	14
<b>Technical quality, adequate</b>	7	7
Non-RV-related issues, adequate	4	4
RV-related technical issues, adequate	3	3
<b>Technical quality, inadequate</b>	4	4
Non-RV-related issues, inadequate	1	1
RV-related technical issues, inadequate	3	3
<i>Acceptability</i>	8	14
<b>Personal preferences, satisfactory</b>	5	8
Organoleptic, satisfactory	2	2
Non-organoleptic, satisfactory	4	5

RV-related, satisfactory	1	1
<b>Personal preferences, unsatisfactory</b>	5	6
Organoleptic, unsatisfactory	1	1
Non-organoleptic, unsatisfactory	3	3
RV-related, unsatisfactory	2	2
<i>Timescale</i>	5	6
<b>Seasons</b>	5	6
<i>Energy</i>	10	13
<i>Access to information</i>	15	30
<b>How much</b>	15	24
Knowledgeable	9	13
Not knowledgeable	8	11
<b>Where</b>	5	6
<i>Suggestions</i>	8	9

Note: The child codes that do not appear in the table but are present in the codebook are those that were not assigned any content during the analysis.

We begin with the Accessibility of water and its physical, economic, and social parameters. Here, water refers to water used for drinking and domestic purposes and not for personal hygiene. In general, RV residents access water resources that are close to their parked vehicles (n = 17 residents), especially exterior spigots on nearby commercial buildings, industrial warehouses, or residences (n = 14). Even for those parked near a water source, hauling water and/or handling large water jugs can be labor-intensive (n = 7). The main RV-specific physical inconveniences are the distance to a tank-filling station (*"I would actually go and they actually had a couple of waste places where you can empty it, fill your water back at it...but it was like pretty far away,"* Participant 23, female, more than ten years of vehicle residency), the difficulty of maneuvering an RV around the city (*"Now I know up here there's a campsite and they have running water for some sinks, but you can't get your RV to it,"* Participant 12, male, less than one year), the limited mobility of the vehicle (*"There is a tank for [water] but because we are not mobile it's not being used but if we were mobile, we would use it,"* Participant 5, female, 4-6 years), and the time or energy needed to manage the onboard tank (*"Yeah, I mean, [the tank] becomes heavy and you have to maintain it, you have to clean it. So I just skip that,"* Participant 10, male, 7-9 years). The inaccessibility of tank-filling stations was also expressed as an Adequacy issue (n = 4), as explained by one participant, *"You have almost 100-gallon tank on there that holds water but there's no place to fill it up"* (Participant 28, male, 1-3 years). Participants did not mention many economic factors except for the expense of bottled water (n = 6). Stealing, sharing, and/or community services are common ways participants acquire water. Nineteen

interviewees reported illegally accessing water, primarily from exterior building taps at night. Several participants (n = 10) benefit from friends sharing water or businesses giving them permission to draw from external faucets. Six participants receive water handouts from charitable organizations, two purchase water through a food bank or food-stamp program, and only one avails herself of a park's public water supply.

The majority of participants (n = 26) rely on multiple sources of water (Adequacy). Fifty-five percent of RV residents have used at least one illegal source, with the rest depending on multiple legal resources. Some participants (n = 7) alluded to water conservation, including minimizing their own consumption or being protective about how others use their shared resources. The primary water Availability issues are unrelated to RV living and are instead associated with the unreliability of shared sources (n = 8) that suddenly become inaccessible often due to overuse or misuse by others (n = 5). These shared resources include public bathroom faucets, illegally accessed spigots, or exterior taps that businesses have given residents permission to access.

Most interviewees who were asked do not have difficulty finding clean drinking water and/or have not had a waterborne illness (Quality, n = 19). Two participants recounted stories of exterior tap water quality problems. Bottled water is common (n = 20), as is drinking water drawn from exterior building faucets (n = 17). Three participants regularly fill their holding tanks with water from external spigots. Five participants who drink water from external taps reported boiling or filtering their water prior to consumption. Though only two participants explicitly mentioned their distrust of external tap water, at least a few others seemed concerned with its quality given their choices to not drink or cook with it. The predominant RV-specific Acceptability issues center on the cleanliness of onboard water systems. Among the five participants who reported using their water tanks, four commented on its maintenance. For example, *"It's a yeah it's more about how how to store the water so that it remains drinkable so like I was saying it's it's the tanks that are built into the system it's the possibility that water is either going to be contaminated by bacteria or an antibacterial agent"* (Participant 36, female, 1-3 years). Holding tank maintenance and filling procedures were generally points of confusion (Access to information, n = 4): *"...When we went to the facility when we took it to go dump it has*

*water there so we did fill up our tanks but...I don't think I filled them right...Because they didn't last they didn't go very long"* (Participant 16, male-female couple, 4-6 years).

Most participants did not indicate any seasonal or pandemic-related effects to their water situations (n = 5), though one participant does harvest rainwater for his domestic water supply, and another remarked on a park's water fountain being unavailable during the winter (Timescale). Participants mainly discussed Energy (n = 10) in terms of boiling or heating water and gas, batteries, and/or electricity for their onboard water systems to function (*"I have my extra, my water tank is full, but I can't use it cuz I don't have electricity to run the pump,"* Participant 13, female, 1-3 years). A few participants recommended ways the city could improve their water situation such as *"... There's no reason the port can't let somebody drives up in the RV. Sure, fill up their water and drive away, and no parking in the parking lot or on the premises,"* Participant 12, less than one year). Two participants suggested that the interview incorporate questions on waterborne diseases and water for pets (Suggestions).

#### 4.5.3 Sanitation

**Table 4.5 Frequencies of codebook elements for sanitation**

Sanitation	Number of participants	Number of occurrences
<i>Accessibility</i>	31	374
<b>Economic, expensive</b>	9	15
Non-RV-related costs, expensive	1	1
RV-related costs, expensive	8	14
<b>Economic, inexpensive</b>	19	25
Non-RV-related costs, inexpensive	1	1
RV-related costs, inexpensive	18	24
<b>Physical, convenient</b>	14	23
Time or distance, convenient	9	14
RV-related, convenient	7	9
<b>Physical, inconvenient</b>	24	64
Energy, inconvenient	11	15
Time or distance, inconvenient	14	19
RV-related, inconvenient	21	30
<b>Social, benefits from/participates in</b>	29	149
Community service, benefits from	16	26
Illegal practices, benefits from	17	30
Sharing, benefits from	20	40
Socially reciprocal behaviors, benefits from	2	3

Status, benefits from	1	2
RV facilities, benefits from	22	48
<b>Social, does not benefit from/participate in</b>	27	98
Community service, does not benefit from	4	4
Illegal practices, does not benefit from	22	32
Sharing, does not benefit from	15	20
Status, does not benefit from	2	3
RV facilities, does not benefit from	18	39
<i>Adequacy</i>	29	125
<b>“Amount” of facilities, enough</b>	6	7
Non-RV-suitable facilities, enough	5	6
RV-suitable facilities, enough	1	1
<b>“Amount” of facilities, not enough</b>	13	21
Non-RV-suitable facilities, not enough	8	13
RV-suitable facilities, not enough	7	8
<b>Consumption, moderates</b>	10	13
Non-RV-related issues, moderates	1	1
RV-related issues, moderates	9	12
<b>Diversification, yes</b>	30	71
<b>Storage, enough</b>	4	6
RV-related/tank-related issues, enough	4	6
<b>Storage, not enough</b>	9	10
RV-related/tank-related issues, not enough	9	10
<i>Availability</i>	21	53
<b>Competition, exists</b>	10	12
Behavior of users, competition exists	9	9
Number of users, competition exists	2	2
RV-related issues, competition exists	1	1
<b>Operation, continuous</b>	8	11
Non-RV-related issues, continuous	4	4
RV-related issues, continuous	4	7
<b>Operation, discontinuous</b>	16	30
Non-RV-related issues, discontinuous	11	15
RV-related issues, discontinuous	11	15
<i>Quality</i>	31	389
<b>Hygienic safety, adequate</b>	30	252
Cleanliness, adequate	5	5
Risk of disease, adequate	30	104
Treatment, adequate	30	89
RV-related issues, adequate	25	54
<b>Hygienic safety, inadequate</b>	22	78
Cleanliness, inadequate	4	6
Risk of disease, inadequate	21	36
Treatment, inadequate	16	23
RV-related issues, inadequate	10	13
<b>Technical quality, adequate</b>	21	29
Non-RV-related issues, adequate	1	1

RV-related technical issues, adequate	20	28
<b>Technical quality, inadequate</b>	19	30
Non-RV-related issues, inadequate	1	1
RV-related technical issues, inadequate	19	29
<i>Acceptability</i>	28	146
<b>Cultural perceptions, inappropriate</b>	8	17
Gender norms, inappropriate	2	2
Other social norms	5	8
Privacy norms, inappropriate	5	5
RV-related issues, inappropriate	2	2
<b>Personal preferences, satisfactory</b>	22	73
Organoleptic, satisfactory	8	8
Non-organoleptic, satisfactory	19	30
RV-related, satisfactory	20	35
<b>Personal preferences, unsatisfactory</b>	17	55
Organoleptic, unsatisfactory	12	21
Non-organoleptic, unsatisfactory	9	13
RV-related, unsatisfactory	15	21
<i>Timescale</i>	7	11
<b>Pandemic</b>	7	11
<i>Energy</i>	5	6
<i>Access to information</i>	31	141
<b>How much</b>	31	87
Knowledgeable	23	46
Not knowledgeable	28	41
<b>Where</b>	28	54
<i>Suggestions</i>	10	18

Note: The child codes that do not appear in the table but are present in the codebook are those that were not assigned any content during the analysis.

Similar to water resources, RV residents indicated using bathroom facilities close by their parked vehicles (Accessibility, n = 9). Six participants suggested that the mobility of their RV would not prevent or has not prevented them from disposing of their fecal waste in the absence of the pump-out program (“*Yeah but I don't have a problem with with going and dumping wherever because my RV runs fine. I can actually drive it no problem, it goes down the road no problem,*” Participant 28, male, 1-3 years). Other mobility barriers (n = 5) include physical disabilities (“*I can drive I just don't drive very well because I can't see right and my equilibrium is off...*,” Participant 13, female, 1-3 years) and parking (“*See the problem with leaving, is that if you move from this spot, somebody else can move right back in while you're going to get it dumped,*” Participant 8, male, 4-6 years). Some participants (n = 8) think the available dump stations are far (“*Well yeah, [the pump-out program] is better than driving all the way to Everett...And then have to go get off the freeway and turn around and come*”

*back on the freeway southbound it's like 20 miles from here to Everett,*" Participant 3, female, 7-9 years), which two residents implied was also the case for RV parts stores (*"Yeah, [I] got to go all the way up to Shoreline [to buy gate valves] or I can get them off Amazon,"* Participant 19, male, 4-6 years). Fifty-eight percent of RV residents who were asked have spent or would spend little to no money disposing of their waste if the pump-out program were not operating; eleven have used or would use highway rest areas, which are typically free (*"There's a place in Tukwila and it's open on Sundays...they let you drain your trailer for free,"* Participant 35, female, 4-6 years). The costs of gas and tank maintenance (*"I can't really afford to get repairs, even if I have somewhere to take it to,"* Participant 36, female, 1-3 years) are the predominant sanitation-related RV expenses (n = 8).

Participants also use public portable toilets, park or community center restrooms, and/or campground or state park sanitation facilities (n = 11). Fifty-five percent of RV residents reported engaging in or being willing to engage in some illegal behavior; including open defecation (n = 4 when it is unclear if they dispose of the excreta afterward); dumping wastewater down drains, into sewer manholes, or onto streets (n = 4) (*"I would pull off [my RV] on a dirt road and I would dump it,"* Participant 25, male, 7-9 years); publicly urinating or collecting and disposing of urine outside (n = 13); throwing away bags of excreta (n = 6); and/or accessing private bathroom facilities (n = 4). At the time of their interview, fifteen residents were not improperly disposing of their RV blackwater (*"No, because I wouldn't know where it [a drain] goes. I might want to drink that water. I don't know what, I don't know about the drains, but I know that a porta potty can takes that kind of stuff so I that's what I would do,"* Participant 24, female, less than one year), and twelve had not practiced open defecation or if they had defecated outside they disposed of it afterward. Nine interviewees share their RV toilet with only one other person, while fourteen were not sharing their onboard sanitation facilities with anyone at the time of their interview (*"I used to have a lot of buddies and stuff come over and my tank would last maybe three weeks before it'd just get really full...Now I don't allow nobody over..."*, Participant 8, male, 4-6 years). Some participants (n = 7) also rely on friends' or family members' bathrooms, a few being RV residents themselves.

Among those interviewees who commented on the Adequacy of the city's sanitation, four described at least some aspect as sufficient, while eight do not think there are enough reliable bathrooms. RV-

specific infrastructure were also considered to be lacking (n = 7), both RV parts stores and wastewater dump stations (*"Because there is no dump around here,"* Participant 10, male, 7-9 years). Nine participants discussed ways they minimize the use of their onboard toilet, including using other bathrooms whenever possible (*"Do as much outside of my RV as possible when it comes to using the restroom so I don't fill up my tanks. You know, just being intentional about it,"* Participant 14, male, less than one year), not disposing of toilet paper in the toilet (*"I don't use toilet paper in it because it builds up too much takes up too much extra room. So I just put it in the waste bin,"* Participant 26, male, 1-3 years), and not sharing with others (*"I don't use a bathroom. I try not to... You know, and I've been not really letting people use it. You know I mean, in the middle of the night, you got to get up and pee, you know? Yeah, because Fred Meyers ain't open and sometimes you just got to be pee so bad you can't make it. And you just gotta go. And, you know. I pee outside on the curb late at night,"* Participant 2, male, 1-3 years). Twenty-five participants depend on both their RV toilet and at least one other bathroom external to their vehicle; three residents do not currently use their onboard toilet. Ten residents referred to multiple dump stations that they have utilized or would utilize if the pump-out program were not running. Unlike for water, several participants commented on their onboard storage of wastewater (n = 9), including the tank's technical quality (*"I was scheduled for a [stationary pump-out appointment]...however I cancelled because I don't have any bales to hold anything in my holding tanks anyways at the moment,"* Participant 19, male, 4-6 years) and fill rate/size (*"Yeah I mean with constant use and the wrong kind of toilet paper it fills up fast,"* Participant 16, male-female couple, 4-6 years).

Having sanitation facilities that are available when needed is a challenge for some RV residents. Both the number and behavior of others are seen as threats to the sustainability of sanitation resources (n = 9), especially bathrooms at businesses whose availability was further limited by the COVID-19 pandemic (Timescale, n = 5). A few participants commented on limited business hours and nighttime bathroom availability. Most participants did not comment on the Availability of the pump-out program and frequency of service; among those who did, four think it is sufficient while three are dissatisfied. In general, most participants are pleased with the program, and sixteen articulated the reason(s) for their satisfaction, including the program's customer service (*"The people in the truck are usually extremely nice. And they get their job done really fast. [The coordinator]...he's*

really nice. On one time he came by and gave us a pizza," Participant 5, female, 4-6 years), the sanitation-related information it offers (*"But uh, I love it, they're knowledgeable. I mean I was thinking about pouring my peepee down the drain over here but he said, you can't really do that because you don't know whether it's a main sewer or rain runoff..."*, Participant 11, male, less than one year), and the convenience it provides to those who have difficulty moving their RV (*"Oh, they are absolutely amazing. Life would be so much, so much different without them. As far as for me...I can't roll up and down the street with this thing I can't it anywhere to dump it out,* Participant 34, female, 1-3 years). Only one participant mentioned attending the program's stationary pump-out event (*"Yeah, yeah. In front of the Ballard market. That was that was cool. I mean, they had they had the road shut off they had us pull up. That was it...I mean, and then and then later that day, [the program coordinator] showed up here after they went back to work. And he he had a pizza pepperoni pizza for us that I guess because we were like maybe one of three people that showed up over there,"* Participant 3, female, 7-9 years).

In the past or if the pump-out program were not operating, eighteen participants would dispose of their blackwater at a dump station (Quality). Leaking tanks (n = 7) and other broken components (n = 7) of onboard sanitation systems are fairly common, though a similar number of respondents reported having no active leaks (n = 9). Thirty-nine percent of interviewees mentioned maintaining their tanks with enzyme treatments. Most RV residents (Access to information, n = 18) have some knowledge of tank maintenance (*"Yeah I fixed the leaks it had when I got it,"* Participant 1, male, less than one year), and several (n = 11) also search online or ask someone for help. Men are more likely than women to have repaired or be able to repair their tanks (14 out of the 18 men compared to 2 out of the 11 women), which some men attributed to past experiences living in RVs, work experience, or general handyman skills. However, the differences in ability across residents do not consistently coincide with length of vehicle residency. For example, at the time of the interview Participant 23 had lived in vehicles for over ten years and in her current RV for five years, yet said, *"I have no clue...No, none whatsoever"* when it came to repairing her sanitation system. Twelve alluded to receiving maintenance instruction from the pump-out program. Women in particular (8 of the 12) seem to rely heavily on the program for advice: *"[The program coordinator] just tells me what to do. He put water in there... put the blue tab things... Right now I need a part because it broke,"* Participant 21, female, 1-3

years. Ten participants were interested in additional tank maintenance education from the program. The majority of participants (n = 22) do not seem to know much about the program's operation (*"I know that they pump out when they come by, that's all I know. That's all I know and I don't know much of anything else. I heard that they may help with registration of vehicles if, if needed, possibly, I don't know, but it may be a different,"* Participant 33, male, 1-3 years). Several (n = 6) participants demonstrated an awareness of environmental contamination from feces and the importance of properly disposing of RV wastewater (*"Well the [pump-out program] that's a big, big plus too because there's too many laws against dumping it in just any old place you want to. I'm not gonna do that. Like I said I appreciate the environment I got the reason I try to keep it as clean as I can so,"* Participant 26, male, 1-3 years). Six participants expressed uncertainty about the dump sites available to them (*"I'm sure there is [a dumping station] somewhere, there's like rest areas and stuff. I'm not originally from Seattle and I'm directionally challenged. It takes me a long time to know my way around somewhere to know where stuff is,"* Participant 7, female, unknown).

The main suggestion by RV residents to improve their sanitation situation was for more portable toilets (in combination with solid waste bins) around the city, especially in areas with high concentrations of tents and RVs (n = 6).

#### 4.5.4 Hygiene

**Table 4.6 Frequencies of codebook elements for hygiene**

Hygiene	Number of participants	Number of occurrences
<i>Accessibility</i>	29	141
<b>Economic, expensive</b>	9	14
Non RV-related costs, expensive	9	12
RV-related costs, expensive	1	2
<b>Economic, inexpensive</b>	5	5
Non-RV-related costs, inexpensive	5	5
<b>Physical, convenient</b>	12	17
Energy, convenient	1	1
Time or distance, convenient	11	14
RV-related, convenient	2	2
<b>Physical, inconvenient</b>	10	20
Energy, inconvenient	8	10
Time or distance, inconvenient	5	5
RV-related, inconvenient	5	5

<b>Social, benefits from/participates in</b>	27	73
Community service, benefits from	17	19
Illegal practices, benefits from	10	18
Sharing, benefits from	19	28
Socially reciprocal behaviors, benefits from	3	3
Status, benefits from	1	1
RV facilities, benefits from	3	4
<b>Social, does not benefit from/participate in</b>	8	12
Community service, does not benefit from	2	2
Illegal practices, does not benefit from	3	4
Sharing, does not benefit from	3	4
RV facilities, does not benefit from	2	2
<i>Adequacy</i>	25	62
<b>“Amount” of facilities, not enough</b>	5	5
Non-RV-related facilities, not enough	4	4
RV-suitable facilities, not enough	1	1
<b>Consumption, moderates</b>	3	3
Non-RV-related issues, moderates	2	2
RV-related issues, moderates	1	1
<b>Diversification, yes</b>	25	47
<b>Storage, enough</b>	2	2
RV-related/tank-related issues, enough	2	2
<b>Storage, not enough</b>	5	5
RV-related/tank-related issues, not enough	5	5
<i>Availability</i>	9	11
<b>Competition, exists</b>	2	2
Behavior of users, competition exists	1	1
Number of users, competition exists	1	1
<b>Operation, continuous</b>	4	4
Non-RV-related issues, continuous	3	3
RV-related issues, continuous	1	1
<b>Operation, discontinuous</b>	4	5
Non-RV-related issues, discontinuous	4	5
<i>Quality</i>	29	222
<b>Hygienic safety, adequate</b>	28	121
Risk of disease, adequate	28	64
Treatment, adequate	28	54
RV-related issues, adequate	3	3
<b>Hygienic safety, inadequate</b>	24	81
Cleanliness, inadequate	2	2
Risk of disease, inadequate	24	54
Treatment, inadequate	10	16
RV-related issues, inadequate	7	9
<b>Technical quality, adequate</b>	10	12
Non-vehicle-related issues, adequate	6	7
RV-related technical issues, adequate	4	5
<b>Technical quality, inadequate</b>	6	8

	Non-RV-related issues, inadequate	3	3
	RV-related technical issues, inadequate	5	5
<i>Acceptability</i>		22	47
	<b>Cultural perceptions, appropriate</b>	1	1
	Privacy norms, appropriate	1	1
	<b>Cultural perceptions, inappropriate</b>	10	11
	Other social norms	9	9
	Privacy norms, inappropriate	2	2
	<b>Personal preferences, satisfactory</b>	13	17
	Organoleptic, satisfactory	7	7
	Non-organoleptic, satisfactory	6	7
	RV-related, satisfactory	3	3
	<b>Personal preferences, unsatisfactory</b>	12	18
	Organoleptic, unsatisfactory	6	6
	Non-organoleptic, unsatisfactory	7	9
	RV-related, unsatisfactory	3	3
<i>Timescale</i>		8	11
	<b>Pandemic</b>	6	6
	<b>Seasons</b>	4	5
<i>Energy</i>		7	17
<i>Access to information</i>		9	16
	<b>How much</b>	9	13
	Knowledgeable	5	7
	Not knowledgeable	6	6
	<b>Where</b>	3	3
<i>Suggestions</i>		6	6

Note: The child codes that do not appear in the table but are present in the codebook are those that were not assigned any content during the analysis.

Just as with water and sanitation, so RV residents access hygiene resources that are nearby their parked vehicle, including showers, laundry facilities, handwashing stations, and/or water resources for personal hygiene (Accessibility, n = 11). A few think the distance to laundry or shower facilities is far. Participants mentioned a variety of physical inconveniences associated with personal hygiene (n = 8), such as carrying water, handling unwieldy water jugs especially when trying to wash their hands, or driving and parking their vehicle when going to do laundry. Eight participants have showered in their RVs, and a few found it inconvenient: *“Honestly like it was super stressful, because first of all there, there’s not enough water in the tank. You know, I had to run out. Or someone ran out, put more water into the thing. And it’s kind of a waste of time, really, to do that...I mean there has to be an easier way to do it you know like transfer it. But I wouldn’t know”* (Participant 15, female, less than one year). While participants did not mention any major RV-related hygiene expenses, laundry is costly for some (n = 7).

Participants depend on family and friends for access to showers (n = 13), laundry facilities (n = 10), and water for personal hygiene (n = 3). A few commented on feeling uncomfortable imposing on their friends. Nine participants mentioned frequenting community centers and hygiene facilities for people experiencing homelessness. One resident mentioned showering at a pop-up hygiene trailer provided by the city as part of its pandemic response (Timescale) and expressed dissatisfaction with its temporary nature (Availability). Some (n = 5) receive clothing and hygiene supply donations from charitable organizations. Ten participants reported engaging in or being willing to engage in illegal activities such as dumping greywater outside, stealing water for showering in their RV, gaining unauthorized access to private shower or laundry facilities, and wearing clothes stolen by friends (Accessibility). Most RV residents who were asked do not shower in their vehicles (n = 23), which a few attributed to the small size of their greywater tank (*"Because this greywater is the way, the holding tank is pretty small, and that would require this too much water. Probably after I use it for probably dump it out. And I don't do that,"* Participant 29, male, 1-3 years) (Adequacy) or to the difficulty of filling the water holding tank (*"See, we can't shower in these RVs because we don't have water in our tanks, you can buy gallons of water all you want, but to take gallon by gallon to fill your tank would take all day...there's not really any places that I found...that you could fill up your tank with water,"* Participant 28, male, 1-3 years) (Accessibility, Adequacy). As the majority of RV residents use laundry and shower facilities outside of their vehicles, their greywater is typically given the opportunity for treatment (Quality).

The majority of participants (Adequacy, n = 25) rely on multiple hygiene resources. Factors such as parking location, finances, and water accessibility influence residents' personal hygiene choices (e.g., Hand laundry or laundromat? Personal cleansing wipes, a sponge bath, or full shower?). Hand sanitizer is common (n = 10). Only one participant mentioned an RV-specific hygiene Availability issue related to the frequency of the pump-out program: *"...I have it a good situation where my friend let's meet take showers in their house so because I'm able to shower at their place my greywater tank doesn't fill up...because of that having them come once a month or every six weeks it's perfectly fine for me"* (Participant 36, female, 1-3 years).

Among those who were asked, 14 participants reported not showering every day, and 10 said they do not do their laundry regularly, often with several weeks in between loads. About 48 percent of interviewees were considered as having poor hand hygiene, and some residents commented on their hands being dirty. For example, one participant remarked: *“I try to keep my hands clean all day long. I don't know why your hands get dirtier living in an RV than they would in a house but your hands get dirtier. I don't know why”* (Participant 27, male, 4-6 years). Ten participants have used untreated or otherwise unsafe (often illegally tapped) water for showering or sponge baths. Six have disposed of or would be willing to dispose of greywater on the ground, three of these being RV residents who shower in their RVs. A few participants believe (Access to information) it is safe to dump greywater on the ground or down stormwater drains (*“So the only way that shower water or sink water can be dumped out on the grass, or the streets is if it's not been held at all. So you basically, you know, you'd have to leave the valves completely open,”* Participant 19, male, 4-6 years). Five residents mentioned broken parts in relation to their onboard hygiene systems (*“There is a shower in there. I just have to get the freshwater tank up and running. [The previous owners] ripped it out,”* Participant 32, male, 4-6 years).

Some participants alluded to cultural norms around personal hygiene (n = 5) and being perceived as unclean (Acceptability). A few participants linked their hand hygiene habits to the COVID-19 pandemic. Four participants mentioned seasonal changes to their personal hygiene, two of which have a solar shower for the summer months (Timescale and Energy). Other examples of energy-related hygiene matters (n = 7) include heating water with propane or using a generator to operate a personal washing machine. Suggestions for improving their hygiene situation (n = 6) were primarily centered on showers (n = 5), including having more convenient access to portable shower trailers.

#### **4.6 Discussion**

WASH conditions among urban vehicle residents have become increasingly relevant for public health with the growth of the population in recent years.<sup>231,232</sup> The objective of the study was to describe the WASH experiences of people living in RVs in Seattle, WA. We interviewed 31 clients of the city's door-to-door wastewater pump-out program and analyzed the data using content analysis. The analysis characterized RV residents' level of service primarily in terms of Accessibility, Adequacy,

Availability, Quality, and Acceptability, Timescale, and Energy. The results provide the first in-depth look at RV residents' WASH conditions from their perspective. In the discussion below we compare our findings to those in the existing literature on WASH and homelessness, though mainly focus on the unique, RV-specific WASH conditions where the contribution of our paper lies. We use insights from interviews with 10 service providers to help interpret the results and inform our guidance for WASH practice and research.

#### *4.6.1 Water*

RV residents' water situation resembles that of other unhoused populations in terms of resources, barriers, and behaviors. Sheltered and unsheltered homeless alike rely on bottled water, both purchased and charitable donations,<sup>227,258</sup> and acquire drinking and domestic water through illegal or informal ways such as through fire hydrants<sup>229</sup> and exterior building spigots.<sup>258</sup> These types of water infrastructure may not meet national engineering codes for plumbing<sup>259</sup> and water quality<sup>260</sup> and can expose residents to harmful chemical, biological, and metal contaminants (Quality). The physical isolation of unhoused populations can also be a barrier to accessing water resources. Unsheltered persons living in secluded encampments<sup>226,227,230,258</sup> are similar to our RV residents, many of whom live in the industrial sections of the city with the majority of oversized-vehicle parking spaces. These remote locations are often sparsely populated and may not have parks and grocery stores nearby, leaving unconventional water resources the most convenient, affordable options (Accessibility). Water Availability for RV residents was primarily an issue of the unavailability of these unconventional sources due to competition as opposed to an issue of limited business or public facility hours of operation as was found for the unhoused in Los Angeles, CA.<sup>229</sup> Similar to other populations,<sup>227</sup> our participants modified their water use in response to uncertainty or to a general lack of water, including minimizing their own consumption and being protective about how others used their shared resources (Adequacy).

Many RVs are outfitted with water systems, including pumps, hoses, faucets, and tanks that offer residents an opportunity for convenient access to running water. The majority of our participants were not using their onboard water systems at the time of their interview, which explains some of the aforementioned similarities to other unhoused populations. We found that uncertainty and effort

around tank management, limited vehicle mobility (including gas and battery issues), and distance to water-tank filling stations were impediments to residents regularly using their systems (Access to information and Accessibility). The small number of participants that used their onboard system still demonstrated an unawareness of safe water storage. While they were concerned about bacteria buildup in their tanks, they did not appreciate the health risks of exterior tap water or the need for their systems to be cleaned regularly (Access to information and Quality).<sup>261,262</sup> Those who discussed cleaning their systems used bleach, which can damage the plumbing if not sufficiently diluted first.<sup>261</sup> Insufficient dilution or improper handling of bleach can also increase the risk of chlorine poisoning.<sup>263</sup> A lack of knowledge and attentiveness can render an onboard water system a high-risk water resource for an RV resident.

For this reason, we suggest that cities looking to assist RV residents in securing clean drinking water not promote the use of onboard systems (e.g., through a tank-filling service modeled after Seattle's mobile wastewater pump-out program) unless they are prepared to provide considerable support. This support should involve safe water storage training, frequent blackwater and greywater mobile pump-outs, and greywater disposal education (Access to information, Quality, Accessibility, and Adequacy). Using onboard water systems generates additional greywater that our participants believed was safe to dispose of outside, an issue we discuss further in the Hygiene section below. Without such support, cities could inadvertently increase RV residents' risk of waterborne diseases and improper wastewater disposal.

Instead, cities might consider installing more five-gallon water-jug filling stations that are typically outside grocery and retail stores. These water vending machines could be available for anyone to use for a nominal fee. Outside food banks or hygiene facilities that RV residents and other unhoused populations frequent may be viable locations. Gas stations or parks may also be convenient locations for RVs parked in industrial sections of a city. Vouchers could be available for those who need them. Technical assistance with minor repairs such as battery replacement may also be useful to help overcome mobility barriers (Quality and Energy), a suggestion we explore further in the Sanitation section below. These stations would provide large quantities of conveniently accessible, clean water at a low cost (Adequacy, Accessibility, and Quality).

The prevalence of water theft suggests that cities looking to engage with RV residents should be aware of this issue. In discussing water theft, we are neither condoning unlawful behavior nor trying to criminalize homelessness. Our intention rather is to underscore the associated public health and economic hazards. As previously mentioned, tapping water from sources that are not intended to be used for drinking water and therefore may not comply to federal safety standards<sup>260</sup> can increase RV residents' risk of exposure to contaminants (Quality). Exterior plumbing fixtures in particular can introduce impurities such as lead, volatile organic chemicals, phthalates, and bisphenol A (BPA)<sup>259</sup> that can lead to a variety of short- and long-term diseases.<sup>264</sup> That our participants did not frequently report illness associated with exterior tap water is not an accurate indication of the health risk. Water theft also has a real cost to property owners. RV residents compared to other unhoused populations are able to steal larger quantities of water at one time if they fill their onboard tanks, which can hold anywhere from twenty to one hundred gallons.<sup>265,266</sup> A couple of our participants drive to fill their holding tanks from external taps, and it seems other Seattle RV residents also do so:

*"...what we have going on here is a situation and there's one example...They pulled up Friday, there was a locking cap around the outside spigot, they hack sawed it off. On the video, you see them filling up like six RVs in a row, and then let the water run all weekend. And they went from a normally \$150...monthly bill, and they had a \$10,000 monthly bill..."* (Service Provider 5).

Based on our results, water theft is also not necessary: the 45 percent of RV residents that did not steal water were not without water. The choice to steal water appears to have been a matter of convenience, which is not to say that there were not real physical Accessibility issues posing as inconveniences. For RV residents living in more isolated sections of the city, it was likely more convenient to draw and carry water by hand from a nearby industrial building than travel to a store to purchase it. Despite this decision still requiring residents to haul water, it did not require them to move their RVs, which can be particularly cumbersome and costly. RV mobility likely affected the prevalence of water theft but was not a primary reason given only 10 of the 19 residents who stole were immobile. Unaffordability did not seem to be a major cause for theft, as only six participants commented negatively on the cost of water, three of whom did not steal.

#### 4.6.2 Sanitation

Sanitation practices common to RV residents and other persons experiencing homelessness include public urination, defecating or urinating in buckets or bottles,<sup>229</sup> and using public portable toilets.<sup>226</sup> Otherwise, RV residents' sanitation situation – especially among those using the pump-out program – is quite distinct from other unhoused populations. One pronounced difference is the prevalence of open defecation. Previous studies suggest that open defecation is common among unhoused populations.<sup>218,258,267</sup> However, only four of our participants reported having openly defecated in the past compared to the twelve who had not; the rest were not explicitly asked or did not provide a clear answer. Social desirability bias, the tendency to underreport socially undesirable behaviors and overreport desirable ones,<sup>268</sup> may help to explain the low reported prevalence of open defecation. Mental health conditions may also account for the difference across RV residents and other unhoused populations. RV residents in general may have a higher mental health status as hypothesized by one service provider:

*“Living in an RV requires a level of organization and self-command. So whether we're talking about mental health, but also to potentially buy an RV...takes a level of organization that that may not, that someone living in a tent or living in a bed roll may not have” (Service Provider 7).*

Having a functional RV toilet may also explain the difference. RV toilets can provide residents a reliable and private facility that decreases their need to openly defecate. During the pandemic, though RV residents also relied on public and business bathrooms, other unhoused populations may have been more affected by closures and limited hours<sup>269,270</sup> because they had fewer options. RV residents would have likely felt more pandemic-related sanitation effects if the pump-out program had not been operating (Timescale). A working RV toilet also offers residents a nighttime facility which other unhoused populations can have trouble locating (Availability).<sup>229</sup>

Despite these benefits, onboard facilities can pose non-trivial health risks to RV residents and the broader public, especially compared to shared public facilities. This finding contradicts the conventional view of shared sanitation as inferior to private facilities.<sup>271</sup> Shared sanitation worldwide is generally categorized as being poorly maintained, unhygienic, and inaccessible compared to private facilities.<sup>272</sup> These characteristics, however, may be more descriptive of residents' onboard sanitation than the facilities external to their RVs (Quality). For example, aging RV tanks are

susceptible to break and leak raw sewage if not consistently maintained. We found nearly half of our participants have had some mechanical issue with their onboard sanitation system. More significantly, the use of onboard sanitation creates the opportunity for waste to be improperly disposed. Unless cities have a mobile pump-out program with frequent service, RV residents are entirely responsible for their wastewater and intimately involved in its disposal (Quality). Shared public facilities, in contrast, ensure RV residents' fecal waste will be treated.

Safe disposal of RV waste in the absence of a mobile pump-out program also requires RV residents to be mobile and willing to move their vehicle. The cost of gas and the time and effort to move their RVs make residents reluctant to drive long distances to dump stations. Concerns over losing their parking spots, drained batteries, and broken systems are further hindrances. For cities that are not interested in a mobile pump-out option, building closer waste disposal sites within city limits could address some of these barriers (Accessibility, Adequacy, Energy, and Quality). To address parking barriers, cities may consider sanctioning safe parking spaces for RV residents to rent and register under their name. This approach would also help outreach workers stay connected RV residents who are typically difficult to track.

*"People basically are in living and being parked and setting up their camp in this illegal window, they really can't be there and in theory parking enforcement could come ticket them at any time...you know they could get displaced it's harder for them to [become stable]... And if people are going to live on in their vehicles then having places where they can do so without being in legal jeopardy seems like a better model" (Service Provider 3).*

Helping RV residents overcome technical barriers to their waste disposal may involve outreach organizations assisting with small repairs.

*"I would rather see a situation where we're saying you know what we expect you to pump out. If you need help with the funding, we have vouchers if you need, you know, help getting your vehicle running, we can help with that...And that's a mind shift that's, I'm not saying make it harder for them. I'm saying help build them up like it's, and when you talk about cost, how much less expensive is it to help somebody get a new alternator, so their RV runs, so they can go around, than driving a truck around to everybody. So it's a, it's a different way of thinking. But I really want to see how we help people up rather than keep them down by being dependent on us" (Service Provider 5).*

Maintenance assistance may need to be targeted toward female residents who we found to have lower maintenance abilities than males, which is not a comment on women's innate skills. This

approach may be more cost-effective than a mobile pump-out program, especially if the stationary pump-out site charges a nominal fee and is used by other RV owners. Aiding residents in becoming mobile again is also a more comprehensive solution, able to change not only their sanitation but also their water and hygiene conditions.

#### 4.6.3 Hygiene

RV residents have similar hygiene experiences to other unhoused populations, given the majority does not use their onboard sinks for handwashing or showers. For example, our participants also depended on housed family and friends for showering and laundry as well as public facilities such as parks, community centers, and facilities for the homeless – except for homeless shelters<sup>228</sup> (Accessibility). Both RV residents and other unhoused populations use untreated water for bathing and other personal hygiene activities (Quality).<sup>229,258,273</sup> In terms of hand hygiene (Acceptability and Quality), RV residents similarly feel that “Being out here is really hard to keep your hands clean,” as expressed by a person experiencing homelessness in Atlanta, GA.<sup>274(p2445)</sup> Running water is also not common among RV residents, and they rely on hand sanitizer<sup>228,229,274</sup> and personal cleansing wipes for maintaining hand hygiene.<sup>274</sup>

Managing RV hygiene facilities is the most complex and high-risk RV WASH task as it involves both onboard water and wastewater facilities. For onboard hygiene infrastructure to be safe, residents must treat their water systems, fill their storage tank with clean water, maintain their greywater tank, and regularly dispose of their wastewater. Based on our findings, one of the most significant RV-related hygiene risks is that of greywater disposal (Quality). Several participants had or would be willing to dispose of untreated greywater outside, three of these being RV residents who shower in their RVs. A few participants believed it was safe to dump greywater on the ground or down stormwater drains. A related though not RV-specific concern was the use of portable washing machines and solar showers (Energy) without any mention of wastewater treatment. While blackwater is the relatively greater hazard,<sup>275,276</sup> disposing of untreated greywater into a densely populated urban environment – especially if done by hundreds of RV residents – could have a substantial effect on human health and the environment. Greywater can contain fecal pathogens,<sup>276,277</sup> contaminants associated with personal care products and pharmaceuticals,<sup>276,278</sup>

and grease from dish washing.<sup>279</sup> These microbial and chemical pollutants pose potential risks to human and ecosystem health.<sup>280–282</sup> We recommend that cities pay attention to greywater management among their RV residents. Our previous suggestions for water filling stations as opposed to a tank-filling service, wastewater disposal sites, and WASH education are a few ways to help address this issue (Quality, Accessibility, and Access to information).

#### 4.6.4 Healthy RV living

In this section we briefly consider the broader context and goal of RV WASH in terms of healthy RV living. WASH is only one prerequisite to health<sup>283</sup> and therefore should not be viewed in isolation. While the focus and contribution of the paper is still RV WASH, we broach this larger idea of healthy living to help cities decide on WASH strategies for RV residents.

In general we found that RV residents living on the streets in immobile vehicles (n = 14) from the perspective of WASH are no better off than any other unsheltered homeless. Unless the city provides door-to-door water, sanitation, and maintenance services, immobile RV residents cannot take full advantage of their onboard systems. Even with such services, immobility may be a sign of the condition of the RV, including its technical safety and the maintenance ability of the owner. While immobile does not always mean derelict, cities should be realistic about the benefit that a single WASH service like a mobile pump-out program can have on the overall health of occupants living in broken-down RVs. The entire state of the vehicle is important to consider, as expressed by one service provider:

*“This is like so like antithetical to social worker background, so I’ll just say that and own it, but I think it is I think it’s detrimental to people to allow them to continue to live in a vehicle that is derelict. You know, it’s not sanitary, they’re living in mold, and, you know, the, the moisture that they’re exposed to and just kind of lack of basic access to hygiene seems to me, like really problematic, especially if folks are dealing with some significant mental health or chemical substance use disorder issues. I think it would behoove us from a public health standpoint to really encourage folks to get out of those vehicles” (Service Provider 4).*

Another topic in connection to healthy RV living is energy access. We suggest that future RV research continue to study the relationship between energy and WASH that emerged from our analysis (e.g., electricity needed to operate water pumps, propane used to heat water). The value of

such research was underlined by several service providers who were concerned about fires related to RV residents' energy use. For example:

*"But whether or not vehicles have functional stovetops or, or other kind of like water heating and cooling is really questionable. And we've had fires from, we had a major explosion in one RV and fire from utilizing a portable propane heater next to the cookstove" (Service Provider 4).*

#### *4.6.5 Limitations and suggestions for future research*

The exploratory nature of the study inherently means it is limited in several respects. First, we were limited in our data collection. We only interviewed RV residents who were connected to the pump-out program. We used convenience rather than random sampling, which means our results are not statistically representative of any larger RV resident population. However, statistical representativeness is arguably not required in qualitative research when the aim is to understand a social phenomenon.<sup>284</sup> We also only conducted interviews during a period when Seattle's 72-hour parking rule had been suspended in response to COVID-19 public health guidelines. This law requires vehicles parked on city streets to be moved every seventy-two hours.<sup>285</sup> Not having to move their RVs and being able to shelter in place may have helped to stabilize residents' WASH experiences in addition to worsening the condition of their vehicle, as stationary RVs can deteriorate quickly.<sup>286</sup> Though residents reported few pandemic-related effects, we recommend future research study RV WASH in a non-pandemic context.

A consequence of the semi-structured nature of the interview was that not every participant was asked every question, nor were questions always presented in the same order. In addition, the two questions about hand hygiene and controlling blackwater and greywater tank odors were added around the twelfth interview. All frequencies should therefore be interpreted as being among "those participants who were asked," a qualifier we tried to indicate throughout our Results section.

The content of our interview was also limited in regard to hygiene. The surprisingly few pandemic-related hygiene remarks from participants may have been a consequence of only having one hand hygiene question in our interview. We recommend future research focus on hygiene, especially greywater knowledge and practices as well as menstrual hygiene, a topic absent from our study in an effort to keep the interview succinct.

Second, we were limited in our data analysis. Counting frequencies from qualitative interview data is subject to the interpretation of the analyst, the structure of the interview, and the coding rules. Our attempt to code separate interview questions as distinct units of analysis and the siloed nature of our interview's water, sanitation, and hygiene questions meant that the full level-of-service implication of a participant's response was sometimes unclear from a single unit of analysis. For example, in a single unit of analysis if a participant discussed using water for personal hygiene but did not explicitly mention the source of water, it was not automatically assumed to be the same source as the one mentioned earlier in the interview as a drinking water source. If the two sources were the same in reality, our decision meant that we missed assigning several level-of-service codes for that participant's hygiene situation. We therefore recommend the frequencies in Tables 4.4-4.6 be viewed as approximate lower bounds, knowing there is the possibility of more participants and occurrences for each subcategory and code. While not a product of the data analysis, certain frequencies may also be low due to social desirability bias<sup>268</sup> associated with sensitive topics such as open defecation and improper wastewater disposal practices.

## **CHAPTER 5 CONCLUSION**

The aim of this dissertation is to contribute to the WASH sector's efforts to reimagine the design and evaluation of WASH interventions through a multi-scale, socio-technical perspective on the nature of infrastructure. I briefly summarize below the different ways and extents to which the research in Chapters 2 through 4 realized this aim.

The first research project in Chapter 2 used quasi-experimental methods to evaluate the effect of water infrastructure access on Indian children's education. I found that girls can benefit more from decreases in water collection time than boys and recommended the construction of off-premises piped water construction in water-insecure areas where girls lag behind educationally. The scope and evaluation techniques of this project (specifically, children's education and estimated effect heterogeneity) are the key contributions to the sector's expanded design and evaluation process.

Chapter 3 also used quasi-experimental techniques to examine the relationships between growth faltering and water, sanitation, and air pollution among China's children and adolescents. I found that different exposures mattered at the inter- and intra-household levels, such as neighborhood excreta management and household indoor air quality, which is informative to the scope and scale of environmentally transformative WASH interventions. This project's scale (inter-household) is the clearest contribution to the dissertation's overall objective.

Finally, Chapter 4 used qualitative content analysis of semi-structured interview data to characterize the level of WASH service among people living in RVs in Seattle. I found similarities with other urban unhoused populations, such as dependence on family and friends for showers and laundry, and several RV-specific risks including unsafe greywater disposal. This project's evaluation technique (qualitative) is its major contribution to the re-envisioned design and evaluation process.

The remainder of the conclusion draws on common concepts underlying the work as a whole in order to comment on two key assumptions and norms behind WASH research and practice. This type of reflection is appropriate to the sector's current reflections.

## 5.1 Key conventions

### 5.1.1 How should community be operationalized?

As discussed in the Introduction and in Chapter 3, the WASH sector is calling for an expanded focus from the individual to community level as part of a more environmentally transformative approach to WASH programming. Though this strategy is currently not clearly defined, interventions with wide coverage that address multiple risks are generally in view.<sup>5</sup> It is therefore understood that community primarily refers to the *setting* of such interventions.<sup>287</sup> However, if community is only construed in spatial terms, there is a risk of engendering a new type of reductionism in WASH research and practice, one that minimizes community to a one-dimensional, local physicality.<sup>288</sup> The consequence may be that important factors are omitted, especially those that are not strictly physical, which could counterproductively restrict the development of comprehensive, multi-scale interventions.

A socio-technical view of infrastructure may help avoid such reductionism. The socio-technical perspective, ipso facto, moves beyond the physical to capture interrelated social and technical factors. For example, using this perspective to document WASH among RV residents in Chapter 4 helped to illuminate community as a *resource*. To many participants, community was a dynamic set of WASH resources determined by social relations (e.g., friendships, family) and the physical infrastructure around their parked RVs – physical infrastructure that itself was governed by social structures, especially for public or illegally accessed infrastructure. A community-level intervention in this context may mean augmenting a common set of WASH resources across RV residents such as portable toilets and shower and drinking water services at public parks, as opposed to implementing an intervention that covers a certain spatial scale. Interestingly, using “community” to imply social cohesion among RV residents would also not be an accurate use of the word, as RV residents do not typically rely on other RV residents to meet their WASH needs. As another example, a socio-technical perspective in Chapter 2 allowed community to be conceived as a *target*, or as the recipient of an intervention. Each household’s community was defined as their caste or religion, which can be related to a household’s WASH access in India.<sup>289,290</sup> The effect of community on the association between water fetching time and learning achievement was estimated to understand if certain communities were more at-risk of water access affecting their children’s education. Though the effect of community was not statistically significant, the sector still may want to consider how community-

level interventions could target socially defined groups. Nonetheless, I recognize that this approach – of having socially defined communities be targets of WASH interventions – is an idea that quickly becomes untenable due to the innumerable combinations of identities that could constitute a socially defined group, not to mention across the countless WASH-related outcomes other than education. Which group or outcome would be prioritized? Rather than putting forward some unrealistic expectation, I intend only to remind the sector that a community can be more than merely spatially proximate households and that there may be context-dependent demographics that modulate the effect of WASH infrastructure, considerations that may help guide the design of an intervention.

How community is defined during the scope and scale stages of a project should also influence the choice of evaluation method. This dissertation highlights the benefits of studying the different conceptualizations of community with different research methods. For example, studies in which community is *setting* are well-suited for quasi-experimental designs such as in Chapter 3 that can estimate the effects of large-scale infrastructure. Chapter 4 demonstrated the utility of qualitative methods for studying community as *resource* and the complex social network of actors involved. It is worth noting that for a single project community could be conceptualized in more than one way, which would require the different communities to be labeled as *setting*, *resource*, and/or *target* or other distinctive names and would possibly require multiple evaluation methods.

In sum, I recommend the sector pay greater attention to social factors including social networks, social cohesion, and demographics in the design and evaluation of community WASH interventions. Where these data are unavailable, qualitative research and/or demographics surveys may be necessary to carry out prior to scoping a project to understand the definition of community that would be most meaningful within that context.

### 5.1.2 *By what standard?*

The second norm to be discussed pertains to measuring the level of WASH service. Globally, WASH infrastructure is typically evaluated in reference to the WHO/UNICEF Joint Monitoring Programme (JMP) benchmarks. These standards establish an acceptable level of service for WASH such that it has the potential to deliver health benefits.<sup>10</sup> While the JMP's categories are helpful starting points for

infrastructure evaluations, they are limited in their focus on technical, household-level factors (school and health facility standards notwithstanding).<sup>291</sup> If infrastructure is to be treated as a multi-scale, socio-technical phenomenon in WASH research and practice, it would require the JMP standards to be applied judiciously and likely augmented. Though I did not use these categories in my research, their limited application and opportunities for augmentation can still be apprehended from this dissertation.

Chapter 4 serves to illustrate these points with regard to socio-technical nature of infrastructure, specifically in terms of who interacts with infrastructure and how they do so. First, the JMP assumes sanitation that is shared between two or more households is less safe than private facilities. Some scholars have suggested this view of shared sanitation is too dismissive and broad,<sup>272,292</sup> an appraisal with which Chapter 4 agrees. Shared sanitation (e.g., bathrooms at grocery stores, parks) is a valuable resource to RV residents and poses relatively low health risks compared to their private onboard facilities. RV sanitation systems require residents to be intimately involved in wastewater disposal in the absence of a mobile pump-out program. The shared facilities used by RV residents, in contrast, did not require them to handle their own waste and risk being exposed to fecal pathogens.

Second, examining individual behaviors and knowledge alongside a technical evaluation may be more instructive for unconventional WASH such as onboard RV WASH compared to housed infrastructure. How people interact with traditional WASH infrastructure is typically regulated, hence focusing on the technical (the provider side) can be sufficiently informative. The ways RV residents interacted<sup>293</sup> with their onboard WASH – whether or not they used it, how they used it, how they maintained it – largely determined the systems' performance and associated health risks (except for sanitation systems). For example, the participants who used their onboard water system did not appreciate the need for their system to be cleaned regularly, which increased their risk of exposure to waterborne pathogens. There was no third-party provider or regulations to mitigate that risk. In making this observation I am not commenting on the need for more regulation of RV or other unconventional WASH. Rather, this example serves to illustrate why the evaluation of unconventional infrastructure may call for more than the JMP standards. Other global examples of non-standard contexts include WASH in informal settlements<sup>294,295</sup> and among pastoral nomads.<sup>296</sup> While applying

the JMP standards to unconventional or generally non-household contexts may not be entirely meaningless (e.g., <sup>229</sup>), as I have illustrated it opens the possibility of mischaracterizing or omitting certain WASH-related risks given some of the starting assumptions are irrelevant. Qualitative methods such as the mixed inductive-deductive approach in Chapter 4 or other methods from the behavioral sciences<sup>297</sup> may be helpful for empirically assessing these types of populations' needs and establishing realistic expectations for WASH service provision.

Chapter 3 highlights the benefits of looking beyond the household level in assessing WASH infrastructure. By including both individual and aggregated exposure levels the analysis was able to reveal critical differences in the nature of inter- and intra-household environmental risks. For example, polluting cooking fuel posed the highest intra-household risks while at the neighborhood level excreta had the largest association with linear growth faltering. As the sector shifts its focus to multi-scale community interventions it should continue assessing household-level exposures to know at which level interventions are more effective.

## **5.2 Future research**

This final section identifies future research directions arising from a few of the interesting parallels across the three chapters' findings. These incipient ideas are intended to spark further inquiry rather than provide detailed research plans.

The first suggestion emerges from Chapters 3 and 4 and pertains to fecal waste management, which the sector recently acknowledged as a priority research topic. In particular, it has been recommended that more evidence be generated on fecal waste management monitoring and evaluation, affordability, appropriate technologies, and sustainability.<sup>298</sup> Chapters 3 and 4 of this dissertation addressed some of these priority topics, primarily evaluation and appropriate technologies, and showed the value of a multi-scale, socio-technical perspective for studying fecal waste management. In terms of evaluation, from a quantitative community-as-*setting* framing, Chapter 3 revealed the importance of separately estimating fecal risks at the individual and collective levels (spatial), whereas Chapter 4 with qualitative methods and a community-as-*resource* framing demonstrated a way to capture the socio-technical interactions involved in fecal waste management (social). Future research

may consider combining these spatial and social approaches (e.g., excreta flow diagrams<sup>299</sup> and qualitative interviews<sup>300</sup>) to support the sector's research agenda.

Taking inspiration from Chapters 2 and 3, a second idea is to assess the relationship between child education and multi-scale sanitation improvements. Rather than a child's tradeoff between water collection and education as in Chapter 2, the proposed mechanism would be through mother's work time<sup>301</sup> (also not via child health as in<sup>302,303</sup>). Improvements in sanitation may allow mothers to spend less time on cleaning and other domestic responsibilities,<sup>212</sup> which may enable them to invest more in their children's education.<sup>38</sup> Data permitting, based on the results of this dissertation it may be worthwhile to implement this idea in an Indian or Chinese context using a quasi-experimental design.

The intersection of WASH and energy may also warrant further exploration. Chapter 3 provides the clearest motivation for this suggestion, having found indoor air pollution, water, and sanitation are connected through their effects on child and adolescent linear growth. However, energy also emerged from the qualitative analysis in Chapter 4 as a potential but understudied link to WASH among RV residents. To my knowledge, the interdependencies between WASH and energy have received little research attention,<sup>304</sup> meaning there are many potential lines of research. One possible avenue would be to examine the relationship between renewable energy technologies and level of WASH service that can be supplied by a WASH service provider or maintained by an individual.

Finally, while it does not arise from the findings, a methodological limitation across all three chapters was the lack of data at the proximate level – that is, at the pathogen, pollutant, or behavioral level. In Chapters 2 and 3 the analyses used indicators of infrastructure type (e.g., piped water, toilet) that did not permit direct analysis of the mechanisms linking the outcomes to WASH or energy infrastructure. Similarly, Chapter 4 was a typology of WASH infrastructure that did not incorporate water quality or fecal pathogen indicators to assess RV residents' WASH conditions. Improving data availability at this proximate level may require more at-scale measurements of infections (e.g., biomarkers), contaminant levels in addition to their fate and transport, and participant observations. These types of data will be key for the sector to evaluate WASH infrastructure and understand its relationship to human health more fully.<sup>6</sup>

## CHAPTER 6 EXCURSUS

### 6.1 What is the role of government in WASH service provision?

Each chapter in this dissertation involved WASH infrastructure that was provided either mostly or entirely by the government – be it the Indian government, Chinese government, or City of Seattle. In response to the sector’s call for larger-scale WASH interventions, some scholars have emphasized the responsibility of government with statements such as “No country in history has delivered at-scale access...without the state having a central role in implementation and regulation.”<sup>305(pe363)</sup> I agree that the government should have a role in providing WASH, but to what extent? Chapter 4 in particular provides an opportunity to think soberly about this question. For example, are RV residents justified in stealing water since the government is not providing it to them as it provides for other housed populations? Does this lack of provision mean the government has brought about inequitable WASH? Inequity on what terms? As Chapter 4 suggested, there are many indicators by which level of service can be assessed, including subjective ones such as personal Acceptability. Should the government be responsible for ensuring equality across all possible criteria? Why or why not?

In posing these questions I am not implying that there should not be engineering standards for WASH or that the government should not be involved in regulating and upholding these standards; the positive externalities and public health effects of WASH support this type of government involvement. Rather, my intention is to call attention to what I think is lost in conversations about the government’s responsibility in WASH provision, which is the role of personal agency, equality under the law, and the irony that the government is both the problem (the perpetrator of inequity) and solution (the panacea for inequity).<sup>306</sup> How instead could the government support individuals in ways that empower them to improve their own WASH conditions without abrogating the law or making them more dependent on itself?

I recognize that my few brief questions and remarks have not addressed every aspect of this topic, and I do not have the expertise or space in this dissertation to properly do so. Nevertheless, I thought the matter sufficiently relevant to my work and wished to broach the subject with the hope of encouraging more serious dialogue among scholars. Serious dialogue, that is, in the sense of allowing alternative viewpoints to be examined and hegemonic narratives to be challenged. Deciding

on the role of the government in WASH provision is not straightforward, and such discourse is necessary to guard against ideological oversimplification.

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**APPENDIX 1 FOR CHAPTER 2 (INDIA)**

## Supplementary methods

### *Instrument validity*

We choose freshwater availability as our candidate instrument by verifying that it satisfies the three assumptions for a valid instrument and claim that it is relevant, exogenous, and excluded.<sup>59</sup>

First, freshwater availability is relevant for determining fetching time. In general, we expect higher freshwater availability to decrease fetching time<sup>307</sup>; that is, the effect on average should be monotonic. For example, increasing freshwater availability may decrease the travel time to the closest source,<sup>18</sup> and/or it may increase the volume of water collected per visit,<sup>308</sup> thereby decreasing the number of visits per day. In a village with a fixed population in the short run, we might reasonably expect the demand for freshwater also to be fixed. Therefore, if freshwater availability were to increase, overcrowding should diminish or stay constant under constant demand conditions. That being said, we recognize that increased freshwater availability may not always result in increased drinking water availability. Politics,<sup>309</sup> leaky infrastructure<sup>310</sup> and complex hydrological cycling<sup>311</sup> complicate but do not reverse the relationship. Thus, the instrument of freshwater availability satisfies both conditions of relevance and monotonicity.

Second, we contend that freshwater availability and learning achievement do not share causes. Freshwater availability is determined at the aggregate-level<sup>42</sup> via quasi-random natural processes and infrastructure investments, and learning achievement is an individual-level variable. Direct reverse causation is unlikely.<sup>26</sup> In other words, because fetching time is largely determined by ecological factors operating at a higher geographical level outside the control of the household,<sup>42</sup> it circumvents the endogeneity of lower household-level features. We strengthen the argument that variation in rainfall is largely exogenous by showing that the estimate for the rainfall coefficient in the first-stage regression is similar in the presence ( $-3.58\text{E-}04 \pm 6.48\text{E-}05$ ) and absence ( $-3.33\text{E-}04 \pm 6.85\text{E-}05$ ) of covariates.

Third, we claim that freshwater availability does not affect learning achievement except through its potential effect on water fetching time. We recognize the plausibility of freshwater availability affecting learning achievement by influencing market conditions such that children are sent out of the house to work, which would also impair their education. We explore potential confounders on the causal

pathway in section 2.6.6 of the main text. Helpfully, Boozer and Suri (2001) also examined a similar issue. They studied schooling choice and child labor in the context of an exogenous shock to the productivity of children, modeled as month-by-region variations in rainfall in Ghana. They found no evidence of an income effect and contended that income may provide a relatively small incentive to parents to remove their children from school to pursue activities in the labor force.<sup>43</sup> However, as income is related to fetching time and learning achievement, we adjust for this confounding by including household income in our models.

While both the groundwater and rainfall variables satisfy the above assumptions, we choose rainfall as our instrument due to data availability. The groundwater data are only available at the district-level for the year 2013. Given the low temporal variability of the groundwater data from a single year,<sup>52</sup> and given that rainfall contributes to groundwater recharge and availability as well as surface waters (for piped supplies),<sup>312</sup> rainfall is an appropriate instrument. The precipitation dataset is well-populated and exhibits high spatial variation (Figure 2.1 in the main text). We further support our decision to use rainfall by performing instrument diagnostic tests (Appendix 1 Table A.9). Executing our first-stage regression with the two-year annual average rainfall supports this choice, as the instrument provides sufficient variation and power for the model to output a significant estimate of fetching time (Table A.8).

#### *Sensitivity to assumptions about data-generating process*

Model selection has important implications for the results and their interpretation. In particular, when modeling semi-continuous data, it is important to specify whether the outcome of interest is an actual or potential outcome. An actual outcome is a fully-observed variable, while a potential outcome is a latent variable that is partially observed.<sup>313</sup> In our context, fetching time may reasonably be understood as either an actual or potential outcome; the literature has examples of both theoretical framings.<sup>18,53,54</sup> When fetching time is considered a potential outcome, all children have an underlying latent fetching time that can be influenced by rainfall. In other words, there are no non-fetchers. Conversely, when fetching time is considered an actual outcome, children with zeros genuinely do not fetch, which would imply that rainfall would not affect their education through our assumed pathway. In our main linear models, we do not distinguish the zeros from the rest of the data and assume that

all children's water collection responsibilities, regardless of their observed fetching time, can be affected by rainfall (an assumption aligning more with the potential-outcome framework). We test the sensitivity of our main model's assumptions by fitting three different first-stage models.

We first apply a Heckman selection model, following the approach that Ilahi and Grimard (2000) used to model women's water collection times in rural Pakistan.<sup>54</sup> The Heckit model, as it is also called, was designed to address selection bias among potential outcomes.<sup>313–315</sup> In the context of fetching time, this two-step selection model assumes that children with zero values for their fetching times are children with missing (latent) values. Given that the children with observed fetching times in our dataset are primarily those with off-premises water (Table A.5), the location of water infrastructure is an appropriate sample-selection criterion in that it is informative of children's status as a fetcher/non-fetcher and uninformative of the exact time children spend collecting water. The Heckit model relies on the assumption that the error terms in the selection and outcome equations are distributed as bivariate normal,<sup>314–316</sup> a limitation similar to that of our main models which produced negative predicted fetching times.

$$Fetch_{it}^* = Selection_{it}\alpha + X_{it}\beta + u_{it} \dots (1)$$

$$Fetch_{it} = 1 \text{ if } Fetch_{it}^* > 0; Fetch_{it} = 0 \text{ otherwise } \dots (2)$$

$$FetchTime_{it}^{\hat{}} = X_{it}\beta + v_{it} \text{ if } Fetch_{it} = 1; FetchTime_{it}^{\hat{}} = 0 \text{ otherwise } \dots (3)$$

The predicted event of water fetching for person  $i$  at time  $t$ ,  $Fetch_{it}$ , is a dummy variable indicating the individual's fetching status and is a function of a latent variable,  $Fetch_{it}^*$ , which reflects the respondent's propensity to fetch depending on a set of covariates  $X_{it}$  and a selection vector  $Selection_{it}$  comprised of a dummy variable indicating the location of household's water supply (off- or on-premises) and a leave-out cluster (village) mean of this location variable. The predicted fetching time  $FetchTime_{it}^{\hat{}}$  is a function of the set of covariates  $X_{it}$  if  $Fetch_{it}$  equals 1.

Our second approach is the Tobit model. Tobit models have also been used for modeling water collection times.<sup>18,53</sup> This model assumes that the same underlying process determines whether or not the fetching time is zero *and* the value of the positive fetching times. In contrast to the Heckit, the Tobit model assumes actual outcomes, meaning that zeros are genuine and observed.<sup>316,317</sup> Consequently, children with zero fetching times are assumed to be non-fetchers. Similar to the

limitation of the Heckit and our main linear two-stage least squares models, the Tobit model assumes that the error term is independently and normally distributed.<sup>316,317</sup>

$$FetchTime_{it}^{\hat{}} = 0 \text{ if } FetchTime_{it}^* = X_{it}\beta + v_{it} \leq 0 \dots (4)$$

$$FetchTime_{it}^{\hat{}} = FetchTime_{it}^* \text{ if } FetchTime_{it}^* = X_{it}\beta + v_{it} > 0 \dots (5)$$

The predicted fetching time  $FetchTime_{it}^{\hat{}}$  is a function of the set of covariates  $X_{it}$  if  $FetchTime_{it}^*$  is greater than 0, and 0 if  $FetchTime_{it}^*$  is less than 0.

Our third approach is a Tweedie model, a model similar to the Tobit in that it assumes actual zeros, but does not assume an underlying normal random variable censored by a random mechanism.<sup>316</sup>

Tweedie models are special cases of exponential dispersion models in which the power mean-variance relationship is flexible and characterized by  $Var(\mu) = \varphi\mu^p$  for  $p \in (0, 1)$ , where  $\mu$  is the mean and  $\varphi > 0$  is the dispersion parameter.<sup>318,319</sup> Tweedie distributions in the range of  $p \in (1, 2)$  belong to the compound Poisson-Gamma distributions, which are useful for modeling semi-continuous outcomes (outcomes such as our continuous fetching time data with a probability mass at zero). We use  $p = 1.1$  given that the resulting shape of the predicted fetching time distribution best approximates that of our observed fetching times. To the best of our knowledge, this sensitivity analysis is the first exploration of using a Tweedie model to estimate water fetching time.

$$FetchTime_{it} \sim Poisson(\lambda) \dots (6)$$

$$FetchTime_{it}^{\hat{}} = 0 \text{ if } FetchTime_{it}^* = 0 \dots (7)$$

$$FetchTime_{it}^{\hat{}} = X_{it}\beta + v_{it} \text{ if } FetchTime_{it}^* > 0 \dots (8)$$

The predicted fetching time  $FetchTime_{it}^{\hat{}}$  is Gamma distributed and is a function of the set of covariates  $X_{it}$  if  $FetchTime_{it}^*$  is greater than 0, and 0 if  $FetchTime_{it}^*$  is equal to 0.

**Table A.1. Household survey water questions**

Question	Response option or fill-in
What is the main source of water for drinking?	Piped, tube well, hand pump, dug open well, covered well, river/canal/stream, pond, tanker truck, rainwater, bottled, other
Is this inside the house or compound?	No outside, yes inside
If water source is outside house or compound: In the current season how much total time daily do [group] spend in fetching and collecting water including waiting in line? Add all trips for each category.	
Adult women	_____ minutes daily
Adult men	_____ minutes daily
Girls under 15	_____ minutes daily
Boys under 15	_____ minutes daily

**Table A.2. Summary of usual water infrastructure types among households whose children were tested**

	<b>2004-2005 (n = 10,981)</b>	<b>2011-2012 (n = 10,450)</b>
<i>Infrastructure type</i>	<b>%</b>	<b>%</b>
Piped	38.1	37.3
Tube well	10.2	10.8
Hand pump	36.8	37.8
Dug, open well	11.3	9.0
Covered well	1.2	0.9
River/canal/stream	0.7	0.7
Pond	0.3	0.3
Tanker truck	0.9	1.7
Rainwater	0.04	0.06
Bottled	0.009	0.3
Other	0.5	1.2

Notes: In the analyses, due to their sparseness, the last four rows were combined into one water infrastructure type. n = 21,431 children tested

**Table A.3. Most common infrastructure type among children who fetch, by category**

<b>Category</b>	<b>Infrastructure type</b>	<b>2004-2005 (n = 10,981)</b>	<b>2011-2012 (n = 10,450)</b>
<i>Sex</i>		<b>%</b>	<b>%</b>
Girl	Hand pump	45.7	53.5
Boy	Hand pump	53.6	55.3
<i>Community</i>			
Dalit	Hand pump	52.6	53.0
Brahmin + SJC	Hand pump	52.6	74.3
<i>Income quantile</i>			
0-25	Hand pump	51.2	63.2
75-100	Hand pump	45.5	39.4
<i>Residence</i>			
Rural	Hand pump	53.3	59.5
Urban	Piped	53.5	57.3

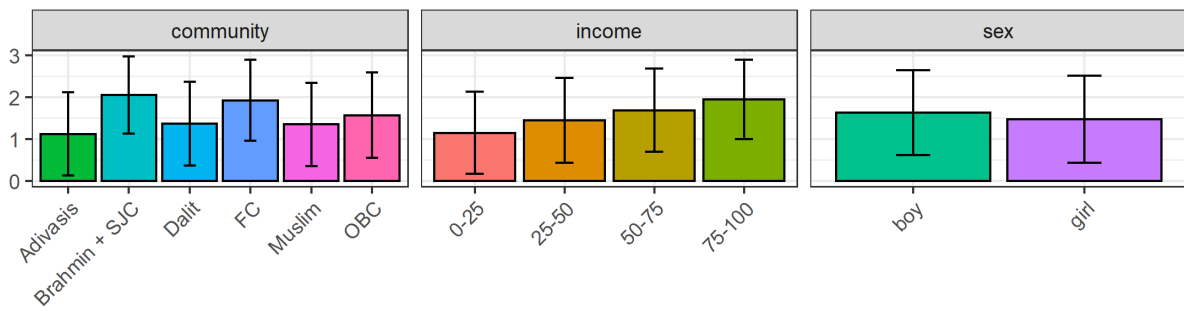
Notes: When more than two groups per category, the most extreme groups were included Brahmins + Sikhs, Jains, and Christians (SJCs) and Dalits; 0-25th quantile and 75-100th quantile. n = 21,431 children tested

**Table A.4. Attendance status (counts) of students who fetch, by sex**

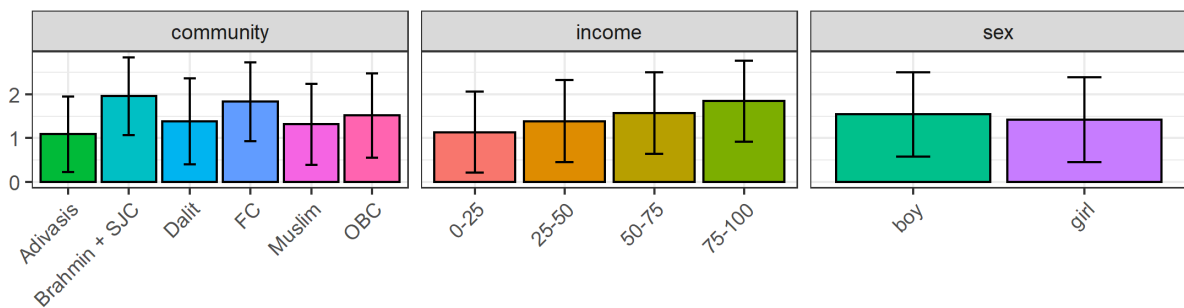
<b>Sex</b>	<b>2004-2005 (n = 10,981)</b>			<b>2011-2012 (n = 10,450)</b>		
	<b>Currently attend</b>	<b>Attended in past</b>	<b>Do not attend or NA</b>	<b>Currently attend</b>	<b>Attended in past</b>	<b>Do not attend or NA</b>
Boy	1008	132	15	1580	16	10
Girl	630	81	4	1280	10	2

Note: n = 21,431 children tested

2004-2005: mathematics

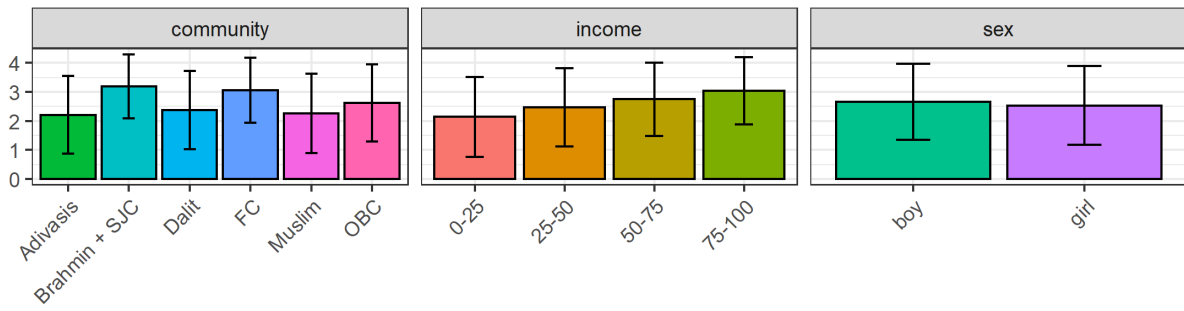


2011-2012: mathematics

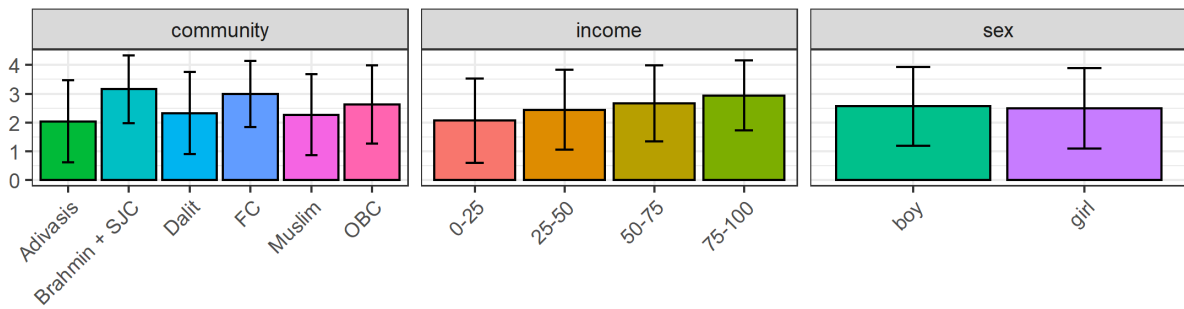


**Figure A.1.1. Average mathematics scores for both survey rounds, by category.** Standard deviations are represented by the black whiskers. We divided households into four income groups by constructing a wealth quartile separately for each state-year. The community graph encompasses the dominant religious groups and castes. We grouped the most privileged caste (Brahmins) with the most privileged religious groups (Sikhs, Jains, and Christians). FC and OBC are abbreviations for Forward Caste and Other Backward Caste. The income graph displays income quartiles (e.g., 0-25 represents the lowest 25<sup>th</sup> percentile). n = 21,431 children tested

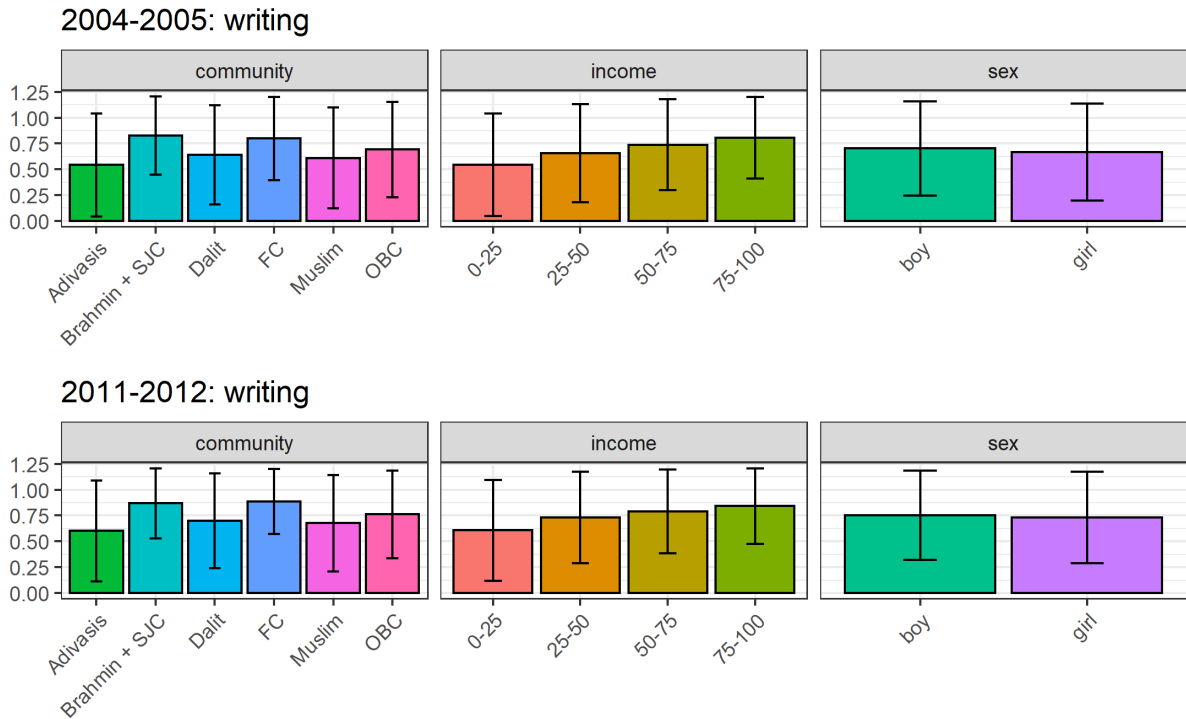
### 2004-2005: reading



### 2011-2012: reading



**Figure A.1.2. Average reading scores for both survey rounds, by category.** Standard deviations are represented by the black whiskers. We divided households into four income groups by constructing a wealth quartile separately for each state-year. The community graph encompasses the dominant religious groups and castes. We grouped the most privileged caste (Brahmins) with the most privileged religious groups (Sikhs, Jains, and Christians). FC and OBC are abbreviations for Forward Caste and Other Backward Caste. The income graph displays income quartiles (e.g., 0-25 represents the lowest 25<sup>th</sup> percentile). n = 21,431 children tested



**Figure A.1.3. Average writing scores for both survey rounds, by category.** Standard deviations are represented by the black whiskers. We divided households into four income groups by constructing a wealth quartile separately for each state-year. The community graph encompasses the dominant religious groups and castes. We grouped the most privileged caste (Brahmins) with the most privileged religious groups (Sikhs, Jains, and Christians). FC and OBC are abbreviations for Forward Caste and Other Backward Caste. The income graph displays income quartiles (e.g., 0-25 represents the lowest 25<sup>th</sup> percentile). n = 21,431 children tested

**Table A.5. Who fetches? A short summary**

<b>Fetching water situation</b>	<b>2004-2005 (n = 10,981)</b>	<b>2011-2012 (n = 10,450)</b>
<i>% of tested children live in HH where...</i>	<b>%</b>	<b>%</b>
Children fetch	17.0	27.7
Adult women fetch	47.9	50.8
Adult men fetch	21.6	29.4
<i>Fetching times of individuals who fetch</i>	<b>Mean, SD (in min)</b>	<b>Mean, SD (in min)</b>
Children (n <sub>2004</sub> =1870, n <sub>2011</sub> =2898)	54.5, 57.4	34.9, 34.4
Adult women (n <sub>2004</sub> =2367, n <sub>2011</sub> =3068)	77.5, 70.5	50.6, 46.3
Adult men (n <sub>2004</sub> =5264, n <sub>2011</sub> =5305)	59.1, 57.3	36.1, 35.9
<i>% of tested children live in a household using...</i>	<b>%</b>	<b>%</b>
Any water off-premises where children fetch	96.5	96.5
Piped water where children fetch	10.4	15.7
Off-premises piped water where children fetch	91.9	93.1
Hand pump where children fetch	22.6	39.8
Open well where children fetch	22.6	33.2
Tube well where children fetch	16.7	23.9

Notes: The first three rows do not represent mutually exclusive categories; for example, children may live in households where women, men, and children fetch. SD is the abbreviation for standard deviation. n = 21,431 children tested

**Table A.6. Water fetching among children aged 8-11 across Indian states, 2004-2012**

State	ID	HH with tested children	% (number) of HH with tested children who do not fetch	Mean fetching time for children who fetch (min)	SD	Year
Andhra Pradesh	28	455	80.2% (365)	46.1	34.9	2004-2005
		349	82.5% (288)	36.2	25.5	2011-2012
Assam	18	136	86.0% (117)	8.9	6.8	2004-2005
		137	94.9% (130)	15.1	11.3	2011-2012
Bihar	10	649	82.6% (536)	74.8	66.1	2004-2005
		638	73.8% (471)	29.3	38.2	2011-2012
Chhattisgarh	22	383	73.6% (282)	31.9	25.8	2004-2005
		496	55.2% (274)	31.7	22.7	2011-2012
Goa	30	29	86.2% (25)	15.0	5.8	2004-2005
		30	96.7% (29)	10.0	NA	2011-2012
Gujarat	24	514	92.0% (473)	84.6	65.2	2004-2005
		373	93.0% (347)	33.1	37.4	2011-2012
Himachal Pradesh	2	176	76.1% (134)	30.5	28.5	2004-2005
		192	71.9% (138)	25.7	16.9	2011-2012
Jammu and Kashmir	1	214	86.9% (186)	46.8	48.0	2004-2005
		210	86.7% (182)	28.6	22.0	2011-2012
Jharkhand	20	217	71.9% (156)	39.1	38.3	2004-2005
		281	61.6% (173)	38.5	31.7	2011-2012
Karnataka	29	861	83.6% (720)	127.9	101.3	2004-2005
		563	77.4% (436)	42.7	27.5	2011-2012
Kerala	32	248	96.0% (238)	53.0	27.5	2004-2005
		270	95.6% (258)	27.5	15.7	2011-2012
Madhya Pradesh	23	906	73.4% (665)	70.4	48.1	2004-2005
		1069	40.4% (432)	41.0	40.1	2011-2012
Maharashtra	27	927	86.4% (801)	47.3	50.9	2004-2005
		747	74.0% (553)	53.0	54.0	2011-2012
Odisha	21	574	82.4% (473)	38.3	26.3	2004-2005

		538	81.8% (440)	45.8	29.4	2011-2012
Punjab	3	518	96.1% (498)	23.1	23.1	2004-2005
		385	84.9% (327)	29.1	23.4	2011-2012
Rajasthan	8	907	87.2% (791)	80.3	70.0	2004-2005
		930	77.4% (720)	41.6	30.3	2011-2012
Tamil Nadu	33	323	84.8% (274)	24.9	18.4	2004-2005
		354	87.0% (308)	49.2	42.7	2011-2012
Uttar Pradesh	9	1640	74.2% (1217)	38.2	32.0	2004-2005
		1657	61.1% (1013)	21.2	23.2	2011-2012
Uttarakhand	5	116	87.1% (101)	56.0	54.3	2004-2005
		120	76.7% (92)	32.1	25.0	2011-2012
West Bengal	19	564	81.2% (458)	22.1	32.5	2004-2005
		479	77.7% (372)	30.2	29.2	2011-2012
Haryana	6	554	96.6% (535)	85.6	78.7	2004-2005
		521	89.4% (466)	40.2	34.8	2011-2012
Delhi	7	70	95.7% (67)	36.7	46.2	2004-2005
		111	92.8% (103)	36.3	26.0	2011-2012

Notes: SD is the abbreviation for standard deviation. n = 21,431 children tested

**Table A.7. Naïve model results**

Variable	Mathematics		Reading		Writing	
	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Fetching time (observed, hrs)	-0.055	[-0.087, -0.023]	-0.070	[-0.12, -0.023]	-0.013	[-0.060, 0.033]
Water in household (referent: off-premises)	0.062	[0.025, 0.098]	0.080	[0.028, 0.13]	0.024	[-0.029, 0.076]
Leave-out village mean water in household	0.076	[0.0067, 0.14]	0.040	[-0.053, 0.13]	0.027	[-0.066, 0.12]
Age	0.20	[0.19, 0.21]	0.27	[0.26, 0.29]	0.061	[0.046, 0.076]
Log-expenditure	0.26	[0.23, 0.29]	0.26	[0.22, 0.30]	0.079	[0.042, 0.12]
Education	0.040	[0.037, 0.044]	0.060	[0.055, 0.065]	0.015	[0.010, 0.020]
Urban (referent: rural)	0.10	[0.061, 0.15]	0.098	[0.040, 0.16]	0.016	[-0.042, 0.074]
Boy (referent: girl)	0.10	[0.079, 0.13]	0.066	[0.032, 0.10]	0.018	[-0.017, 0.053]
Year (referent: 2004-2005)	-0.29	[-0.33, -0.25]	-0.29	[-0.34, -0.23]	-0.012	[-0.067, 0.042]
<i>Water infrastructure usual (referent: MOFP)</i>						
Tube well	0.034	[-0.017, 0.085]	0.068	[-0.0033, 0.14]	0.019	[-0.052, 0.090]
Hand pump	-0.036	[-0.080, 0.0078]	-0.091	[-0.15, -0.032]	-0.042	[-0.10, 0.018]
Open well	-0.023	[-0.081, -0.035]	0.0073	[-0.073, 0.088]	-0.017	[-0.097, 0.063]
Covered well	0.067	[-0.046, 0.18]	0.029	[-0.12, 0.17]	0.018	[-0.13, 0.16]
River	-0.015	[-0.19, 0.16]	-0.13	[-0.36, 0.11]	-0.029	[-0.26, 0.21]
Pond	-0.11	[-0.42, 0.19]	-0.026	[-0.35, 0.30]	-0.044	[-0.37, 0.28]
Tanker truck/rainwater/bottled/other	-0.049	[-0.15, 0.052]	-0.11	[-0.25, 0.035]	-0.043	[-0.19, 0.099]
<i>Community (referent: Brahmin + SJs)</i>						
Other Backward Class	-0.13	[-0.18, -0.072]	-0.15	[-0.23, -0.080]	-0.018	[-0.092, 0.056]
Dalit	-0.22	[-0.28, -0.16]	-0.33	[-0.40, -0.25]	-0.047	[-0.13, 0.032]
Forward caste	-0.040	[-0.10, 0.021]	-0.059	[-0.14, 0.021]	0.012	[-0.068, 0.092]
Muslim	-0.32	[-0.38, -0.25]	-0.45	[-0.55, -0.36]	-0.081	[-0.18, 0.014]
Adivasis	-0.29	[-0.37, -0.21]	-0.36	[-0.48, -0.24]	-0.087	[-0.21, 0.032]
<i>Month (referent: January)</i>						
February	-0.015	[-0.079, 0.050]	-0.028	[-0.12, 0.068]	0.0031	[-0.093, 0.099]

March	0.080	[0.0098, 0.15]	0.067	[-0.033, 0.17]	0.057	[-0.044, 0.16]
April	0.035	[-0.035, 0.11]	-0.032	[-0.13, 0.064]	0.028	[-0.069, 0.12]
May	-0.043	[-0.11, 0.028]	0.11	[-0.20, -0.015]	0.024	[-0.071, 0.12]
June	-0.042	[-0.11, 0.030]	-0.044	[-0.15, 0.061]	0.041	[-0.064, 0.15]
July	-0.031	[-0.11, 0.046]	-0.094	[-0.21, 0.022]	0.022	[-0.094, 0.14]
August	0.046	[-0.036, 0.13]	-0.032	[-0.15, 0.086]	0.051	[-0.067, 0.17]
September	-0.068	[-0.16, 0.027]	-0.0047	[-0.14, 0.13]	0.069	[-0.070, 0.21]
October	-0.16	[-0.32, 0.0047]	-0.22	[-0.42, -0.013]	-0.069	[-0.27, 0.13]
November	-0.066	[-0.16, 0.028]	-0.079	[-0.22, 0.060]	-0.083	[-0.22, 0.055]
December	-0.042	[-0.11, 0.030]	-0.083	[-0.18, 0.019]	-0.046	[-0.15, 0.055]
<i>District ID (2-68) (referent: district 1)</i>				Not shown		
Constant	-2.12	[-2.35, -1.90]	-1.82	[-2.17, -1.52]	-0.46	[-0.78, -0.14]
Adjusted R <sup>2</sup>	0.24		0.21		0.14	
n	21431		21431		21431	

Notes: The 95 percent confidence intervals (CIs) are constructed from cluster-robust standard errors at the village level. Water in household is a dummy variable representing the location of the usual water infrastructure (1 = on-premises). Leave-out village mean water in HH is a continuous variable representing the average location of the usual household water infrastructure for each village. Water infrastructure referent MOFP is mostly off-premises piped water. Community referent is Brahmins and Sikhs, Jains, and Christians.

**Table A.8. Main specification (linear model): First-stage results**

<b>First-stage variable</b>	<b>Estimate</b>	<b>95% CI</b>
Two-year average annual rainfall	-0.00036	[-0.00049, -0.00023]
Water in household (referent: off-premises)	-0.26	[-0.28, -0.23]
Leave-out village mean water in household	-0.030	[-0.068, 0.0078]
Age	0.0090	[0.0041, 0.014]
Log-expenditure	-0.010	[-0.025, 0.0041]
Education	-0.0031	[-0.0047, -0.0015]
Urban (referent: rural)	-0.0071	[-0.025, 0.011]
Boy (referent: girl)	-0.099	[-0.11, -0.084]
Year (referent: 2004-2005)	-0.0065	[-0.029, 0.016]
<i>Water infrastructure usual (four most common)</i> <i>(referent: MOFP)</i>		
Tube well	-0.00069	[-0.031, 0.030]
Hand pump	0.052	[0.033, 0.073]
Open well	0.029	[-0.0069, 0.066]
Covered well	0.038	[-0.020, 0.096]
River	0.018	[-0.080, 0.12]
Pond	0.010	[-0.28, 0.30]
Tanker truck/rainwater/bottled/other	-0.11	[-0.15, -0.066]
<i>Community (referent: Brahmin + SJs)</i>		
Other Backward Class	0.0057	[-0.013, 0.024]
Dalit	0.015	[-0.0093, 0.039]
Forward caste	0.018	[-0.0063, 0.043]
Muslim	0.023	[-0.0052, 0.051]
Adivasis	-0.0033	[-0.042, 0.035]
<i>Month (referent: January)</i>		
February	-0.025	[-0.050, 0.00021]
March	-0.00025	[-0.030, 0.029]
April	0.022	[-0.0050, 0.050]
May	0.095	[0.057, 0.13]
June	0.096	[0.050, 0.14]
July	0.12	[0.072, 0.17]
August	0.12	[0.055, 0.18]
September	0.036	[0.0084, 0.081]
October	-0.0059	[-0.073, 0.061]
November	-0.0022	[-0.035, 0.030]
December	-0.00049	[-0.028, 0.027]
Constant	0.34	[0.22, 0.45]
Adjusted R <sup>2</sup>	0.33	
n	21431	

Notes: Outcome in first stage is observed fetching time of children (in hours). The 95 percent confidence intervals (CIs) of the first-stage estimates are constructed from cluster-robust standard errors at the village level. Water in household is a dummy variable representing the location of the usual water infrastructure (1 = on-premises). Leave-out village mean water in HH is a continuous variable representing the average location of the usual household water infrastructure for each village. Water infrastructure referent MOFP is mostly off-premises piped water. Community referent is Brahmins and Sikhs, Jains, and Christians.

**Table A.9. Main specification (linear model): Second-stage results**

Second-stage variable	Mathematics		Reading		Writing	
	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Predicted fetching time	-1.23	[-2.32, -0.14]	-1.53	[-2.80, -0.26]	-0.87	[-1.36, -0.37]
Water in HH (referent: off-premises)	-0.24	[-0.52, 0.035]	-0.30	[-0.63, 0.032]	-0.20	[-0.32, -0.070]
Leave-out village mean water in HH	0.061	[-0.029, 0.15]	0.0020	[-0.12, 0.12]	0.0078	[-0.045, 0.060]
Age	0.21	[0.20, 0.23]	0.29	[0.27, 0.31]	0.069	[0.061, 0.077]
Log-expenditure	0.26	[0.22, 0.29]	0.25	[0.21, 0.30]	0.073	[0.054, 0.091]
Education	0.037	[0.032, 0.043]	0.056	[0.049, 0.063]	0.013	[0.0099, 0.015]
Urban (referent: rural)	0.082	[0.032, 0.13]	0.089	[0.023, 0.16]	0.0053	[-0.019, 0.030]
Boy (referent: girl)	-0.0080	[-0.12, 0.11]	-0.076	[-0.21, 0.060]	-0.066	[-0.12, -0.013]
Year (referent: 2004-2005)	-0.31	[-0.36, -0.26]	-0.32	[-0.38, -0.25]	-0.023	[-0.051, 0.0042]
<i>Water infrastructure usual (referent: MOFP)</i>						
Tube well	0.043	[-0.026, 0.11]	0.073	[-0.020, 0.17]	0.020	[-0.021, 0.060]
Hand pump	0.0044	[-0.071, 0.079]	-0.038	[-0.13, 0.055]	0.0016	[-0.033, 0.036]
Open well	0.0032	[-0.072, 0.078]	0.043	[-0.058, 0.14]	-0.00047	[-0.043, 0.042]
Covered well	0.097	[-0.034, 0.23]	0.085	[-0.079, 0.25]	0.027	[-0.041, 0.096]
River	-0.022	[-0.23, 0.18]	-0.15	[-0.43, 0.14]	-0.030	[-0.12, 0.060]
Pond	-0.089	[-0.56, 0.39]	-0.0095	[-0.49, 0.47]	-0.043	[-0.069, -0.016]
Tanker truck/rainwater/bottled/other	-0.15	[-0.33, 0.022]	-0.26	[-0.48, -0.032]	-0.13	[-0.22, -0.045]
<i>Community (referent: Brahmin + SJs)</i>						
Other Backward Class	-0.13	[-0.19, -0.069]	-0.15	[-0.23, -0.074]	-0.0095	[-0.038, 0.019]
Dalit	-0.20	[-0.27, -0.13]	-0.29	[-0.38, -0.21]	-0.028	[-0.060, 0.0049]
Forward caste	-0.017	[-0.086, 0.053]	-0.030	[-0.12, 0.057]	0.033	[-2.02E-05, 0.067]
Muslim	-0.30	[-0.38, -0.22]	-0.44	[-0.55, -0.33]	-0.063	[-0.10, -0.021]
Adivasis	-0.30	[-0.39, -0.21]	-0.35	[-0.48, -0.22]	-0.089	[-0.14, 0.040]
<i>Month (referent: January)</i>						
February	-0.028	[-0.10, 0.048]	-0.073	[-0.18, 0.029]	-0.015	[-0.054, 0.024]
March	0.11	[0.030, 0.18]	0.083	[-0.027, 0.19]	0.051	[0.0087, 0.093]

April	0.11	[0.033, 0.18]	0.016	[-0.14, 0.17]	0.047	[0.0083, 0.087]
May	0.090	[-0.031, 0.21]	0.035	[-0.13, 0.20]	0.098	[0.036, 0.016]
June	0.11	[-0.022, 0.23]	0.11	[-0.092, 0.30]	0.12	[0.057, 0.18]
July	0.14	[-0.021, 0.30]	0.12	[-0.11, 0.35]	0.11	[0.034, 0.20]
August	0.23	[0.044, 0.42]	0.20	[0.043, 0.35]	0.15	[0.058, 0.25]
September	0.035	[-0.077, 0.15]	0.11	[-0.13, 0.36]	0.092	[0.040, 0.14]
October	-0.11	[-0.30, 0.080]	-0.23	[-0.37, -0.10]	-0.082	[-0.17, 0.0068]
November	-0.058	[-0.15, 0.037]	-0.084	[-0.20, 0.027]	-0.071	[-0.12, -0.025]
December	-0.040	[-0.12, 0.044]	-0.11	[-0.43, 0.22]	-0.060	[-0.10, -0.018]
Constant	-1.97	[-2.38, -1.56]	-1.51	[-2.04, -0.98]	-0.27	[-0.47, -0.056]
Adjusted R <sup>2</sup>	0.23		0.20		0.13	
n	21431		21431		21431	

Instrument diagnostic tests	Test statistic, p-value	Test outcome	Test statistic, p-value	Test outcome	Test statistic, p-value	Test outcome
Weak instruments	39.91, <0.000	Pass	39.91, <0.000	Pass	39.91, <0.000	Pass
Wu-Hausman	13.56, <0.000	Pass	10.77, <0.0010	Pass	31.07, <0.000	Pass

Notes: Predicted fetching time covariate is in hours. The 95 percent confidence intervals (CIs) for the second-stage estimates are constructed from cluster bootstrapped standard errors at the village level (1000 replications). Water in household is a dummy variable representing the location of the usual water infrastructure (1 = on-premises). Leave-out village mean water in HH is a continuous variable representing the average location of the usual household water infrastructure for each village. Water infrastructure referent MOFP is mostly off-premises piped water. Community referent is Brahmins and Sikhs, Jains, and Christians. Instrumental variable checks: Sargan test was not passed when combined rainfall and groundwater instruments.

**Table A.10. Contributions of caregivers' fetching responsibilities to children's learning achievement**

Second-stage variable	Mathematics		Reading		Writing	
	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Women predicted fetching time	-0.37	[-0.66, 0.076]	-0.46	[-0.79, -0.12]	-0.26	[-0.38, -0.14]
Men predicted fetching time	-0.94	[-1.72, -0.16]	-1.17	[-2.06, -0.27]	-0.66	[-1.02, -0.30]

Notes: The 95 percent confidence intervals (CIs) of the first-stage estimates are constructed from cluster-robust standard errors at the village level. The 95 percent CIs of the second-stage estimates are constructed from cluster bootstrapped standard errors at the village level (1000 replications). Rainfall refers to the two-year average rainfall in centimeters. The outcome for the first-stage regression is caregiver fetching time (hours), and the outcome for the three separate second-stage regressions are the three test scores. n = 21,431 children tested

**Table A.11. Robustness checks for potential confounders or variables on the causal pathway**

Second-stage variable	Mathematics		Reading		Writing	
	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Predicted fetching time	-1.29	[-2.34, -0.25]	-1.43	[-2.65, -0.20]	-0.84	[-1.30, -0.37]
Water in household (referent: off-premises)	-0.27	[-0.54, 0.011]	-0.28	[-0.60, 0.051]	-0.19	[-0.32, -0.071]
Leave-out village mean water in household	0.058	[-0.029, 0.15]	0.0022	[-0.11, 0.12]	0.0069	[-0.041, 0.055]
Age	0.17	[0.15, 0.19]	0.22	[0.20, 0.24]	0.052	[0.043, 0.060]
Log-expenditure	0.22	[0.18, 0.26]	0.21	[0.16, 0.26]	0.050	[0.031, 0.069]
Education	0.035	[0.030, 0.040]	0.053	[0.046, 0.060]	0.011	[0.0087, 0.014]
Urban (referent: rural)	0.088	[0.037, 0.14]	0.10	[0.035, 0.16]	0.0057	[-0.019, 0.031]
Boy (referent: girl)	-0.022	[-0.14, 0.091]	-0.088	[-0.22, 0.046]	-0.067	[-0.12, -0.015]
Year (referent: 2004-2005)	-0.11	[-0.42, 0.20]	-0.045	[-0.42, 0.33]	0.17	[0.026, 0.31]
<i>Water infrastructure usual (most common) (referent: MOFP)</i>						
Tube well	0.070	[-0.0013, 0.14]	0.10	[0.011, 0.19]	0.029	[-0.011, 0.069]
Hand pump	0.019	[-0.053, 0.090]	-0.037	[-0.13, 0.051]	0.0013	[-0.033, 0.035]
Open well	0.027	[-0.047, 0.10]	0.053	[-0.043, 0.15]	-0.0031	[-0.044, 0.038]
<i>Community (referent: Brahmin + SJs)</i>						
Other Backward Class	-0.11	[-0.17, -0.050]	-0.12	[-0.20, -0.047]	-0.0069	[-0.034, 0.020]
Dalit	-0.17	[-0.24, -0.099]	-0.24	[-0.32, -0.15]	-0.022	[-0.054, 0.0099]
Forward caste	-0.019	[-0.087, 0.050]	-0.04	[-0.11, 0.058]	0.028	[-0.0034, 0.059]
Muslim	-0.28	[-0.36, -0.20]	-0.38	[-0.49, -0.28]	-0.073	[-0.11, -0.033]
Adivasis	-0.27	[-0.36, -0.17]	-0.31	[-0.44, -0.18]	-0.084	[-0.14, -0.031]
<i>Month (referent: January)</i>						
February	-0.053	[-0.13, 0.023]	-0.10	[-0.20, 0.0036]	-0.025	[-0.063, 0.013]
March	0.090	[0.011, 0.17]	0.062	[-0.046, 0.17]	0.049	[0.0073, 0.091]
April	0.10	[0.030, 0.18]	0.0082	[-0.090, 0.11]	0.041	[0.0030, 0.080]
May	0.11	[-0.0094, 0.22]	0.061	[-0.083, 0.20]	0.089	[0.033, 0.15]
June	0.11	[-0.021, 0.24]	0.10	[-0.055, 0.26]	0.11	[0.048, 0.17]

July	0.15	[-0.014, 0.31]	0.14	[-0.062, 0.33]	0.10	[0.022, 0.19]
August	0.21	[0.018, 0.39]	0.15	[-0.077, 0.37]	0.13	[0.038, 0.23]
September	-0.00083	[-0.11, 0.11]	0.058	[-0.087, 0.20]	0.072	[0.018, 0.13]
October	-0.11	[-0.31, 0.096]	-0.22	[-0.47, 0.033]	-0.098	[-0.20, 0.0015]
November	-0.066	[-0.17, 0.033]	-0.076	[-0.21, 0.062]	-0.076	[-0.12, -0.030]
December	-0.047	[-0.13, 0.032]	-0.12	[-0.22, -0.016]	-0.057	[-0.098, -0.016]
HDDS (referent: score 0)						
Score 1	-0.37	[-1.13, 0.40]	-0.55	[-1.52, 0.42]	0.0021	[-0.29, 0.30]
Score 2	0.29	[-0.34, 0.91]	0.24	[-0.64, 1.12]	0.13	[-0.073, 0.33]
Score 3	-0.048	[-0.64, 0.54]	0.019	[-0.78, 0.82]	-0.092	[-0.31, 0.12]
Score 4	-0.15	[-0.81, 0.51]	-0.26	[-1.04, 0.52]	0.094	[-0.19, 0.38]
Score 5	0.25	[-0.42, 0.92]	0.23	[-0.51, 0.97]	-0.11	[-0.41, 0.20]
Score 6	0.21	[-0.81, 0.38]	-0.15	[-0.79, 0.49]	0.11	[-0.18, 0.40]
Score 7	0.17	[-0.29, 0.63]	0.015	[-0.46, 0.49]	-0.083	[-0.32, 0.16]
Score 8	-0.060	[-0.36, 0.24]	0.037	[-0.26, 0.34]	0.061	[-0.11, 0.23]
Score 9	0.021	[-0.13, 0.17]	-0.072	[-0.23, 0.089]	-0.051	[-0.14, 0.037]
Farm days	-0.015	[-0.019, -0.012]	-0.021	[-0.026, -0.016]	-0.0055	[-0.0074, -0.0036]
Days absent	0.00016	[-0.00086, 0.0012]	0.00036	[-0.0011, 0.0018]	0.00040	[-0.00017, 0.0010]
Height	0.011	[0.0092, 0.013]	0.017	[0.014, 0.019]	0.0046	[0.0037, 0.0055]
Constant	-2.54	[-2.96, -2.13]	-2.49	[-3.02, -1.96]	-0.49	[-0.69, -0.29]
n	19601		19601		19601	

Notes: The 95 percent confidence intervals (CIs) of the second-stage estimates are constructed from cluster-robust standard errors at the village level. Rainfall refers to the two-year average rainfall in centimeters. The outcome for the first-stage regression is children's fetching time (hours), and the outcomes for the three separate second-stage regressions are the three test scores. Water in household is a dummy variable representing the location of the usual water infrastructure (1 = on-premises). Leave-out village mean water in household is a continuous variable representing the average location of the usual household water infrastructure for each village. HDDS refers to the Household Dietary Diversity Score, which is defined as the number of unique food (groups) consumed by the household in the thirty days prior to the survey. This score is a proxy measure of household food access.<sup>92</sup> The farm day and days absent variables are included as covariates in both stages and refer to the children's days spent out of school over the past month and children's days spent farming over the last year prior to that of the survey, respectively. Height is measured in centimeters and only included for children with valid measurements within six standard deviations of the sample mean.

**Table A.12. Linear probability models accounting for ordinality of test scores** <sup>50</sup>

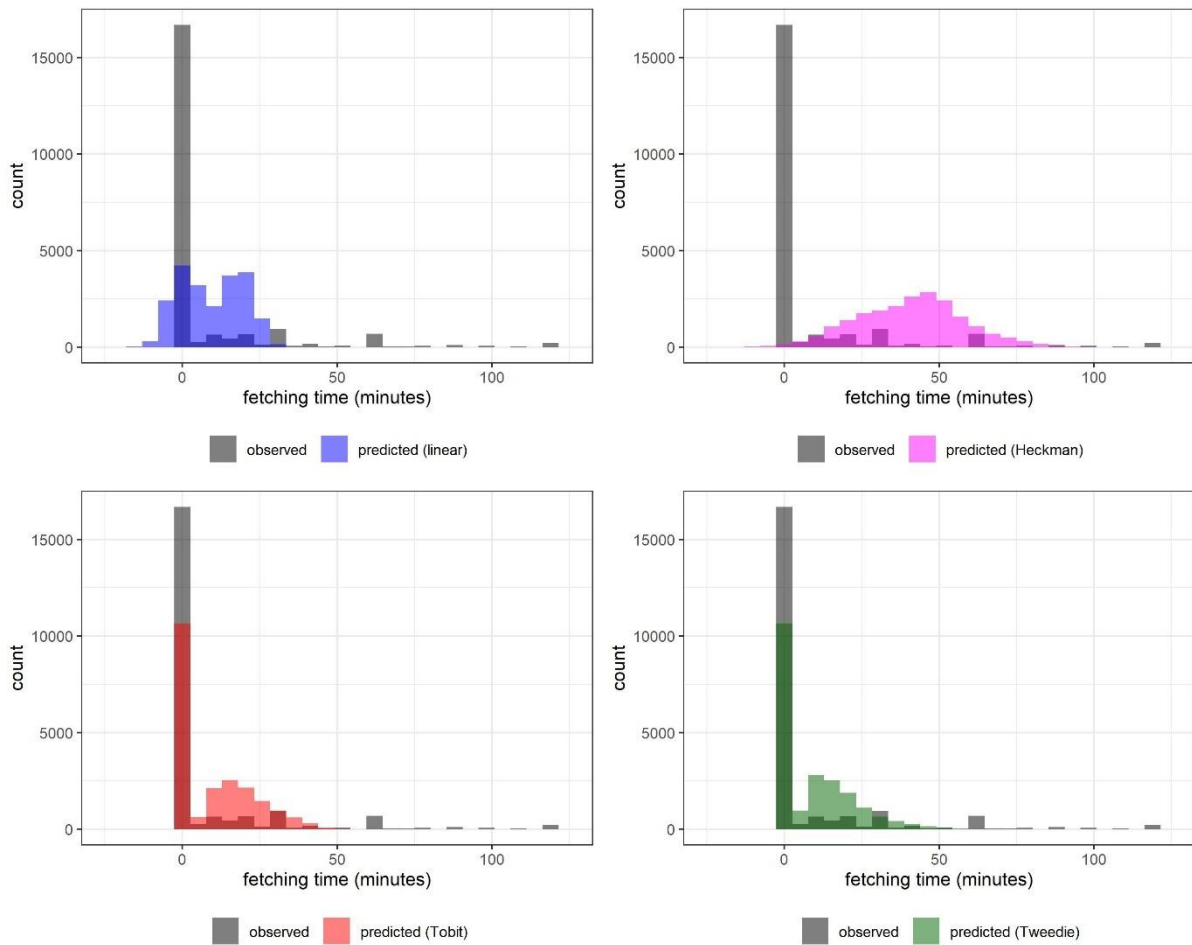
<b>Mathematics test score</b>				
	≥ Number	≥ Subtract	≥ Divide	
Predicted fetching time	-0.53 [-0.87, -0.19]	-0.82 [-1.35, -0.29]	0.12 [-0.30, 0.54]	
<b>Reading test score</b>				
	≥ Letter	≥ Word	≥ Sentence	≥ Paragraph
Predicted fetching time	-0.37 [-0.61, -0.13]	-0.67 [-1.06, -0.28]	-0.77 [-1.28, -0.25]	0.28 [-0.16, 0.72]
<b>Writing test score</b>				
	Writes with two or fewer mistakes			
Predicted fetching time	-0.87 [-1.33, -0.40]			

Notes: Referent for mathematics model is “cannot recognize a number”; referent for reading model is “cannot recognize a letter”; and referent for writing model is “cannot write.” For each column, the point estimate is listed followed by the bracketed 95 percent confidence interval, constructed from cluster-robust standard errors at the village level. n = 21,431 children tested

**Table A.13. Sensitivity to assumptions about the data-generating process**

Second-stage	Heckit		Tobit		Tweedie	
	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Predicted fetching time						
Mathematics	-0.30	[-0.99, 0.39]	-0.25	[-0.45, -0.050]	-0.17	[-0.35, 0.011]
Reading	-0.37	[-1.46, 0.71]	-0.22	[-0.49, 0.063]	-0.16	[-0.40, 0.075]
Writing	-0.21	[-0.46, 0.040]	-0.090	[-0.19, 0.00068]	-0.10	[-0.19, -0.011]
n	21431		21431		21431	

Notes: The 95 percent confidence intervals (CIs) are constructed from cluster bootstrapped standard errors at the village level (1000 replications). Heckit: 16663 censored, 4768 observed. The inverse Mills ratio (not shown) is 0.016 [-0.67, 0.70], and its insignificance may suggest that a sample-selection model is inappropriate; sigma (estimator of the standard errors of the residual in the second step) is 0.71; rho (correlation of errors in the two steps) is 0.023. Tobit: 16663 left-censored, 4768 uncensored. While the many of the results may not be significantly different from zero at the 0.05 alpha level, we are cautious about accepting the null hypotheses given that the effect sizes are large, and the confidence intervals predominantly consist of negative values.<sup>320</sup>



**Figure A.2. Sensitivity to assumptions about the data-generating process: Comparing the predicted fetching times with the observed fetching times (minutes) across the different methods for dealing with zeros (including main linear model).** Observed data range from 0-600 minutes. Given the focus is on zero fetching time, the x-axes were restricted to (-25, 125) minutes. No model predicts exact zeros; the bin at  $x = 0$  contains values close to zero. The predictive fit of the Tobit and Tweedie are similar to one another and fit the observed data the best. Interestingly, the difference in predictions is clustered around the ten-minute fetching time mark, with the three alternate models underpredicting relative to the linear model and to the observed data.  $n = 21,431$  children tested

**APPENDIX 2 FOR CHAPTER 3 (CHINA)**

**IRB APPROVAL**

June 25, 2021

Dear LEIGH HAMLET:

On 6/25/2021, University of Washington IRB Committee B reviewed the following application:

Type of Review:	Initial Study
Title of Study:	Environmental health and child height in China: An analysis of panel data from 1989-2015
Investigator:	LEIGH HAMLET
IRB ID:	STUDY00013590
Funding:	None
IND, IDE, or HDE:	None

**IRB Approval**

Under FWA #00006878, the IRB approved your activity.

- **Depending on the nature of your study, you may need to obtain other approvals or permissions to conduct your research. For example, you might need to apply for access to data or specimens (e.g., to obtain UW student data). Or, you might need to obtain permission from facilities managers to approach possible subjects or conduct research procedures in the facilities (e.g., Seattle School District; the Harborview Emergency Department).**
- Your application qualified for expedited review (“minimal risk”; Category 5).
- Under the Revised Common Rule this IRB approval is valid until study completion. In other words, there is no expiration date and you are not required to submit Continuing Review Reports to maintain your approval. However, you are still required to (1) obtain IRB approval before making any changes (modifications) to your research, and (2) provide the IRB with any Reportable New Information such as breaches of confidentiality or unanticipated problems.
- This approval applies only to the activities described in your application.

**Determinations, waivers, and regulations**

The IRB made the determinations and waivers listed in the table below. Note that any granted waivers of consent or parent permission do not override a subject’s refusal to provide broad consent.

Requirement	Determination or Waiver
Involvement of children	Approved—Category 404 “no more than minimal risk”
Parental permission	Waived
Assent	Assent is waived

Thank you for your commitment to ethical and responsible research. We wish you great success!

Sincerely,  
Deborah Dickstein, MSPH  
Human Subjects Review Administrator, Team B  
206-543-5971 [dickstei@uw.edu](mailto:dickstei@uw.edu)

**IRB APPROVAL OF MODIFICATION**

July 7, 2021

Dear LEIGH HAMLET:

On 7/7/2021, University of Washington IRB Committee B reviewed the following application:

Type of Review:	Modification / Update
Title of Study:	Environmental health and child height in China: An analysis of panel data from 19892015
Investigator:	LEIGH HAMLET
STUDY ID:	STUDY00013590
MOD ID:	MOD00010383
Funding:	None
IND, IDE, or HDE:	None

**IRB Approval**

Under FWA #00006878, the IRB approved modifications to your research.

- COVID NOTE: Researchers must comply with current infection control requirements and complete a self-assessment that activities fit within allowable research as described on the [HSD website](#).
- Your modification(s) to the research qualified for expedited review (“minimal risk”; Category “minor change”).

Thank you for your commitment to ethical and responsible research. We wish you great success!

Sincerely,

Jordyn Wheeler

IRB Administrator | Human Subjects Division | University of Washington

[Jwl44@uw.edu](mailto:Jwl44@uw.edu) | 206.543.2529

*China Health and Nutrition Survey*

**Agreement for the Use of Confidential Data**

Name, Title, and Email Address of Researcher: \_\_\_\_\_

Leigh Hamlet, Graduate Research Assistant, lhamlet@uw.edu

Researcher's Institutional Address: Department of Civil & Environmental Engineering,

University of Washington College of Engineering, 201 More Hall Box 252700, Seattle, WA, 98195

Researcher's Signature: \_\_\_\_\_ Date: 08/06/2021

Other scholars at this institution who will have access to these CHNS data:

Name, Title, and Email Address of Researcher: Department of Civil & Environmental Engineering

Jessica Kaminsky, PhD, Associate Professor, jkaminsk@uw.edu

Name, Title, and Email Address of Researcher: Department of Global Health

Suman Chakrabarti, MS, Graduate Research Assistant, sc428@uwnetid.mail.onmicrosoft.com

Name, Title, and Email Address of Researcher: \_\_\_\_\_

\_\_\_\_\_

Name, Title, and Email Address of Researcher: \_\_\_\_\_

\_\_\_\_\_

Name of Department or Institute: Department of Civil & Environmental Engineering

Name and Title of Department Chair or Institute Director: Laura Lowes, PhD

\_\_\_\_\_

Chair/Director's Institutional Address: \_\_\_\_\_

University of Washington College of Engineering, 201 More Hall Box 252700, Seattle, WA, 98195

Signature of Chair/Director:  Date: 8/10/2021

## Supplementary methods

### *Data*

Within each province (Beijing, Chongqing, Guangxi, Guizhou, Heilongjiang, Henan, Hubei, Hunan, Jiangsu, Liaoning, Shandong, or Shanghai), the China Health and Nutrition Survey (CHNS) stratifies counties by income and randomly selects four through a weighted sampling scheme, in addition to the provincial capital city and a low-income city. Within each county or city, villages and urban/suburban neighborhoods (collectively referred to as communities, or primary sampling units) are also randomly selected. Within each community, the CHNS randomly selects households and interviews all members of those households. The CHNS includes individual- and household-level surveys given to each household, as well as a community survey that is completed using several sources, including neighborhood officials, informants, market visits, and official records.<sup>321,322</sup> Due to purposeful sampling at the province and county/city levels and loss to follow-up among households, the data are not representative at the national, province, or community levels, despite the original baseline sample being representative of each province.

The dataset was obtained by merging the individual and household level datasets (after which  $n = 109,496$ , where  $n$  is the number of person-year observations). To create our household- and community-level exposure and income variables, we sequentially removed rows with missing data for these variables (after which  $n = 104,453$ , referred to as the “original” dataset in Appendix 2 Tables A16 and A17). It is important to note that we removed the ambiguous “other” category from polluting fuel ( $n = 243$ ) and the “unknown” category from water treatment ( $n = 9$ ). Then, we dropped five communities that had data for one survey year AND had no roads and/or postal service data OR population density data (after which  $n = 104,091$ ). We removed individuals without height measurements (after which  $n = 97,770$ ). We retained individuals with valid height measurements (within  $\pm 6$  SD of the World Health Organization (WHO) Growth Standards median) who were 0 through 228 months of age (after which  $n = 22,666$ ) and merged this child panel dataset with parental height and education data from the household surveys (after which  $n = 20,177$ ). Finally, we removed rows (each representing a single person-year) with missing data for our main model covariates (after which  $n = 12,045$ , referred to as the “final” dataset in Appendix 2 Tables A16, A17, and A19).

### *Covariates*

To retain our sample of repeated individuals, we filled in missing community-level population density (rate of missingness approximately 44 percent) and public goods/services data (rate of missingness less than 10 percent for all four variables) using linear predictive models with a linear trend for survey year, as well as province and community fixed effects and their interactions with survey year. For communities with missing values, we only imputed if they had at least two non-missing values (minimum was 16 per community). We limited our predictions to the range present in the data, replacing predictions outside of the range with the minimum (0.10) or maximum (12.03) log population density value (order of magnitude of the maximum supported by <sup>323(p80)</sup>).

On extracting data on education from the CHNS, we coded each secondary vocational school attendance as 0.5 years of education rather than a full year to indicate its inequivalence to a corresponding year of high school.<sup>324</sup>

### *Extension: Instrumental variables regression robustness check for household polluting fuel*

We first tested the relevance of the instruments by calculating Pearson correlation coefficients. The polluting fuel outcome and coal subsidy variables were positively and statistically significantly related (0.21,  $p < 0.00$ ), and polluting fuel was negatively and significantly associated with the gas subsidy variable (-0.17,  $p < 0.00$ ). We thought it reasonable to assume that these subsidies do not affect HAD except through fuel use. As Wang et al. (2021) discovered, since 2017 energy subsidies in China have not reduced households' fiscal and non-energy expenditures.<sup>325</sup> Though the time period is more contemporary than ours, the finding may suggest that subsidies would not affect HAD through changes in households' spending on, say, nutritious foods.

We proceeded with fitting our first stage using a binomial GEE model with household polluting fuel as our outcome, our full set of controls (excluding community-level exposures), a linear time trend, and community fixed effects. We predicted polluting fuel using from the first-stage and redefined the predictions such that a predicted value over 0.5 was assigned a value of 1 and below 0.5 was assigned 0 (to recapture the binary nature of the original variable). We then fit a linear ordinary least-squares second stage using the predicted polluting fuel values and residuals from the first stage, with

HAD as our outcome and the same controls. We clustered our second-stage standard errors by community. We cluster-bootstrapped both stages together to obtain the correct, cluster-robust standard errors on the second-stage estimates (replicates = 200). The results are presented in Appendix 2 Figure A4.

**Table A1. Generalized estimating equation estimates of height-for-age difference**

	Community + household model			Community model			Household model		
	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95
Community no treated water	0.065	-0.65	0.78	0.060	-0.50	0.62			
Community no piped water	-0.77	-1.40	-0.13	-0.27	-0.79	0.25			
Community open pit/no toilet	0.11	-0.46	0.69	-0.21	-0.69	0.28			
Community excreta	-0.865	-1.41	-0.32	-0.63	-1.08	-0.17			
Community polluting fuel	-0.066	-0.81	0.68	-0.53	-1.18	0.13			
Household no treated water	0.0071	-0.45	0.46				-0.0040	-0.36	0.35
Household no piped water	0.51	0.12	0.89				0.17	-0.15	0.48
Household open pit/no toilet	-0.31	-0.61	-0.0084				-0.28	-0.54	-0.033
Household excreta	0.22	-0.033	0.48				0.0033	-0.21	0.22
Household polluting fuel	-0.44	-0.79	-0.10				-0.45	-0.75	-0.14
Mother's height	0.25	0.22	0.28	0.25	0.22	0.29	0.25	0.22	0.28
Father's height	0.22	0.19	0.24	0.22	0.19	0.25	0.22	0.19	0.24
Female	0.67	-0.76	2.10	0.67	-0.76	2.09	0.68	-0.74	2.11
Number of children in household	-0.26	-0.43	-0.093	-0.27	-0.44	-0.10	-0.27	-0.44	-0.10
Mother's education	0.012	-0.047	0.071	0.013	-0.046	0.072	0.012	-0.047	0.071
Father's education	0.051	-0.012	0.11	0.051	-0.012	0.11	0.050	-0.012	0.11
Log community income	0.27	-0.082	0.61	0.26	-0.088	0.61	0.27	-0.069	0.62
Log household income	0.061	-0.070	0.19	0.066	-0.065	0.20	0.058	-0.073	0.19
Community electricity	-0.25	-1.92	1.41	-0.24	-1.90	1.43	-0.15	-1.82	1.51
Household electricity	-0.53	-1.40	0.33	-0.55	-1.41	0.32	-0.57	-1.44	0.30
Han	-0.83	-1.53	-0.14	-0.80	-1.50	-0.11	-0.80	-1.49	-0.10
Log population density	-0.010	-0.10	0.078	-0.0081	-0.10	0.080	-0.0049	-0.093	0.083
Public goods/services	-0.060	-0.14	0.021	-0.059	-0.14	0.022	-0.063	-0.14	0.018
Log GNI per capita	0.082	-1.55	1.71	0.059	-1.57	1.69	0.41	-1.21	2.03
Wave	0.51	0.10	0.93	0.52	0.10	0.93	0.47	0.058	0.89
Age spline knot 1	-5.39	-6.40	-4.38	-5.42	-6.44	-4.41	-5.37	-6.39	-4.36
Age spline knot 2	-5.57	-6.89	-4.26	-5.57	-6.89	-4.26	-5.57	-6.89	-4.26
Age spline knot 3	-7.55	-8.46	-6.64	-7.57	-8.48	-6.66	-7.54	-8.45	-6.63
Age spline knot 4	-12.83	-14.88	-10.77	-12.85	-14.91	-10.80	-12.82	-14.88	-10.76
Age spline knot 5	-4.63	-5.34	-3.92	-4.64	-5.35	-3.94	-4.62	-5.33	-3.92
Age spline knot 1*Female	0.52	-0.96	2.00	0.55	-0.92	2.03	0.51	-0.97	1.99
Age spline knot 2*Female	-2.78	-4.68	-0.88	-2.77	-4.67	-0.87	-2.78	-4.68	-0.88
Age spline knot 3*Female	1.81	0.56	3.07	1.83	0.57	3.08	1.80	0.55	3.06
Age spline knot 4*Female	0.065	-1.97	4.04	1.04	-1.97	4.04	1.02	-1.99	4.03

Age spline knot 5*Female	-0.77	2.57	4.51	3.54	2.57	4.50	3.53	2.56	4.50
Intercept	0.11	-85.69	-60.07	-73.01	-85.81	-60.21	-75.41	-88.12	-62.69
F-statistic, degrees-of-freedom (between- and within-group), p-value; marginal R <sup>2</sup>	54.5, 35 and 11710, 0.00; 0.42			62.9, 30 and 11715, 0.00; 0.42			62.9, 30 and 11715, 0.00; 0.42		

Notes: Confidence intervals are reported at the 95 percent confidence level. Standard errors are clustered by individual and are robust to heteroskedasticity. Interaction terms are denoted by an asterisk. All age spline coefficients are jointly significant at  $\alpha = 0.05$ . The null hypothesis for the heteroskedasticity-robust F-statistics is that all exposures and covariates, excluding community fixed effects and the intercept, are zero at any level of significance (i.e., testing the models against a null model with an intercept and community fixed effects). The marginal R<sup>2</sup> statistic measures improvement in fit between the estimated model and an intercept-only (null) model and shares the same intuition and interpretation as R<sup>2</sup>, though can take values less than zero if the intercept-only model is superior to the estimated model.<sup>326,327</sup> As there is no well-established statistic for assessing GEE model fit,<sup>328</sup> the statistics presented here should be interpreted with caution. n = 12,045 person-year observations (4998 unique individuals, 3200 unique households, 300 unique communities, 12 unique provinces)

**Table A2. Mixed model estimates of height-for-age difference**

	Community + household model			Community model			Household model		
	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95
Community no treated water	0.20	-0.58	0.98	0.22	-0.35	0.78			
Community no piped water	-0.68	-1.30	-0.064	-0.22	-0.74	0.31			
Community open pit/no toilet	-0.0029	-0.58	0.57	-0.29	-0.78	0.20			
Community excreta	-1.43	-2.02	-0.85	-1.18	-1.67	-0.68			
Community polluting fuel	-0.62	-1.38	0.14	-1.03	-1.70	-0.35			
Household no treated water	0.021	-0.47	0.51				-0.028	-0.39	0.33
Household no piped water	0.48	0.097	0.86				0.11	-0.24	0.47
Household open pit/no toilet	-0.29	-0.62	0.041				-0.37	-0.66	-0.091
Household excreta	0.24	-0.0048	0.49				-0.16	-0.38	0.058
Household polluting fuel	-0.40	-0.78	-0.0087				-0.59	-0.94	-0.25
Mother's height	0.26	0.22	0.30	0.26	0.22	0.30	0.26	0.22	0.30
Father's height	0.23	0.20	0.26	0.23	0.20	0.26	0.23	0.20	0.26
Female	0.81	-0.64	2.26	0.80	-0.64	2.25	0.82	-0.63	2.27
Number of children in household	-0.39	-0.58	-0.20	-0.39	-0.58	-0.21	-0.41	-0.60	-0.23
Mother's education	0.045	-0.013	0.10	0.045	-0.012	0.10	0.056	-0.0031	0.11
Father's education	0.074	0.0033	0.15	0.074	0.0030	0.15	0.079	0.0081	0.15
Log community income	0.48	0.091	0.86	0.47	0.083	0.85	0.54	0.16	0.92
Log household income	0.029	-0.11	0.17	0.033	-0.11	0.18	0.017	-0.13	0.16
Community electricity	0.15	-1.73	2.03	0.18	-1.73	2.08	0.44	-1.48	2.35
Household electricity	-0.62	-1.67	0.44	-0.63	-1.69	0.43	-0.71	-1.76	0.34
Han	0.072	-0.55	0.69	0.090	-0.53	0.71	0.11	-0.52	0.74
Log population density	0.019	-0.076	0.11	0.020	-0.075	0.11	0.039	-0.057	0.14
Public goods/services	-0.098	-0.19	-0.0084	-0.098	-0.19	-0.0080	-0.11	-0.20	-0.015
Log GNI per capita	-0.54	-2.77	1.69	-0.55	-2.78	1.68	-0.13	-2.40	2.14
Wave	0.54	-0.019	1.11	0.55	-0.017	1.11	0.50	-0.076	1.08
Age spline knot 1	-5.17	-6.36	-3.97	-5.20	-6.40	-4.00	-5.17	-6.37	-3.96
Age spline knot 2	-5.23	-6.84	-3.62	-5.23	-6.84	-3.62	-5.24	-6.86	-3.63
Age spline knot 3	-7.27	-8.44	-6.11	-7.29	-8.46	-6.12	-7.26	-8.44	-6.08
Age spline knot 4	-12.34	-14.83	-9.85	-12.36	-14.84	-9.87	-12.32	-14.83	-9.81
Age spline knot 5	-4.36	-5.13	-3.60	-4.37	-5.14	-3.60	-4.34	-5.12	-3.56
Age spline knot 1*Female	0.34	-1.19	1.866	0.37	-1.15	1.89	0.34	-1.18	1.86
Age spline knot 2*Female	-2.90	-4.79	-1.01	-2.89	-4.78	-0.99	-2.88	-4.79	-0.97

Age spline knot 3*Female	1.69	0.44	2.95	1.71	0.46	2.95	1.69	0.45	2.93
Age spline knot 4*Female	0.77	-2.20	3.74	0.77	-2.19	3.74	0.77	-2.21	3.75
Age spline knot 5*Female	3.43	2.47	4.40	3.43	2.46	4.40	3.45	2.49	4.42
Intercept	-74.28	-90.52	-58.03	-74.40	-90.65	-58.15	-78.35	-94.67	-62.02
Simulated likelihood-ratio test statistic, p-value	954.27, 0.00			946.04, 0.00			933.26, 0.00		

Notes: Confidence intervals are reported at the 95 percent confidence level. Standard errors are clustered by community and are robust to heteroskedasticity. Interaction terms are denoted by an asterisk. Models are estimated using maximum likelihood with random effects at the community, household, and individual levels. All age spline coefficients are jointly significant at  $\alpha = 0.05$ . Simulated likelihood ratio test statistic indicates whether the increase in the likelihood of the estimated model is higher than expected, using data from the simulated null model. The null model (here, a random-intercepts model) is assumed to be correct under the null hypothesis. The test was performed using the DHARMA package (version 0.4.6),<sup>329</sup> which is based on a parametric bootstrap (replicates = 200). As there is no well-established goodness-of-fit statistic for linear mixed models,<sup>330</sup> we recommend the results be interpreted with caution.  $n = 12,045$  person-year observations (4998 unique individuals, 3200 unique households, 300 unique communities, 12 unique provinces)

**Table A3. Generalized estimating equation estimates of height-for-age z-score**

	Community + household model			Community model			Household model		
	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95
Community no treated water	-0.026	-0.15	0.10	0.00020	-0.10	0.10			
Community no piped water	-0.17	-0.27	-0.060	-0.11	-0.20	-0.026			
Community open pit/no toilet	-0.013	-0.12	0.089	-0.050	-0.14	0.035			
Community excreta	-0.094	-0.19	0.0017	-0.052	-0.13	0.030			
Community polluting fuel	0.013	-0.12	0.14	-0.043	-0.16	0.070			
Household no treated water	0.028	-0.048	0.10				0.0090	-0.052	0.070
Household no piped water	0.055	-0.012	0.12				-0.020	-0.074	0.035
Household open pit/no toilet	-0.035	-0.087	0.016				-0.039	-0.081	0.0042
Household excreta	0.041	-0.0032	0.085				0.016	-0.022	0.053
Household polluting fuel	-0.055	-0.12	0.0063				-0.051	-0.10	0.0025
Mother's height	0.042	0.036	0.047	0.042	0.036	0.047	0.042	0.036	0.047
Father's height	0.035	0.031	0.040	0.035	0.031	0.040	0.035	0.031	0.040
Female	0.24	-0.20	0.69	0.24	-0.20	0.69	0.25	-0.20	0.69
Number of children in household	-0.037	-0.066	-0.0077	-0.038	-0.067	-0.0085	-0.037	-0.066	-0.0085
Mother's education	-0.0016	-0.011	0.0083	-0.0015	-0.011	0.0083	-0.0018	-0.012	0.0081
Father's education	0.0081	-0.0024	0.018	0.0080	-0.0024	0.018	0.0080	-0.0024	0.018
Log community income	0.010	-0.049	0.070	0.0095	-0.050	0.069	0.017	-0.0055	0.040
Log household income	0.017	-0.0052	0.040	0.018	-0.0048	0.041	0.014	-0.045	0.073
Community electricity	0.013	-0.30	0.33	0.018	-0.29	0.33	0.023	-0.29	0.33
Household electricity	-0.045	-0.22	0.13	-0.048	-0.22	0.12	-0.048	-0.22	0.12
Han	-0.12	-0.24	-0.0026	-0.12	-0.24	0.0022	-0.12	-0.23	0.0042
Log population density	0.0044	-0.011	0.020	0.0046	-0.011	0.020	0.0049	-0.011	0.020
Public goods/services	-0.018	-0.032	-0.0041	-0.018	-0.032	-0.0042	-0.019	-0.033	-0.0052
Log GNI per capita	-0.044	-0.37	0.28	-0.047	-0.37	0.27	0.00011	-0.32	0.32
Wave	0.12	0.034	0.20	0.12	0.034	0.20	0.11	0.029	0.20
Age spline knot 1	-0.60	-0.90	-0.31	-0.61	-0.91	-0.31	-0.60	-0.90	-0.30
Age spline knot 2	-0.62	-0.98	-0.26	-0.62	-0.98	-0.26	-0.62	-0.98	-0.25
Age spline knot 3	-0.51	-0.74	-0.28	-0.52	-0.75	-0.29	-0.51	-0.74	-0.28
Age spline knot 4	-1.95	-2.60	-1.29	-1.95	-2.61	-1.30	-1.94	-2.60	-1.29
Age spline knot 5	-0.11	-0.25	0.041	-0.11	-0.25	0.039	-0.10	-0.25	0.044
Age spline knot 1*Female	-0.026	-0.44	0.39	-0.020	-0.44	0.40	-0.028	-0.44	0.39
Age spline knot 2*Female	-0.52	-1.02	-0.011	-0.51	-1.02	-0.010	-0.52	-1.02	-0.012

Age spline knot 3*Female	0.0053	-0.32	0.33	0.0086	-0.31	0.33	0.0031	-0.32	0.32
Age spline knot 4*Female	-0.26	-1.18	0.65	-0.26	-1.18	0.66	-0.27	-1.19	0.65
Age spline knot 5*Female	0.39	0.19	0.59	0.39	0.19	0.59	0.39	0.19	0.59
Intercept	-12.02	-14.46	-9.59	-12.03	-14.47	-9.60	-12.38	-14.80	-9.96
F-statistic, degrees-of-freedom (between- and within-group), p-value; marginal R <sup>2</sup>	50.4, 0.00; 0.40			57.9, 0.00; 0.40			57.9, 0.00; 0.40		

Notes: Confidence intervals are reported the 95 percent confidence level. Standard errors are clustered by individual and are robust to heteroskedasticity. Interaction terms are denoted by an asterisk. All age spline coefficients are jointly significant at  $\alpha = 0.05$ . The null hypothesis for the heteroskedasticity-robust F-statistics is that all exposures and covariates, excluding community fixed effects and the intercept, are zero at any level of significance (i.e., testing the models against a null model with an intercept and community fixed effects). The marginal R<sup>2</sup> statistic measures improvement in fit between the estimated model and an intercept-only (null) model and shares the same intuition and interpretation as R<sup>2</sup>, though can take values less than zero if the intercept-only model is superior to the estimated model.<sup>326,327</sup> As there are no established statistics for assessing GEE model fit,<sup>328</sup> the statistics presented here should be interpreted with caution. n = 12,045 person-year observations (4998 unique individuals, 3200 unique households, 300 unique communities, 12 unique provinces)

**Table A4. Sensitivity analysis: Generalized estimating equation estimates of height-for-age difference with additional controls**

	Community + household model			Community model			Household model		
	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95
Community no treated water	0.22	-0.58	1.02	0.21	-0.42	0.83			
Community no piped water	-1.07	-1.77	-0.36	-0.56	-1.15	0.019			
Community open pit/no toilet	0.17	-0.47	0.80	-0.12	-0.66	0.42			
Community excreta	-1.07	-1.69	-0.46	-0.76	-1.28	-0.24			
Community polluting fuel	-0.15	-0.92	0.62	-0.46	-1.16	0.23			
Household no treated water	-0.0023	-0.51	0.50				0.030	-0.36	0.42
Household no piped water	0.51	0.093	0.93				0.047	-0.30	0.39
Household open pit/no toilet	-0.28	-0.61	0.053				-0.24	-0.52	0.040
Household excreta	0.29	0.010	0.57				0.027	-0.21	0.26
Household polluting fuel	-0.30	-0.67	0.066				-0.32	-0.65	0.0092
Mother's height	0.26	0.23	0.30	0.26	0.23	0.30	0.26	0.22	0.30
Father's height	0.24	0.22	0.27	0.24	0.22	0.27	0.24	0.22	0.27
Female	0.78	-2.73	4.29	0.71	-2.83	4.26	0.80	-2.72	4.33
Number of children in household	-0.21	-0.39	-0.020	-0.22	-0.40	-0.029	-0.22	-0.40	-0.029
Mother's education	0.0041	-0.058	0.067	0.0039	-0.058	0.066	0.0036	-0.059	0.066
Father's education	0.030	-0.035	0.096	0.030	-0.036	0.095	0.030	-0.036	0.095
Log community income	0.27	-0.11	0.65	0.27	-0.11	0.65	0.27	-0.11	0.65
Log household income	-0.0015	-0.14	0.14	0.0023	-0.14	0.14	-0.0030	-0.14	0.14
Community electricity	0.12	-2.01	2.25	0.16	-1.97	2.29	0.27	-1.86	2.41
Household electricity	-0.24	-1.25	0.76	-0.26	-1.27	0.74	-0.28	-1.29	0.73
Han	-1.15	-1.90	-0.40	-1.12	-1.87	-0.37	-1.12	-1.86	-0.37
Log population density	-0.042	-0.13	0.044	-0.041	-0.13	0.045	-0.037	-0.12	0.049
Public goods/services	-0.089	-0.18	0.00021	-0.088	-0.18	0.00044	-0.091	-0.18	-0.0019
Log GNI per capita	-2.41	-5.02	0.19	-2.41	-5.01	0.20	-1.70	-4.28	0.89
Wave	1.24	0.55	1.94	1.24	0.54	1.94	1.11	0.42	1.81
Age spline knot 1	-6.03	-8.40	-3.66	-6.12	-8.51	-3.73	-6.05	-8.43	-3.67
Age spline knot 2	-6.58	-9.44	-3.73	-6.66	-9.54	-3.78	-6.65	-9.52	-3.77
Age spline knot 3	-8.52	-10.45	-6.59	-8.58	-10.53	-6.64	-8.56	-10.50	-6.61
Age spline knot 4	-14.38	-19.50	-9.25	-14.53	-19.70	-9.36	-14.45	-19.60	-9.30
Age spline knot 5	-5.67	-6.84	-4.51	-5.72	-6.90	-4.55	-5.72	-6.89	-4.55
Age spline knot 1*Female	0.78	-2.45	4.02	0.87	-2.39	4.13	0.76	-2.49	4.01
Age spline knot 2*Female	-2.90	-6.79	1.00	-2.82	-6.75	1.11	-2.90	-6.82	1.01
Age spline knot 3*Female	1.95	-0.61	4.50	2.00	-0.58	4.58	1.93	-0.63	4.50
Age spline knot 4*Female	0.90	-6.13	7.92	1.01	-6.08	8.10	0.85	-6.21	7.91

Age spline knot 5*Female	3.93	2.45	5.41	3.96	2.46	5.45	3.94	2.45	5.42
Medical insurance	0.39	0.12	0.66	0.38	0.11	0.65	0.39	0.13	0.66
Energy intake, per 1000 Calories per day	0.30	0.027	0.57	0.30	0.027	0.57	0.32	0.050	0.59
Protein intake, per 10 grams per day	0.11	0.054	0.16	0.11	0.056	0.16	0.10	0.051	0.16
Intercept	-63.54	-81.94	-45.15	-63.73	-82.10	-45.36	-68.59	-86.79	-50.38

Notes: Confidence intervals are reported at the 95 percent confidence level. Standard errors are clustered by individual and are robust to heteroskedasticity. Interaction terms are denoted by an asterisk. Additional variables include daily energy intake, daily protein intake, and medical insurance. Energy intake is per 1000 U.S. Calories (1000 kilocalories) and is a three-day average. Protein intake is per 10 grams and is a three-day average. n = 10,381 person-year observations

**Table A5. Sensitivity analysis: Using height measurements within  $\pm 5$  SDs**

	Community + household model			Community model			Household model		
	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95
Community no treated water	0.053	-0.66	0.76	0.072	-0.49	0.63			
Community no piped water	-0.70	-1.34	-0.067	-0.22	-0.74	0.30			
Community open pit/no toilet	0.088	-0.49	0.66	-0.23	-0.72	0.25			
Community excreta	-0.87	-1.41	-0.33	-0.64	-1.10	-0.19			
Community polluting fuel	-0.046	-0.79	0.69	-0.46	-1.11	0.19			
Household no treated water	0.029	-0.42	0.48				0.017	-0.34	0.37
Household no piped water	0.49	0.11	0.88				0.18	-0.14	0.49
Household open pit/no toilet	-0.31	-0.61	-0.0070				-0.29	-0.54	-0.04
Household excreta	0.22	-0.040	0.47				-0.0046	-0.22	0.21
Household polluting fuel	-0.40	-0.74	-0.053				-0.40	-0.70	-0.10
Mother's height	0.25	0.22	0.28	0.25	0.22	0.29	0.25	0.22	0.28
Father's height	0.22	0.19	0.24	0.22	0.19	0.24	0.22	0.19	0.24
Female	0.68	-0.75	2.10	0.68	-0.75	2.10	0.69	-0.74	2.11
Number of children in household	-0.26	-0.43	-0.090	-0.27	-0.43	-0.10	-0.26	-0.43	-0.095
Mother's education	0.014	-0.045	0.073	0.014	-0.044	0.073	0.014	-0.045	0.072
Father's education	0.050	-0.013	0.11	0.050	-0.013	0.11	0.049	-0.013	0.11
Log community income	0.23	-0.11	0.58	0.23	-0.12	0.57	0.24	-0.10	0.58
Log household income	0.065	-0.065	0.20	0.070	-0.061	0.20	0.063	-0.067	0.19
Community electricity	-0.39	-2.08	1.30	-0.37	-2.06	1.32	-0.28	-1.97	1.40
Household electricity	-0.50	-1.38	0.38	-0.51	-1.39	0.37	-0.54	-1.42	0.34
Han	-0.84	-1.54	-0.15	-0.82	-1.51	-0.12	-0.81	-1.51	-0.12
Log population density	-0.0091	-0.10	0.079	-0.0077	-0.10	0.080	-0.0045	-0.093	0.084
Public goods/services	-0.060	-0.14	0.022	-0.059	-0.14	0.022	-0.063	-0.14	0.019
Log GNI per capita	0.16	-1.47	1.79	0.14	-1.49	1.77	0.49	-1.13	2.11
Wave	0.50	0.085	0.92	0.51	0.090	0.92	0.46	0.046	0.88
Age spline knot 1	-5.35	-6.35	-4.34	-5.38	-6.38	-4.37	-5.33	-6.34	-4.32
Age spline knot 2	-5.53	-6.84	-4.22	-5.53	-6.84	-4.22	-5.53	-6.84	-4.22
Age spline knot 3	-7.51	-8.42	-6.61	-7.53	-8.44	-6.62	-7.51	-8.41	-6.60
Age spline knot 4	-12.72	-14.77	-10.68	-12.74	-14.78	-10.69	-12.71	-14.76	-10.66
Age spline knot 5	-4.62	-5.33	-3.92	-4.64	-5.34	-3.93	-4.62	-5.32	-3.91
Age spline knot 1*Female	0.42	-1.04	1.89	0.45	-1.01	1.92	0.41	-1.06	1.88
Age spline knot 2*Female	-2.75	-4.65	-0.85	-2.75	-4.65	-0.85	-2.75	-4.65	-0.86
Age spline knot 3*Female	1.78	0.52	3.03	1.79	0.54	3.04	1.77	0.52	3.02
Age spline knot 4*Female	1.05	-1.95	4.05	1.03	-1.97	4.04	1.03	-1.97	4.03

Age spline knot 5*Female	3.52	2.56	4.49	3.52	2.55	4.48	3.51	2.55	4.48
Intercept	-73.027	-85.84	-60.22	-73.12	-85.91	-60.32	-75.53	-88.24	-62.82

Notes: Confidence intervals are reported at the 95 percent confidence level. Standard errors are clustered by individual and are robust to heteroskedasticity. Analyses included the full set of controls, linear time trend, and community fixed effects. Valid height measurements were those within  $\pm 5$  standard deviations (SDs) of the World Health Organization (WHO) growth standard median. The results are similar to the main results in Appendix 2 Table A1.  $n = 12,031$  person-year observations

**Table A6. Heterogeneity analysis: Age**

	Community + household model			Community model			Household model		
	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95
Community no treated water	-1.58	-2.86	-0.30	-0.57	-1.46	0.32			
Community no piped water	-0.90	-2.05	0.25	-0.88	-1.70	-0.064			
Community open pit/no toilet	0.22	-0.81	1.26	0.0087	-0.82	0.84			
Community excreta	1.04	0.066	2.02	1.33	0.52	2.14			
Community polluting fuel	0.62	-0.63	1.87	0.34	-0.65	1.32			
Household no treated water	0.99	0.047	1.94				0.050	-0.58	0.68
Household no piped water	0.040	-0.78	0.86				-0.38	-0.95	0.19
Household open pit/no toilet	-0.19	-0.82	0.43				-0.028	-0.52	0.47
Household excreta	0.29	-0.23	0.82				0.78	0.35	1.22
Household polluting fuel	-0.26	-1.02	0.49				0.13	-0.44	0.69
Age	-0.12	-0.17	-0.075	-0.12	-0.17	-0.075	-0.14	-0.19	-0.10
Community no treated water*Age	0.17	0.056	0.28	0.068	-0.00053	0.14			
Community no piped water*Age	0.017	-0.086	0.12	0.058	-0.0076	0.12			
Community open pit/no toilet*Age	-0.011	-0.10	0.080	-0.019	-0.089	0.051			
Community excreta*Age	-0.20	-0.29	-0.12	-0.21	-0.28	-0.14			
Community polluting fuel*Age	-0.056	-0.16	0.046	-0.076	-0.15	-0.0011			
Household no treated water*Age	-0.097	-0.19	-0.0088				-0.0041	-0.057	0.049
Household no piped water*Age	0.041	-0.039	0.12				0.052	0.0015	0.10
Household open pit/no toilet*Age	-0.0090	-0.069	0.051				-0.022	-0.067	0.024
Household excreta*Age	-0.0057	-0.056	0.044				-0.079	-0.12	-0.038
Household polluting fuel*Age	-0.019	-0.087	0.049				-0.055	-0.10	-0.0066
Intercept	-83.10	-96.07	-70.13	-83.56	-96.56	-70.57	-86.43	-99.26	-73.60

Notes: Confidence intervals are reported at the 95 percent confidence level. Standard errors are clustered by individual and are robust to heteroskedasticity. Analyses included the full set of controls, linear time trend, and community fixed effects. Here age was a continuous variable as opposed to a spline, and the interaction between age and sex was removed to simplify the interpretation of the interactions between age and the exposures. Interaction terms are denoted by an asterisk; the reference category is an individual in an environment with no exposures. Overall, the effect of age on HAD is exposure-dependent. The positive interaction terms for community-level no treated water and no piped water may suggest that HAD is less associated with age for children and adolescents in communities with 100 percent coverage of no treated water or no piped water compared to those in communities with full piped or treated

water coverage, all else equal. Conversely, as children and adolescents age, their growth faltering is higher if they live in communities with full excreta coverage and in households using polluting cooking fuel than in communities and households without these exposures.  $n = 12,045$  person-year observations

**Table A7. Heterogeneity analysis: Sex**

	Community + household model			Community model			Household model		
	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95
Community no treated water	0.47	-0.48	1.42	0.47	-0.22	1.16			
Community no piped water	-0.52	-1.36	0.31	-0.32	-0.96	0.33			
Community open pit/no toilet	0.020	-0.73	0.77	-0.39	-1.02	0.23			
Community excreta	-0.64	-1.34	0.061	-0.41	-1.00	0.18			
Community polluting fuel	-0.70	-1.65	0.26	-1.03	-1.81	-0.24			
Household no treated water	0.0089	-0.63	0.65				0.22	-0.23	0.67
Household no piped water	0.23	-0.342	0.79				0.032	-0.40	0.46
Household open pit/no toilet	-0.40	-0.81	0.0037				-0.44	-0.78	-0.11
Household excreta	0.22	-0.13	0.56				0.055	-0.24	0.35
Household polluting fuel	-0.31	-0.81	0.18				-0.57	-0.96	-0.17
Female	0.17	-0.39	0.73	0.18	-0.37	0.74	0.39	-0.090	0.87
Community no treated water*Female	-0.91	-2.12	0.30	-0.93	-1.73	-0.14			
Community no piped water*Female	-0.34	-1.42	0.73	0.19	-0.58	0.96			
Community open pit/no toilet*Female	0.35	-0.68	1.37	0.55	-0.26	1.36			
Community excreta*Female	-0.60	-1.55	0.34	-0.54	-1.31	0.22			
Community polluting fuel*Female	1.40	0.29	2.51	1.11	0.25	1.98			
Household no treated water*Female	-0.0090	-0.94	0.92				-0.50	-1.08	0.086
Household no piped water*Female	0.51	-0.26	1.28				0.27	-0.27	0.82
Household open pit/no toilet*Female	0.23	-0.38	0.84				0.41	-0.058	0.89
Household excreta*Female	0.056	-0.46	0.58				-0.11	-0.52	0.31
Household polluting fuel*Female	-0.29	-0.98	0.39				0.26	-0.26	0.77
Intercept	-72.86	-85.78	-59.94	-73.09	-86.00	-60.17	-75.53	-88.37	-62.70

Notes: Confidence intervals are reported at the 95 percent confidence level. Standard errors are clustered by individual and are robust to heteroskedasticity. Analyses included the full set of controls, linear time trend, and community fixed effects, except the age-spline and sex interaction was removed to simplify the interpretations of the interactions between sex and the exposures. Interaction terms are denoted by an asterisk; the reference category is a male living in an environment with no exposures. Community polluting fuel use prevalence is more detrimental to male compared to female growth, and community no treated water may be worse for females, all else being equal. n = 12,045 person-year observations

**Table A8. Heterogeneity analysis: Ethnicity**

	Community + household model			Community model			Household model		
	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95
Community no treated water	0.25	-1.16	1.67	-0.69	-1.72	0.35			
Community no piped water	0.18	-0.97	1.33	0.76	-0.10	1.63			
Community open pit/no toilet	0.84	-0.61	2.29	0.28	-0.99	1.54			
Community excreta	0.79	-0.36	1.94	0.72	-0.26	1.69			
Community polluting fuel	-0.021	-1.58	1.54	-0.37	-1.63	0.89			
Household no treated water	-0.94	-1.92	0.033				-0.69	-1.40	0.024
Household no piped water	0.60	-0.18	1.38				0.92	0.33	1.51
Household open pit/no toilet	-0.53	-1.24	0.17				-0.16	-0.77	0.46
Household excreta	-0.15	-0.73	0.44				0.14	-0.36	0.63
Household polluting fuel	-0.35	-1.16	0.47				-0.045	-0.69	0.61
Han	0.016	-1.16	1.20	0.060	-1.12	1.24	-0.56	-1.54	0.42
Community no treated water*Han	-0.032	-1.63	1.56	1.18	0.017	2.34			
Community no piped water*Han	-1.50	-2.82	-0.17	-1.64	-2.64	-0.63			
Community open pit/no toilet*Han	-0.84	-2.37	0.69	-0.55	-1.87	0.77			
Community excreta*Han	-2.05	-3.32	-0.77	-1.65	-2.73	-0.57			
Community polluting fuel*Han	0.0044	-1.63	1.64	-0.11	-1.40	1.18			
Household no treated water*Han	1.23	0.12	2.33				0.93	0.14	1.73
Household no piped water*Han	-0.15	-1.05	0.75				-1.03	-1.71	-0.35
Household open pit/no toilet*Han	0.27	-0.51	1.06				-0.14	-0.81	0.52
Household excreta*Han	0.46	-0.19	1.11				-0.17	-0.71	0.38
Household polluting fuel*Han	-0.11	-1.01	0.79				-0.45	-1.15	0.25
Intercept	-73.71	-86.51	-60.90	-73.79	-86.57	-61.01	-76.15	-88.86	-63.43

Notes: Confidence intervals are reported at the 95 percent confidence level. Standard errors are clustered by individual and are robust to heteroskedasticity. Analyses included the full set of controls, linear time trend, and community fixed effects. Interaction terms are denoted by an asterisk; the reference category is a non-Han individual living in an environment with no exposures. The effects of community and household no treated water may be worse among non-Han than Han, while community excreta and community and household no piped water affect Han more negatively than non-Han, all else being equal. n = 12,045 person-year observations

**Table A9. Heterogeneity analysis: Community income**

	Community + household model			Community model			Household model		
	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95
Community no treated water	-0.11	-0.88	0.66	0.030	-0.59	0.65			
Community no piped water	-0.61	-1.43	0.21	-0.22	-0.84	0.41			
Community open pit/no toilet	0.41	-0.31	1.13	-0.014	-0.59	0.56			
Community excreta	-1.62	-2.31	-0.93	-1.27	-1.86	-0.68			
Community polluting fuel	-0.075	-0.85	0.71	-0.60	-1.29	0.085			
Household no treated water	0.13	-0.38	0.63				0.068	-0.33	0.46
Household no piped water	0.42	-0.12	0.96				0.14	-0.26	0.54
Household open pit/no toilet	-0.40	-0.82	0.025				-0.26	-0.59	0.065
Household excreta	0.33	0.0013	0.66				-0.11	-0.39	0.17
Household polluting fuel	-0.50	-0.87	-0.13				-0.52	-0.84	-0.19
Log community income	0.86	0.22	1.49	0.85	0.22	1.49	0.61	0.051	1.17
Community no treated water*Income	-0.68	-1.75	0.40	-0.16	-0.88	0.56			
Community no piped water*Income	0.42	-0.57	1.40	0.20	-0.47	0.88			
Community open pit/no toilet*Income	0.95	-0.066	1.97	0.68	-0.12	1.48			
Community excreta*Income	-1.46	-2.33	-0.59	-1.21	-1.94	-0.49			
Community polluting fuel*Income	-0.34	-1.54	0.86	-0.69	-1.64	0.25			
Household no treated water*Income	0.46	-0.34	1.26				0.20	-0.31	0.71
Household no piped water*Income	-0.19	-0.90	0.52				-0.030	-0.51	0.45
Household open pit/no toilet*Income	-0.23	-0.86	0.39				0.038	-0.45	0.53
Household excreta*Income	0.25	-0.23	0.72				-0.23	-0.62	0.16
Household polluting fuel*Income	-0.34	-1.11	0.43				-0.53	-1.11	0.045
Intercept	-74.91	-87.81	-62.01	-74.97	-87.81	-62.12	-76.68	-89.39	-63.96

Notes: Confidence intervals are reported at the 95 percent confidence level. Standard errors are clustered by individual and are robust to heteroskedasticity. Analyses included the full set of controls, linear time trend, and community fixed effects. Interaction terms are denoted by an asterisk. "Income" refers to the natural logarithm of the community median household-level income. The reference category is an individual in an environment with no exposures. The benefits of community income to HAD are lessened in communities with 100 percent excreta coverage compared to 0 percent excreta coverage. n = 12,045 person-year observations

**Table A10. Heterogeneity analysis: Community population density**

	Community + household model			Community model			Household model		
	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95
Community no treated water	0.51	-1.74	2.76	-1.41	-3.03	0.21			
Community no piped water	-2.50	-4.63	-0.374	-0.50	-2.11	1.11			
Community open pit/no toilet	1.11	-0.81	3.03	1.44	-0.14	3.01			
Community excreta	-0.45	-2.43	1.52	0.54	-1.01	2.10			
Community polluting fuel	-0.50	-2.39	1.39	-0.72	-2.56	1.12			
Household no treated water	-1.85	-3.39	-0.30				-1.55	-2.66	-0.44
Household no piped water	1.97	0.55	3.39				0.92	-0.16	2.00
Household open pit/no toilet	0.28	-0.90	1.46				-0.32	-0.63	-0.01
Household excreta	1.10	0.019	2.18				0.96	0.13	1.79
Household polluting fuel	-0.52	-0.87	-0.16				-0.046	-1.13	1.04
Log population density	0.018	-0.19	0.23	0.036	-0.17	0.24	0.0052	-0.15	0.16
Community no treated water*Density	-0.059	-0.38	0.27	0.22	-0.010	0.46			
Community no piped water*Density	0.27	-0.064	0.60	0.036	-0.21	0.28			
Community open pit/no toilet*Density	-0.15	-0.44	0.14	-0.25	-0.49	-0.018			
Community excreta*Density	-0.073	-0.37	0.22	-0.19	-0.42	0.050			
Community polluting fuel*Density	0.082	-0.18	0.34	0.044	-0.22	0.30			
Household no treated water*Density	0.28	0.059	0.50				0.24	0.076	0.39
Household no piped water*Density	-0.23	-0.46	-0.012				-0.12	-0.29	0.043
Household open pit/no toilet*Density	-0.088	-0.27	0.090				-0.12	-0.55	0.31
Household excreta*Density	-0.14	-0.30	0.023				-0.15	-0.28	-0.027
Household polluting fuel*Density	-0.59	-1.11	-0.078				-0.057	-0.21	0.10
Intercept	-75.30	-88.12	-62.48	-74.07	-86.87	-61.26	-75.88	-88.58	-63.18

Notes: Confidence intervals are reported at the 95 percent confidence level. Standard errors are clustered by individual and are robust to heteroskedasticity. Analyses included the full set of controls, linear time trend, and community fixed effects. Interaction terms are denoted by an asterisk. "Density" refers to the natural logarithm of the community-level population density plus one. The reference category is an individual living in an environment with no exposures. Population density has a more negative effect on HAD among communities with 100 percent coverage of pit/no toilets compared to 0 percent coverage and in households with excreta compared to households without excreta. The effect of density on HAD is less among households with no treated water compared to households with treated water. n = 12,045 person-year observations

**Table A11. Heterogeneity analysis: Urban/rural status**

	Rural								
	Community + household model			Community model			Household model		
	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95
Community no treated water	0.20	-0.65	1.06	0.0018	-0.64	0.65			
Community no piped water	-0.79	-1.51	-0.074	-0.18	-0.77	0.41			
Community open pit/no toilet	0.29	-0.37	0.94	0.092	-0.45	0.63			
Community excreta	-0.89	-1.51	-0.28	-0.65	-1.17	-0.14			
Community polluting fuel	-0.31	-1.28	0.65	-0.82	-1.69	0.045			
Household no treated water	-0.18	-0.73	0.36				-0.14	-0.55	0.27
Household no piped water	0.62	0.18	1.06				0.29	-0.068	0.65
Household open pit/no toilet	-0.17	-0.52	0.18				-0.097	-0.39	0.19
Household excreta	0.22	-0.067	0.51				-0.0039	-0.25	0.24
Household polluting fuel	-0.49	-0.92	-0.072				-0.54	-0.92	-0.16
Intercept	-76.76	-93.18	-60.34	-76.89	-93.35	-60.44	-80.00	-96.26	-63.75
	Urban								
	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95
Community no treated water	-0.58	-1.90	0.74	-0.074	-1.23	1.08			
Community no piped water	-0.36	-1.75	1.04	-0.15	-1.35	1.05			
Community open pit/no toilet	-0.61	-1.86	0.63	-1.29	-2.38	-0.20			
Community excreta	-0.34	-1.56	0.88	-0.17	-1.20	0.86			
Community polluting fuel	0.65	-0.54	1.84	0.33	-0.68	1.33			
Household no treated water	0.51	-0.32	1.35				0.32	-0.41	1.04
Household no piped water	0.21	-0.55	0.96				-0.0023	-0.68	0.68
Household open pit/no toilet	-0.67	-1.25	-0.092				-0.79	-1.29	-0.29
Household excreta	0.16	-0.39	0.71				0.066	-0.39	0.52
Household polluting fuel	-0.29	-0.89	0.31				-0.16	-0.66	0.34
Intercept	-68.26	-91.43	-45.08	-67.59	-90.74	-44.44	-69.45	-92.43	-46.47

Notes: Exploring heterogeneity across rural/urban status required estimating two separate models and examining the overlap of the confidence intervals across each exposure (with more overlap indicating less heterogeneity). Confidence intervals were computed at the 95 percent confidence level from cluster-robust standard errors by individual. Analyses included the full set of controls, a linear time trend, and community fixed effects. There is overlap of the

confidence intervals of the corresponding exposure coefficients across the rural and urban analyses, suggesting there may not be substantial differences in the effects on HAD across rural/urban status.  $n_{\text{rural}} = 8529$  person-year observations;  $n_{\text{urban}} = 3516$  person-year observations

**Table A12. Excreta mechanism**

	Outcome: Household excreta presence			Outcome: Community excreta proportion		
	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95
Log population density	-0.0065	-0.018	0.0054	-0.0061	-0.017	0.0049
Household open pit/no toilet	0.080	0.027	0.13			
Community open pit/no toilet	-0.0022	-0.11	0.11	0.11	0.024	0.20
Household animal ownership	0.093	0.017	0.17			
Community animal ownership	-0.043	-0.17	0.087	0.049	-0.051	0.15

Notes: Estimates are from two linear regressions with household and community excreta levels as the outcomes. Both models included survey year and community fixed effects. Confidence intervals were computed at the 95 percent confidence level from cluster-robust standard errors by community. Animal categories include pigs, sheep/goats, poultry, and other livestock. n = 9376 person-year observations

**Table A13. Piped water mechanism**

	Outcome: Household hygiene			Outcome: Community hygiene		
	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95
Community no piped water	0.055	-0.018	0.13	-0.024	-0.069	0.021
Household no piped water	-0.0071	-0.077	0.063			

Notes: Estimates are from two linear regressions with household and community cleanliness as the outcomes. Both models included survey year and community fixed effects. Confidence intervals were computed at the 95 percent confidence level from cluster-robust standard errors by community. n = 4287 person-year observations

**Table A14a. Associations between community baseline exposures and changes in exposures from 1989 to 2011**

		Community baseline level (1989)											
		Community-level exposure											
		No treated water			No piped water			Excreta			Open pit/no toilet		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Average (standard deviation) community-level change (2011-1989)	No treated water	0.038 (0.19)	-0.30 (0.14)	-0.45 (0.40)	-0.24 (0.36)	-0.28 (0.41)	-0.43 (0.40)	-0.23 (0.33)	-0.29 (0.42)	-0.42 (0.41)	-0.24 (0.34)	-0.28 (0.41)	-0.40 (0.41)
	No piped water	-0.077 (0.18)	-0.097 (0.24)	-0.49 (0.46)	0.026 (0.11)	-0.33 (0.39)	-0.77 (0.28)	-0.067 (0.28)	-0.34 (0.42)	-0.62 (0.40)	-0.10 (0.29)	-0.36 (0.42)	-0.50 (0.47)
	Excreta	-0.16 (0.25)	-0.13 (0.15)	-0.32 (0.37)	-0.17 (0.25)	-0.22 (0.29)	-0.40 (0.41)	0.019 (0.15)	-0.22 (0.25)	-0.60 (0.30)	-0.14 (0.23)	-0.31 (0.32)	-0.28 (0.39)
	Open pit/no toilet	-0.31 (0.37)	-0.24 (0.29)	-0.29 (0.33)	-0.25 (0.35)	-0.40 (0.34)	-0.20 (0.29)	-0.20 (0.30)	-0.35 (0.32)	-0.24 (0.37)	-0.028 (0.080)	-0.39 (0.37)	-0.35 (0.31)
	Polluting fuel	-0.70 (0.33)	-0.54 (0.42)	-0.60 (0.30)	-0.58 (0.37)	-0.69 (0.24)	-0.57 (0.33)	-0.52 (0.39)	-0.69 (0.30)	-0.57 (0.25)	-0.51 (0.40)	-0.66 (0.30)	-0.65 (0.26)
	HAD (cm)	2.83 (5.24)	4.24 (3.99)	4.73 (5.13)	4.06 (4.83)	3.86 (4.23)	4.74 (6.25)	3.93 (4.95)	4.07 (5.02)	4.68 (5.43)	3.16 (4.46)	4.47 (5.68)	4.61 (4.65)
n		35	15	87	47	67	41	37	67	35	34	59	44

Notes: For the first five rows of community-level exposures, each cell displays the mean (and standard deviation) change in the community exposure from 1989 to 2011. The cells in the last row for HAD show the mean (and standard deviation) change in the community-average HAD in centimeters from 1989 to 2011. All changes are calculated by subtracting the 1989 values from the 2011 values. The columns represent the relative community-level baseline conditions in 1989: “Low” represents communities at or below the first quartile for a particular baseline condition; “Med” is an abbreviation for medium and includes communities between the first and third quartiles; and “High” encompasses communities at or above the third quartile. Polluting fuel and electricity are excluded as columns in this table (but included in Appendix 2 Figure A7) due to their first and third quartiles both being equal to one. For no treated water, no piped water, and excreta, the magnitudes of the changes in exposures generally increase across the low, medium, and high baseline exposure categories (from light to dark orange) and decrease across the development indicator levels (from dark to light orange). That is, the communities with the worst water and excreta conditions at baseline (“High”) experienced the largest changes in those exposures, and the least-developed communities at baseline (those with the lowest income, lowest education, and poorest roads) experienced the greatest improvements in those exposures from 1989 to 2011; however, the relatively large standard deviations compared to the mean values suggests there is high variability across communities and that the patterns may not be universal. The relationships between baseline conditions and changes are less clear for open pit/no toilet and polluting fuel. A positive change in average community HAD suggests children and adolescents were generally taller in 2011 than in 1989. The largest positive changes in HAD appear to be in communities with worst sanitation conditions at baseline (“High”), though there is substantial variability in HAD within each baseline level, as indicated by the large standard deviations relative to the means. There is no apparent relationship between the average change in community mean HAD and baseline income. n = 137 communities

**Table A14b. Associations between community baseline development and changes in exposures from 1989 to 2011**

		Community baseline level (1989)							
		Community-level development indicator							
		Log median income			Average maximum household education			Roads	
		Low	Med	High	Low	Med	High	Absent	Present
Average (standard deviation) community-level change (2011-1989)	No treated water	-0.31 (0.45)	-0.32 (0.38)	-0.28 (0.39)	-0.40 (0.42)	-0.33 (0.41)	-0.16 (0.32)	-0.27 (0.37)	-0.34 (0.42)
	No piped water	-0.54 (0.47)	-0.32 (0.41)	-0.17 (0.36)	-0.44 (0.45)	-0.30 (0.44)	-0.25 (0.37)	-0.42 (0.45)	-0.26 (0.40)
	Excreta	-0.32 (0.37)	-0.25 (0.34)	-0.20 (0.28)	-0.22 (0.37)	-0.26 (0.29)	-0.29 (0.35)	-0.34 (0.34)	-0.18 (0.30)
	Open pit/no toilet	-0.18 (0.24)	-0.33 (0.33)	-0.30 (0.41)	-0.25 (0.33)	-0.29 (0.35)	-0.32 (0.33)	-0.30 (0.34)	-0.27 (0.33)
	Polluting fuel	-0.58 (0.24)	-0.70 (0.27)	-0.50 (0.42)	-0.61 (0.35)	-0.65 (0.31)	-0.59 (0.29)	-0.67 (0.25)	-0.56 (0.37)
	HAD (cm)	4.06 (4.73)	4.15 (5.32)	4.39 (5.08)	5.27 (4.46)	3.78 (4.58)	3.63 (6.45)	4.41 (4.98)	3.97 (5.21)
n		35	68	44	43	59	34	69	68

Notes: The cells in the last row for HAD show the mean (and standard deviation) change in the community-average HAD in centimeters from 1989 to 2011. All changes are calculated by subtracting the 1989 values from the 2011 values. The columns represent the relative community-level baseline conditions in 1989: “Low” represents communities at or below the first quartile for a particular baseline condition; “Med” is an abbreviation for medium and includes communities between the first and third quartiles; and “High” encompasses communities at or above the third quartile. Roads is only measured in terms of absence/presence. For no treated water, no piped water, and excreta, the magnitudes of the changes in exposures generally increase across the low, medium, and high baseline exposure categories (from light to dark orange) and decrease across the development indicator levels (from dark to light orange). That is, the least-developed communities at baseline (those with the lowest income, lowest education, and poorest roads) experienced the greatest improvements in those exposures from 1989 to 2011; however, the relatively large standard deviations compared to the mean values suggests there is high variability across communities and that the patterns may not be universal. The relationships between baseline conditions and changes are less clear for open pit/no toilet and polluting fuel. A positive change in average community HAD suggests children and adolescents were generally taller in 2011 than in 1989. There is no apparent relationship between the average change in community mean HAD and baseline income. n = 137 communities

**Table A15a. Attrition bias sensitivity analysis: Logit model results**

	Community + household model			Community model			Household model		
	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95	Estimate	Lower 95	Upper 95
Community no treated water	-0.12	-0.92	0.69	-0.24	-1.05	0.57			
Community no piped water	0.51	-0.095	1.11	0.44	-0.14	1.03			
Community open pit/no toilet	-0.59	-1.33	0.14	-0.73	-1.45	-0.0045			
Community excreta	0.26	-0.35	0.87	0.23	-0.39	0.85			
Community polluting fuel	-0.86	-1.65	-0.078	-0.90	-1.66	-0.14			
Household no treated water	-0.12	-0.39	0.14				-0.17	-0.54	0.20
Household no piped water	-0.063	-0.29	0.16				0.15	-0.12	0.42
Household open pit/no toilet	-0.13	-0.32	0.051				-0.30	-0.54	-0.07
Household excreta	-0.031	-0.17	0.11				0.032	-0.16	0.22
Household polluting fuel	-0.031	-0.20	0.14				-0.23	-0.43	-0.029
Mother's height	-0.0021	-0.014	0.010	-0.0020	-0.014	0.010	-0.0019	-0.013	0.010
Father's height	-0.0058	-0.016	0.0044	-0.0056	-0.016	0.0045	-0.0062	-0.017	0.0041
Female	0.34	-2.02	2.70	0.32	-2.05	2.68	0.27	-2.04	2.59
Number of children in household	0.072	-0.029	0.17	0.072	-0.029	0.17	0.071	-0.030	0.17
Mother's education	-0.061	-0.087	-0.035	-0.059	-0.085	-0.033	-0.060	-0.086	-0.034
Father's education	-0.023	-0.047	0.00033	-0.022	-0.046	0.0013	-0.025	-0.048	-0.00084
Log community income	0.45	-0.040	0.94	0.44	-0.046	0.93	0.45	-0.044	0.94
Log household income	-0.013	-0.090	0.064	-0.0086	-0.086	0.069	-0.017	-0.10	0.060
Community electricity	-5.49	-8.91	-2.08	-5.51	-8.93	-2.09	-5.88	-9.53	-2.23
Household electricity	0.62	0.15	1.10	0.63	0.15	1.10	0.62	0.14	1.10
Han	-0.21	-0.49	0.080	-0.21	-0.50	0.078	-0.22	-0.50	0.072
Log population density	-0.013	-0.11	0.084	-0.012	-0.11	0.085	-0.010	-0.11	0.085
Public goods/services	0.097	0.00024	0.20	0.099	0.0012	0.20	0.099	0.0039	0.19
Log GNI per capita	13.24	11.43	15.06	13.24	11.42	15.06	13.31	11.58	15.05
Wave	-4.10	-4.60	-3.60	-4.10	-4.61	-3.60	-4.07	-4.55	-3.59
Age spline knot 1	-10.75	-12.27	-9.23	-10.78	-12.30	-9.27	-10.73	-12.27	-9.19
Age spline knot 2	-10.02	-11.63	-8.40	-10.05	-11.66	-8.44	-10.01	-11.65	-8.37
Age spline knot 3	-8.53	-9.62	-7.44	-8.55	-9.63	-7.46	-8.50	-9.61	-7.40
Age spline knot 4	-17.97	-20.95	-15.00	-18.04	-21.00	-15.08	-17.94	-20.95	-14.92
Age spline knot 5	-5.04	-5.69	-4.38	-5.04	-5.70	-4.39	-5.04	-5.71	-4.37
Age spline knot 1*Female	-0.21	-2.42	2.00	-0.19	-2.41	2.02	-0.14	-2.31	2.04
Age spline knot 2*Female	-0.15	-2.64	2.34	-0.12	-2.62	2.38	-0.085	-2.54	2.37
Age spline knot 3*Female	-0.34	-2.04	1.36	-0.33	-2.03	1.38	-0.31	-1.97	1.36
Age spline knot 4*Female	-0.60	-5.24	4.04	-0.56	-5.21	4.10	-0.48	-5.04	4.09

Age spline knot 5*Female	-0.44	-1.37	0.50	-0.43	-1.37	0.50	-0.40	-1.32	0.52
Intercept	-44.13	-56.37	-31.88	-44.19	-56.45	-31.93	-44.59	-56.42	-32.77

Notes: Confidence intervals were computed at the 95 percent confidence level from cluster-robust standard errors by community. Analyses were done with the *glm.cluster* function in the *miceadds* package (version 3.9.14)<sup>63</sup> and included the full set of controls, linear time trend, and community fixed effects. The coefficients are in terms of log-odds and may be interpreted as the associations with loss-to-follow-up (outcome equal to one if the individual is observed only once in the dataset). Most of our exposures are statistically insignificantly related to whether or not an individual is observed once. n = 12,045 person-year observations

**Table A15b. Attrition bias sensitivity analysis: Sorting across exposure type**

	Household exposure type										
	No piped water		No treated water		Open pit/no toilet		Excreta around dwelling		Polluting cooking fuel		
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	
Loss to follow-up											
Observed only once (lost)	0.38	0.62	0.58	0.42	0.54	0.46	0.41	0.59	0.69	0.32	
Observed more than once (retained)	0.36	0.64	0.60	0.40	0.58	0.42	0.40	0.60	0.69	0.32	

Notes: This cross-tabulation shows the proportion of the sample in each intersecting category of exposure and loss to follow-up. The similarities across the two rows suggest that sample attrition does not strongly sort on household exposure. n = 12,045 person-year observations

**Table A16. Original and final panel dataset characteristics**

	Dataset	
	Original (n = 104,453 person-year obs)	Final (n = 12,045 person-year obs)
Number of unique...		
Individuals	32694	4998
Households	8443	3200
Communities	311	300
Provinces	12	12

**Table A17. Number of individuals per community**

Individuals per community	Dataset	
	Original (n = 104,453 person-year obs)	Final (n = 12,045 person-year obs)
1-25	2	232
25-50	13	67
50-75	71	1
75-100	44	0
100-125	74	0
125-150	67	0
150+	40	0

**Table A18. Exposure (household-level) survey items**

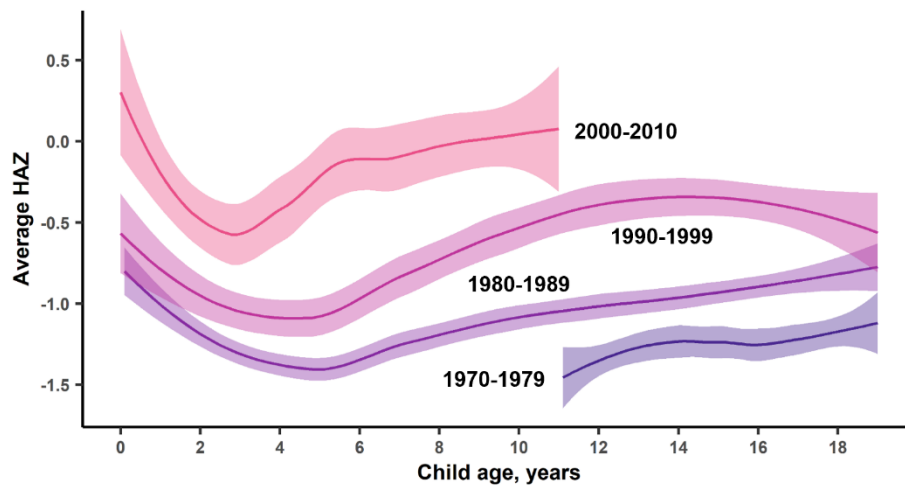
<b>Exposure</b>	<b>Survey question</b>	<b>Survey response options</b>
Treated water	What is the source of this water? (If more than one, record the most important.)	1989, 1991: Underground water; open well; spring, river, lake; rainwater, snow; water factory; don't know 1993-2011: Groundwater (< 5 m); open well (≤ 5 m); creek, spring, river, lake; ice/snow; water plant; other (specify); unknown
Piped water	How does your household obtain drinking water? (If more than one, record the most important.)	1989, 1991: Piped/tap in house; piped/tap in courtyard; pressurized well in courtyard; other place 1993-2011: In-house tap water; in-yard tap water; in-yard well; other place (specify)
Open pit/no toilet	What kind of toilet facilities does your household have?	1989, 1991: Inside house, flush; inside house, no flush; outside house, flush; outside house, no flush; cement open pit; earth open pit; none; other (specify) 1993-2011: No bathroom; flush, in-house; no flush, in-house; flush, outside house, public restroom; no flush, outside house, public restroom; cement open pit; earth open pit; other (specify)
Excreta	Is there any excreta around the dwelling place (observation by interviewer)?	1989, 1991: No excreta; very little excreta; some excreta apparent; much excreta 1993-2011: No excreta; very little excreta; some excreta; much excreta
Polluting fuel	What kind of fuel does your household normally (or usually) use for cooking? (If more than one, record the one most often used.)	1989, 1991: Coal; electricity; kerosene; liquid propane; natural propane; wood; charcoal; other (specify) 1993-2011: Coal; electricity; kerosene; liquified natural gas; natural gas; wood, sticks, straw, etc.; charcoal; other (specify)

Note: The response options are grouped into 1989, 1991 and 1993-2011 to mark the slight differences in language.

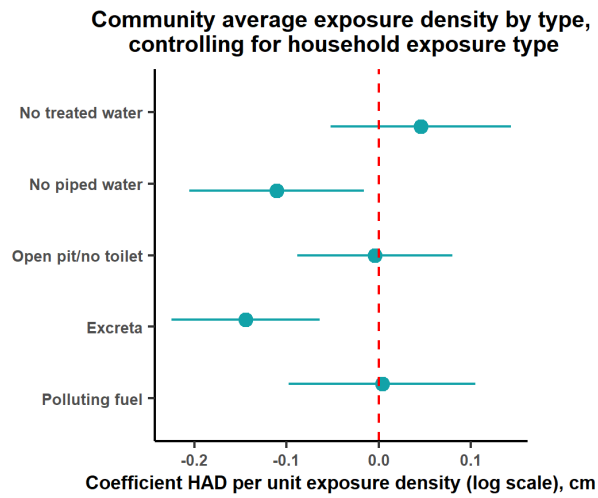
**Table A19. Final panel dataset characteristics**

<b>Number of data points</b>	<b>Number of individuals</b>
1	4998
2	3368
3	1987
4	1109
5	468
6	108
7	7
Sum	12,045

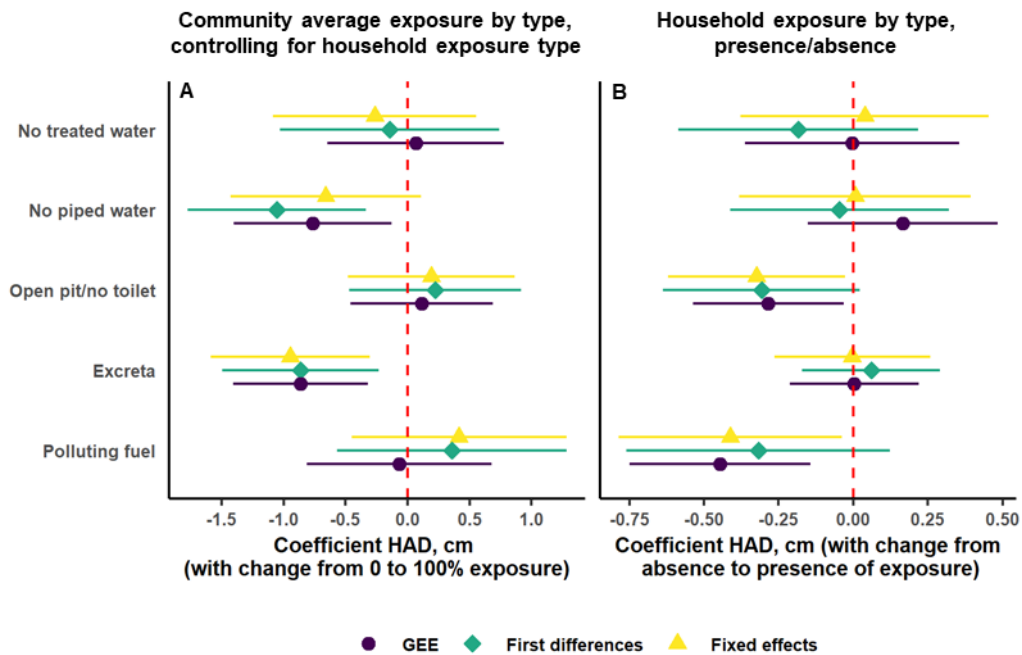
Note: The number of data points corresponds to the number of surveys in which the individuals were included.



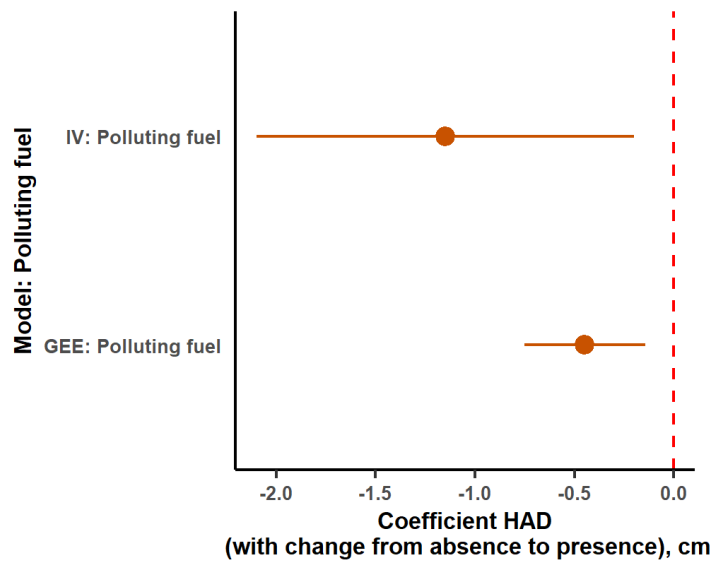
**Figure A1. Height-for-age z-score of children and adolescents aged 0-228 months, by birth cohort.** Curves fitted by locally estimated scatterplot smoothing (loess) represent mean height-for-age z-score (HAZ) by cohort with 95 percent confidence intervals. WHO Growth Standards were used to calculate growth indicators. Birth cohort 1970-1979 consists of individuals who at the time of the first survey in 1989 were at minimum 10 years of age. Birth cohort 2000-2010 excludes individuals born in 2011 and consists of individuals who at the time of the last survey in 2011 were at most 11 years of age. n = 12,045 person-year observations



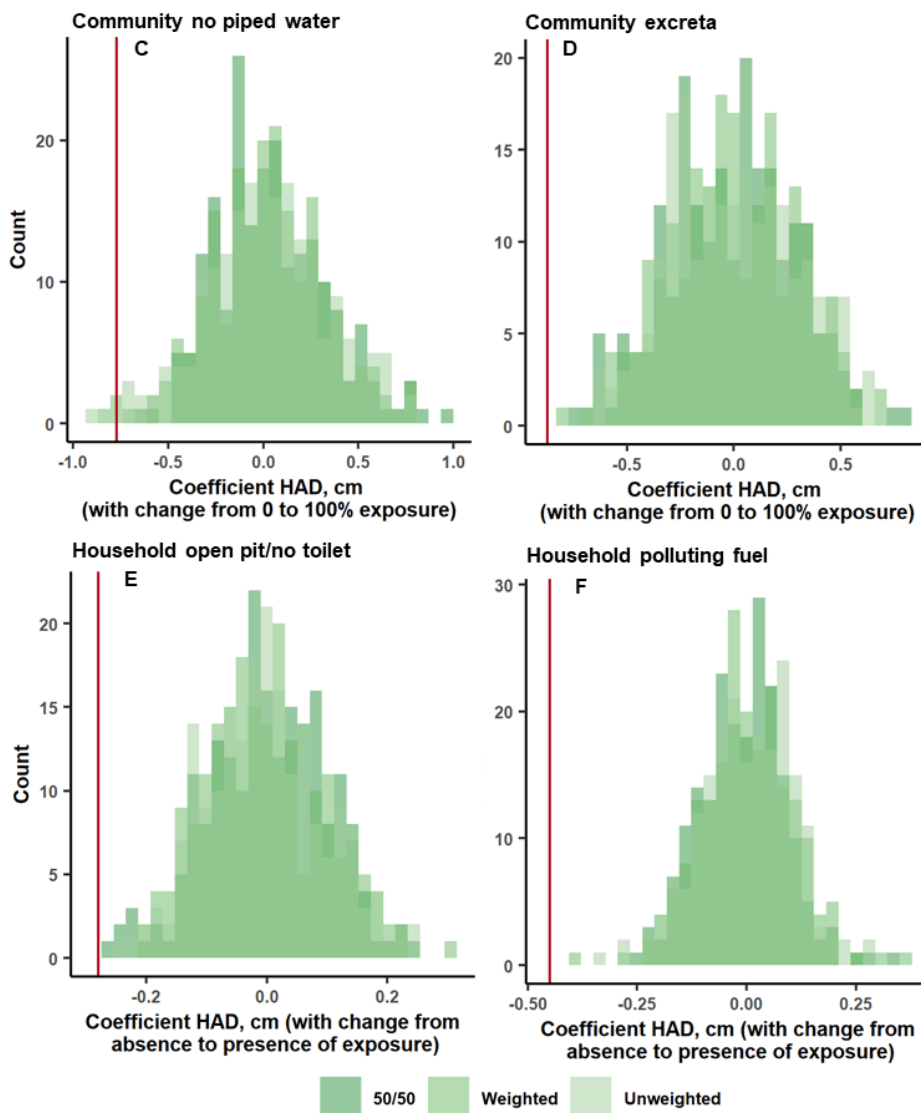
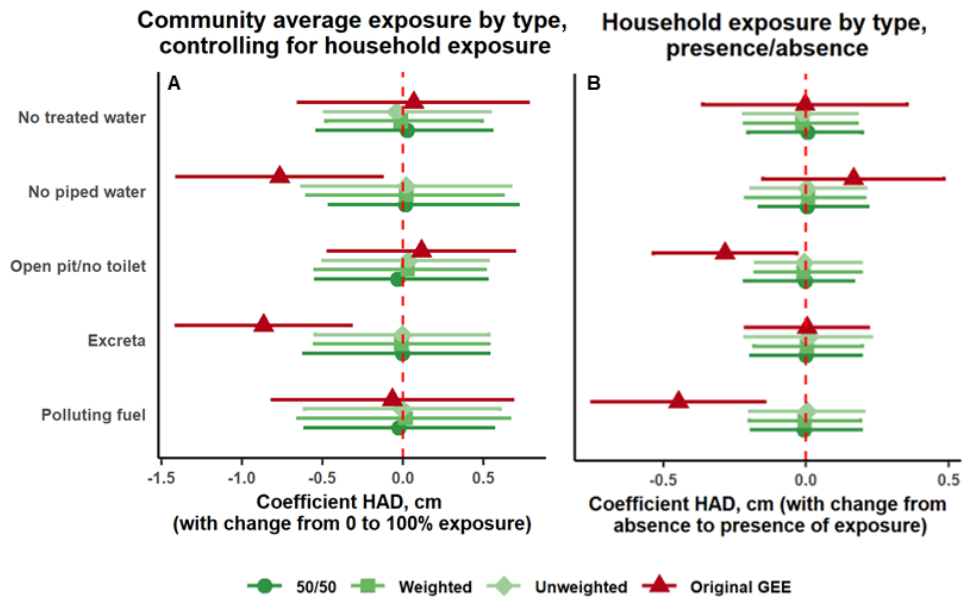
**Figure A2. Community average exposure density by type, controlling for household exposure type.** Single model (mutually adjusted) with full set of covariates, linear time trend, and community fixed effects; estimated using 95 percent confidence intervals with robust standard errors clustered at the individual level. Exposure densities calculated by multiplying the proportion of community exposed to a particular exposure by community population density (on natural log scale). No piped: -0.11, 95CI[-0.20, -0.016]; excreta: -0.14, 95CI[-0.22, -0.060]. n = 12,045 person-year observations



**Figure A3. Comparing GEE, first-differences, and individual fixed effects community and household exposure effects.** Confidence intervals were computed at the 95 percent confidence level. Standard errors are robust to heteroskedasticity and are clustered by individual for GEE and by community for first-differences and individual fixed effects. All analyses included the full set of covariates, linear time trend, and community fixed effects, except for the first-differences model, which instead of a linear time trend included an intercept and “t-2” dummy variables for the survey years.<sup>331</sup> First-differences models were run with R’s *lm* function, and the *vcovCR* function in the *clubSandwich* package (version 0.4.2)<sup>332</sup> was used to compute standard errors. Individual fixed effects models were run with the *feols* function in the *fixest* package (version 0.10.4),<sup>333</sup> and standard errors were computed with the *se* function in the *sjstats* package (version 0.18.1).<sup>334</sup> *Panel A*: Comparing the effects of community average exposures by type, controlling for household exposure type, mutually adjusted exposures (i.e., one model). First-differences goodness-of-fit statistics: Adjusted  $R^2 = 0.040$ , F-statistic = 9.46 on 35 and 7011 degrees-of-freedom with  $p = 0.00$ ; Individual fixed effects goodness-of-fit statistics: Adjusted  $R^2 = 0.68$ , within  $R^2 = 0.048$ , F-statistic = 6.19 on 5026 and 7018 degrees-of-freedom with  $p = 0.00$ . *Panel B*: Comparing the effects of household exposures by type, mutually adjusted exposures. First-differences goodness-of-fit statistics: Adjusted  $R^2 = 0.038$ , F-statistic = 10.32 on 30 and 7016 degrees-of-freedom with  $p = 0.00$ ; Individual fixed effects goodness-of-fit statistics: Adjusted  $R^2 = 0.68$ , within  $R^2 = 0.045$ , F-statistic = 6.19 on 5021 and 7023 degrees-of-freedom with  $p = 0.00$ .  $n = 12,045$  person-year observations for GEE and individual fixed effects;  $n = 7047$  person-year observations for first-differences

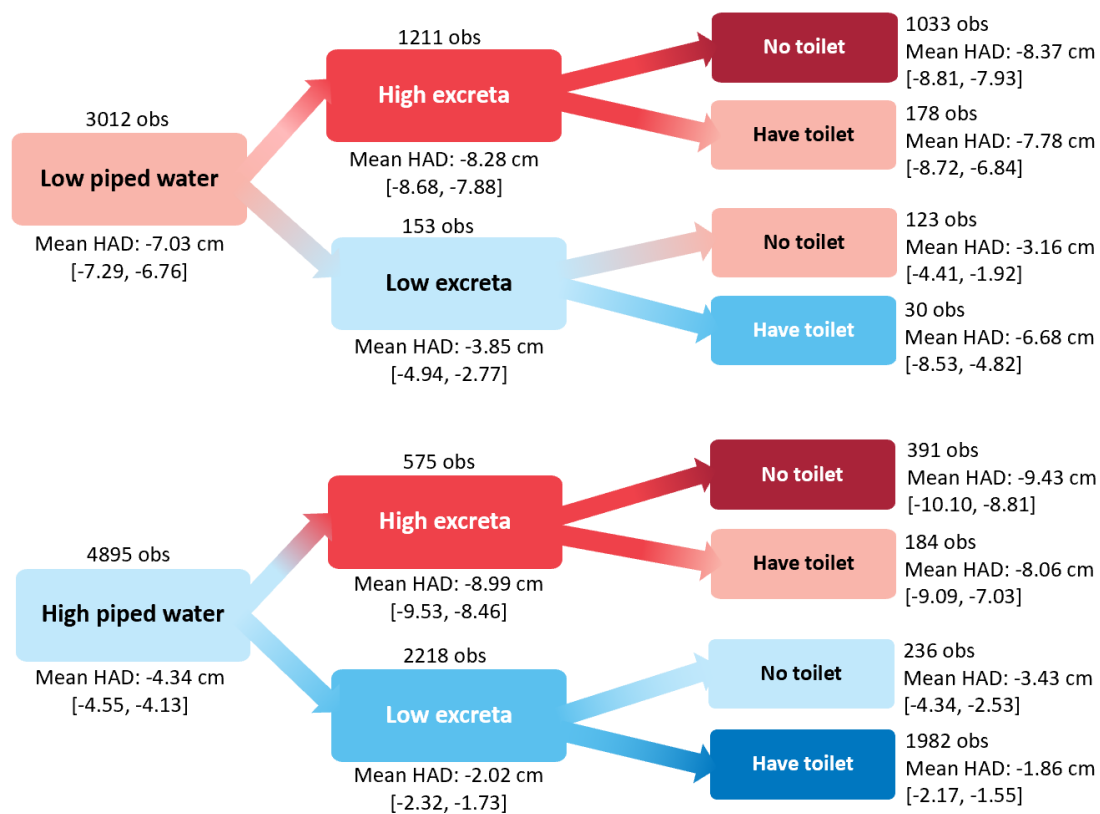


**Figure A4. Household polluting fuel robustness check.** Both household-level models included the full set of covariates, linear time trend, and community fixed effects. Confidence intervals were computed at the 95 percent confidence level. Standard errors are clustered by community and are robust to heteroskedasticity (via bootstrapping, 200 replicates). GEE: -0.45, 95CI[-0.75, -0.14]; IV: -1.15, 95CI[-2.10, -0.20]. First-stage heteroskedasticity-robust joint significance test of the two instruments (coal and gas subsidies): asymptotic Chi-squared statistic of 26.25 (standard error: 2.0E-6) (null hypothesis: both coefficients are zero).  $n_{IV} = 2949$  person-year observations;  $n_{GEE} = 12,045$  person-year observations

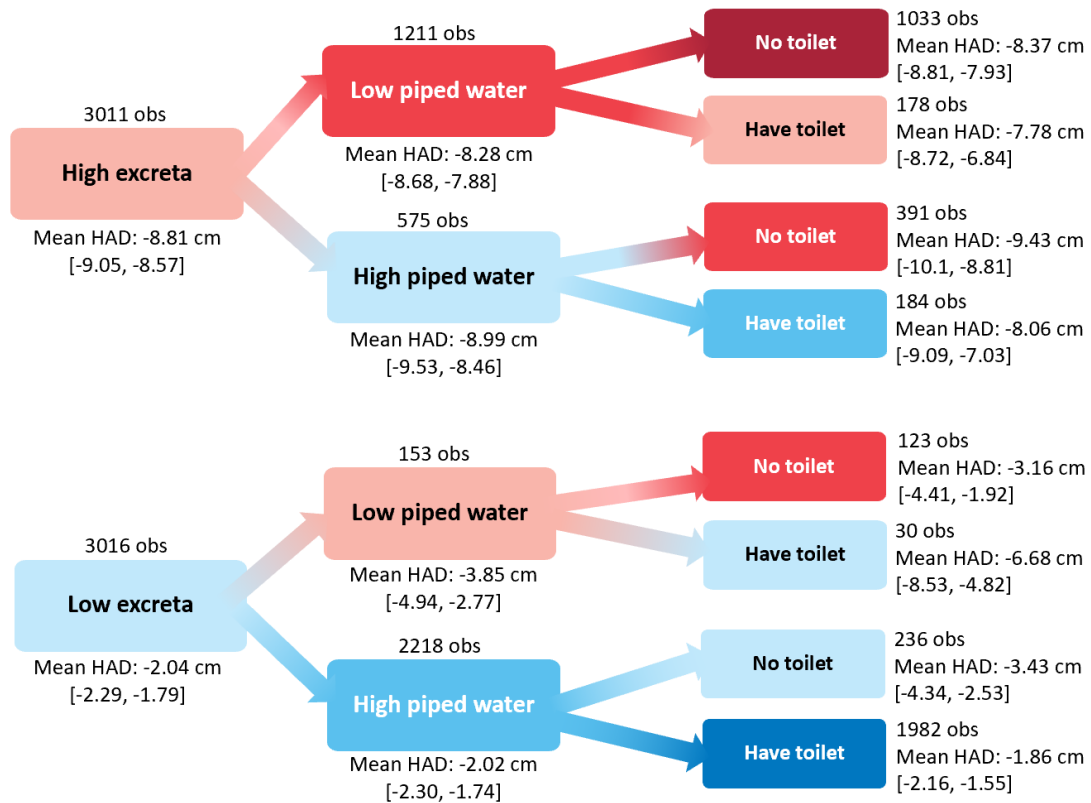


**Figure A5. Randomization inference test.** Confidence intervals were computed at the 95 percent confidence level. Standard errors are robust to heteroskedasticity and are clustered by individual. All GEE models had the full set of controls, a linear time trend variable, and community fixed effects. Our null hypothesis was that our household and community exposures had no effects on HAD. For each exposure we sampled independent Bernoulli  $p$  random variables for each household, assigning each household a value of 0 or 1 with the probability of success  $p$ . We conducted three series of tests, each with a different  $p$ , as we were unsure of the implications of their different assumptions: (1)  $p = 0.5$  (“50/50”); (2)  $p =$  overall exposure mean (“Weighted” by household size due to double-counting the exposure value for every individual within a household); or (3)  $p =$  exposure mean when each household was given the same weight independent of household size (“Unweighted”). We repeated this process 200 times for each of the three types of  $p$  values.

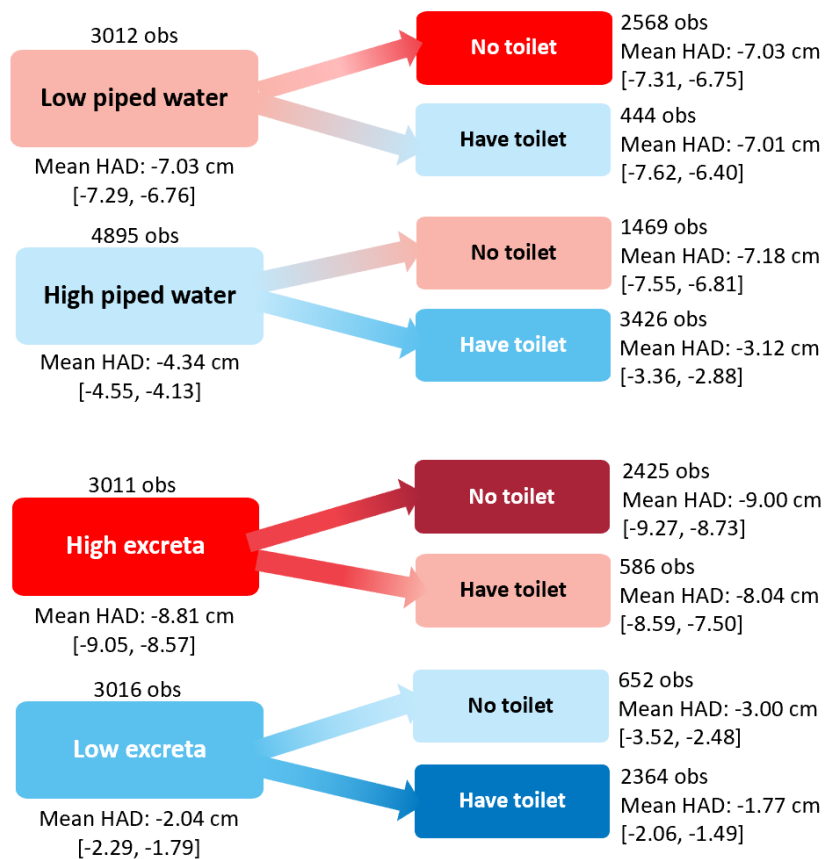
$p(\text{No piped comm, excreta comm, open pit hh, polluting fuel hh}): p_{\text{weighted}} = (0.37, 0.41, 0.57, 0.69)$ ;  $p_{\text{Unweighted}} = (0.33, 0.35, 0.51, 0.62)$  *Panels A and B:* Comparisons of the community (Panel A) and household (Panel B) GEE model coefficients to the coefficients generated by the falsification test. Error bars on the falsification test coefficients are the 2.5<sup>th</sup> (lower bound) and 97.5<sup>th</sup> (upper bound) percentiles of the vector of 200 estimates for each exposure. *Panels C-F:* Histograms of the 200 coefficients for the four significant exposures, with the GEE point estimates denoted by the red lines. While there is a small possibility that our community no piped water finding is random, per the overlap of the red line and histogram in Panel C, this series of tests provides reasonably convincing evidence that our results were not obtained by chance.  $n = 12,045$  person-year observations



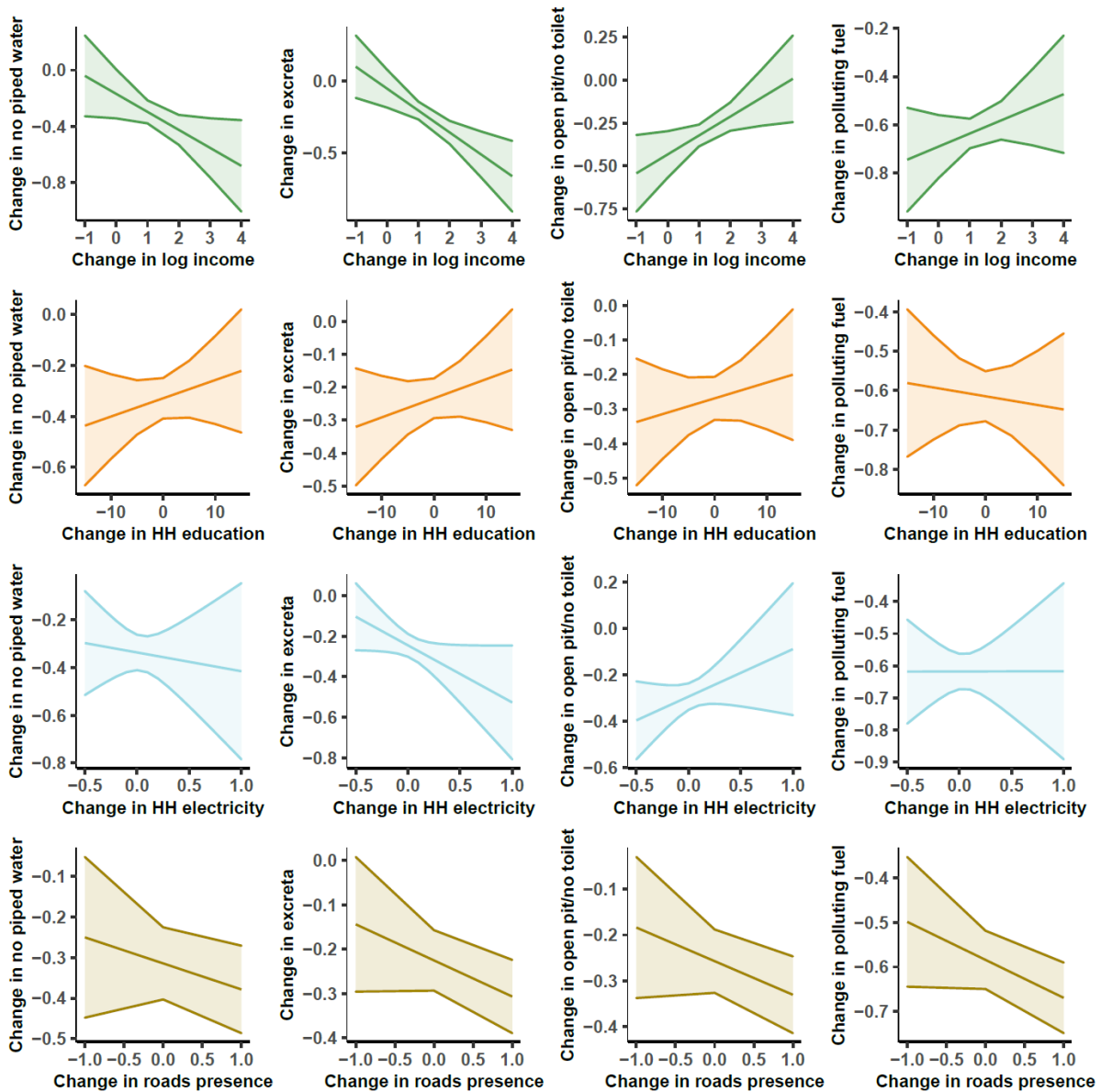
**Figure A6a. Community piped water, community excreta, and household toilet combinations.** Sample sizes and mean HAD with 95 percent confidence intervals are reported at each node. The colors represent the nature of the hypothesized effect on HAD, blue being good and red being bad. The colors are also gradated to indicate a worsening bad or bettering good effect on HAD with the additions of other exposures. “Low” refers to communities at or below the 25<sup>th</sup> percentile of the exposure’s distribution in the full sample; “high” refers to communities at or above the 75<sup>th</sup> percentile. Example interpretation of one combination: 4895 person-year observations are in communities with high piped water and an average HAD of -4.34 cm. Light blue indicates this situation should be beneficial to HAD. Among these observations, 575 of them are individuals in communities with high excreta and a mean HAD of -8.99 cm. The bright red color for this node indicates that we hypothesized the effect of excreta to be negative and the protective effect of piped water to be minimal. Finally, among these observations, individuals that live in households without toilets (391 observations) have a mean HAD of -9.43 cm. The dark red color suggests these individuals are assumed to be the worst off relative to the other two subsamples. The figure was created in Microsoft PowerPoint. n = 12,045 person-year observations



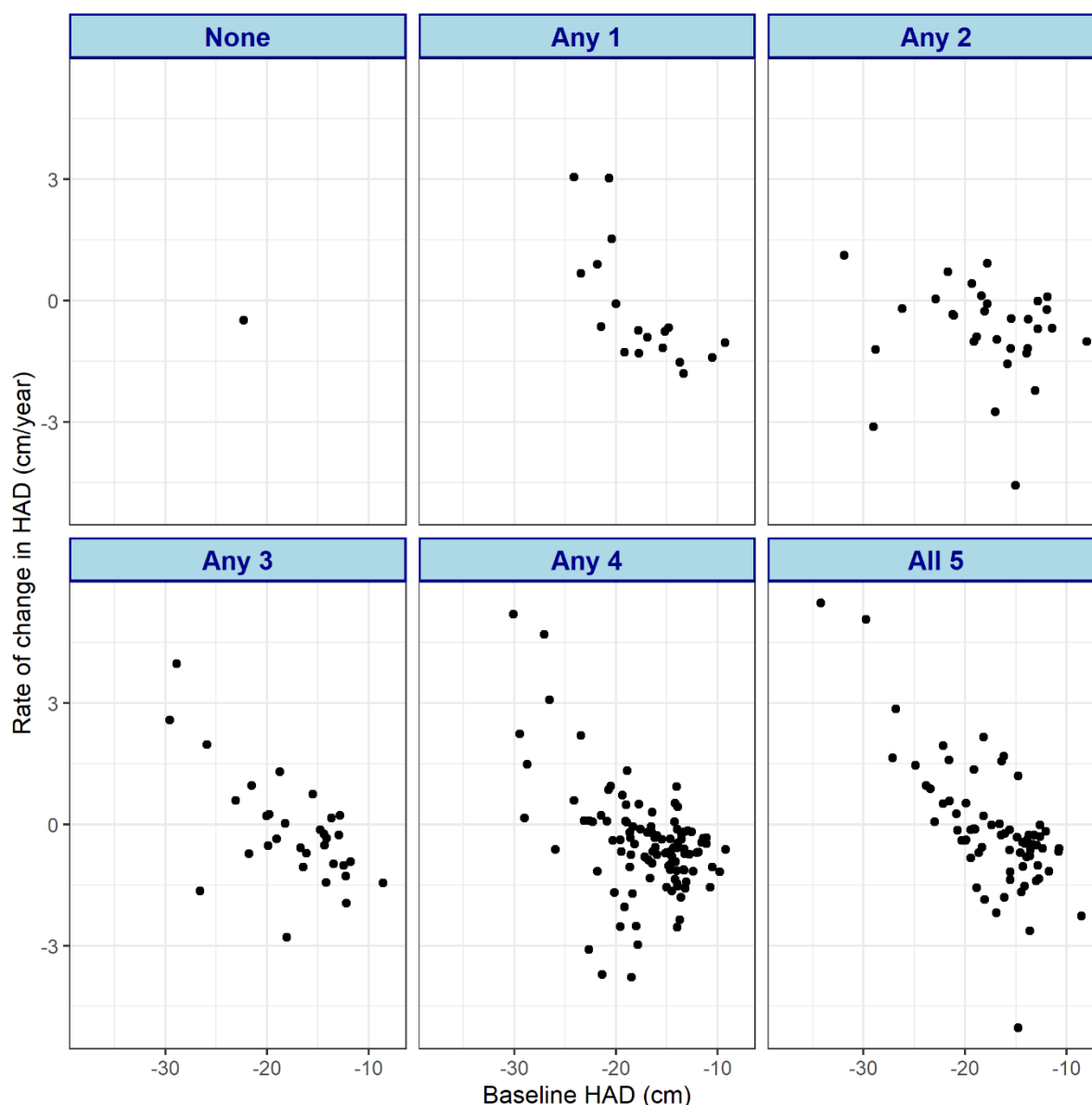
**Figure A6b. Community excreta, community piped water, and household toilet combinations.** Sample sizes and mean HAD with 95 percent confidence intervals are reported at each node. The colors represent the nature of the hypothesized effect on HAD, blue being good and red being bad. The colors are also gradated to indicate a worsening bad or bettering good effect on HAD with the additions of other exposures. “Low” refers to communities at or below the 25<sup>th</sup> percentile of the exposure’s distribution in the full sample; “high” refers to communities at or above the 75<sup>th</sup> percentile. The figure was created in Microsoft PowerPoint. n = 12,045 person-year observations



**Figure A6c. Community piped water or community excreta and household toilet combinations.** Sample sizes and mean HAD with 95 percent confidence intervals are reported at each node. The colors represent the nature of the hypothesized effect on HAD, blue being good and red being bad. The colors are also gradated to indicate a worsening bad or bettering good effect on HAD with the additions of other exposures. “Low” refers to communities at or below the 25<sup>th</sup> percentile of the exposure’s distribution in the full sample; “high” refers to communities at or above the 75<sup>th</sup> percentile. The figure was created in Microsoft PowerPoint. n = 12,045 person-year observations



**Figure A7. Predicted changes in community-level exposures for given changes in community-averaged development indicators.** We plot the predicted changes and 95 percent confidence intervals across 1989 to 2011 in community-level no piped water, excreta, open pit/no toilet, and polluting fuel prevalence (i.e., proportion of community with the exposure) from four bivariate linear prediction models. Predicted values were computed using the *ggpredict* function in the *ggeffects* package (version 0.15.1).<sup>177</sup> Our four predictors include the change in the log community median per capita income, the change in the community-average maximum household education, the change in the community-average household electricity prevalence, and the change in the presence/absence of roads in the community. A negative value on the y-axis suggests that in 2011 the model predicted lower levels of an exposure than in 1989. A positive value means the levels of that exposure were predicted to have increased from 1989 to 2011. A negative value on the x-axis in terms of income, education, electricity, or roads indicates development was lower in 2011 than in 1989. Therefore, a negative *slope*, such as between the changes in no piped water and income, indicates communities with the largest increase in income are predicted to have the largest reductions in no piped water prevalence across 1989 to 2011. A positive *slope*, such as between the changes in open pit/no toilet and education, suggests communities that have improved the least or regressed in terms of educational attainment are predicted to have improved the most in terms of reductions in open pit/no toilet prevalence. A *slope* of 0 indicates no relationship.  $n = 12,045$  person-year observations



**Figure A8. Assessing regression to the mean effect (due to the statistical artifact related to multiple observations on the same individual).** We only included those children and adolescents (1) below the 10<sup>th</sup> percentile in HAD (cm) among individuals of the same age (year) and (2) individuals with more than one measurement (n = 257 individuals). The x-axis represents HAD at baseline (first survey child was measured), and the y-axis represents the change in HAD between baseline and endline surveys divided by the length of time between the baseline and endline surveys. A positive rate of change in HAD corresponds to growing taller. Each panel represents one of the five summed household exposure levels at baseline. For example, “None” represents individuals from households with no exposures (cleanest households) at baseline. Based on this figure, we find evidence of a counter-acting effect to our main results. Recall that at the household level for open pits/no toilets and polluting cooking fuel, decreasing exposure was associated with improvements to HAD; in other words, clean environments are associated with growth. Contrarily, the regression to the mean effect implies that children and adolescents with the highest improvement in HAD are those who were shortest and from the dirtiest environments at baseline; those who are the tallest and from the cleanest environments see the least growth due to regression to the mean. In general very few short children and adolescents are from clean environments at baseline. Consequently, the regression to the mean effect biases our main estimates toward the null and makes our conclusions more conservative (i.e., it “works against” our results).

**APPENDIX 3 FOR CHAPTER 4 (SEATTLE)**

**DETERMINATION OF EXEMPT STATUS**

March 11, 2021

Dear LEIGH HAMLET:

On 3/11/2021, the University of Washington Human Subjects Division (HSD) reviewed the following application:

Type of Review:	Initial Study
Title of Study:	Evaluation of Seattle Public Utilities Recreational Vehicle Wastewater Pumping Program
Investigator:	LEIGH HAMLET
IRB ID:	STUDY00012853
Funding:	None

**Exempt Status**

**HSD determined that your proposed activity is human subjects research that qualifies for exempt status (Category 2).**

- COVID NOTE: Researchers must comply with current infection control requirements and complete a self-assessment that activities fit within allowable research as described on the [HSD website](#).
- This determination is valid for the duration of your research.
- This means that your research is exempt from the federal human subjects regulations, including the requirement for IRB approval and continuing review.
- **Depending on the nature of your study, you may need to obtain other approvals or permissions to conduct your research. For example, you might need to apply for access to data or specimens (e.g., to obtain UW student data). Or, you might need to obtain permission from facilities managers to approach possible subjects or conduct research procedures in the facilities (e.g., Seattle School District; the Harborview Emergency Department).**
- HSD does not make determinations on behalf of other institutions. If other institutions are involved in the research, they may need to make their own determination or they may decide to be guided by our determination.

If you consider changes to the activities in the future and know that the changes will require IRB review (or you are not certain), you may request a review or new determination by submitting a Modification to this application. For information about what changes require a Modification, refer to the [GUIDANCE: Exempt Research](#).

Thank you for your commitment to ethical and responsible research. We wish you great success!

Sincerely,

Greg Wallace, IRB Administrator - Team B  
206.221.7973 – [gkw@uw.edu](mailto:gkw@uw.edu)

**DETERMINATION OF EXEMPT STATUS**

July 13, 2021

Dear LEIGH HAMLET:

On 7/13/2021, the University of Washington Human Subjects Division (HSD) reviewed the following application:

Type of Review:	Modification / Update
Title of Study:	Water, Sanitation, and Hygiene Among Vehicle Residents: A Case Study of the Seattle Public Utilities Recreational Vehicle Wastewater Pump Out Pilot Program
Investigator:	LEIGH HAMLET
IRB ID:	STUDY00012853 MOD00010424
Funding:	None

**Exempt Status**

**HSD determined that your proposed activity is human subjects research that qualifies for exempt status (Category 2).**

- This determination is valid for the duration of your research.
- This means that your research is exempt from the federal human subjects regulations, including the requirement for IRB approval and continuing review.
- **Depending on the nature of your study, you may need to obtain other approvals or permissions to conduct your research. For example, you might need to apply for access to data or specimens (e.g., to obtain UW student data). Or, you might need to obtain permission from facilities managers to approach possible subjects or conduct research procedures in the facilities (e.g., Seattle School District; the Harborview Emergency Department).**
- HSD does not make determinations on behalf of other institutions. If other institutions are involved in the research, they may need to make their own determination or they may decide to be guided by our determination.

If you consider changes to the activities in the future and know that the changes will require IRB review (or you are not certain), you may request a review or new determination by submitting a Modification to this application. For information about what changes require a Modification, refer to the [GUIDANCE: Exempt Research](#).

Thank you for your commitment to ethical and responsible research. We wish you great success!

Sincerely,

Greg Wallace, IRB Administrator - Committee B 206.221.7973  
– [gkw@uw.edu](mailto:gkw@uw.edu)

## Interview guide

THIS IS NOW BEING RECORDED.

Thank you again for taking the time to talk with me today.

### *Demographics and general information about vehicle living*

“I want to first start off with some quick demographic questions. None of this information will ever be used to identify you.”

How would you describe your race or ethnicity?

What is your gender?

What is your age?

“Now, I’m hoping you can answer some a couple more brief questions about vehicle living.”

How long have you lived in a vehicle?

Probe: Where did you live before living in this vehicle?

How long have you lived in *this* vehicle?

### *RV dumping knowledge and practices*

“Now, I’m hoping we can switch gears a bit and talk more in-depth about how you handle your biological waste. (May need to clarify that when I say biological waste I mean feces and urine.) Remember, this is something that as a student I’m very interested in learning more about.”

What do you know about the Seattle Public Utilities Pump-Out Program?

If participant doesn’t know about it, then ask again: So, you’re saying that you don’t use it, correct?

If they don’t use it, then ask: OK, how do you dispose of your biological waste?

If they do use it, then ask: What’s been your experience working with Chris and the Seattle Public Utilities Pump-Out Program?

How long does it take for your tank to fill?

How do you maintain your waste collection system/tank/bucket?

Probe: Is there somewhere you can go to get things fixed? Can you do the work yourself?

One thing I've seen Chris doing is trying to help people keep their onboard waste collection tanks in good working order. What are your thoughts on receiving tank maintenance training?

Probe: What kind of suggestions have you received?

How do you dump your waste when you don't have access to the pump-out program or a designated dumping place? Please remember your responses are anonymous.

Probe: How often does that happen?

If they don't use it, then may be able to skip maintenance questions and jump to: How do you dump your waste when you don't have access to a designated dumping place?

How does the mobility of your vehicle affect your ability to dispose of your waste?

How much would you normally spend on dumping your biological waste per year?

How much do you think you've saved by using the Pump-Out Program?

#### *WASH access and behaviors*

"Let's change gears one more time and talk more about your water and bathroom access.

Remember, any questions you're not comfortable answering you can skip."

Where do you get your drinking water?

Sometimes it can be hard to find *clean* water to drink. Can you tell me about a time when you weren't able to find clean water?

What are the biggest barriers to getting drinking water?

Where do you get your water from other things like cooking?

Where do you go to take a shower?

Where do you go to wash your clothes?

What are the biggest barriers to getting water for these other things?

Can you store water anywhere? If so, where, and how much?

How many people use your toilet?

Where else do you use the bathroom?

What are the biggest barriers to going to or finding a bathroom?

(A couple of miscellaneous questions that got added in later; may or may not appear in interviews.)

Can you tell me about your hand hygiene habits?

How do you control the odors associated with your greywater or blackwater tanks?

“Before we finish the interview, is there anything else you’d like to add or return to? Is there anything else I should have asked you that I didn’t?”

I AM NOW ENDING THE RECORDING.

## Mezzich's kappa calculation explanation

This appendix outlines and compares the processes by which Eccleston et al. (2001) and Mezzich et al. (1981) calculated Mezzich's kappa. The processes will be most comprehensible if the reader reviews the two articles referenced below.

Eccleston P, Werneke U, Armon K, Stephenson T, MacFaul R. Accounting for overlap? An application of Mezzich's  $\kappa$  statistic to test interrater reliability of interview data on parental accident and emergency attendance. *Journal of Advanced Nursing*. 2001;33(6):784-790. doi:[10.1046/j.1365-2648.2001.01718.x](https://doi.org/10.1046/j.1365-2648.2001.01718.x)

Mezzich JE, Kraemer HC, Worthington DRL, Coffman GA. Assessment of agreement among several raters formulating multiple diagnoses. *Journal of Psychiatric Research*. 1981;16(1):29-39. doi:[10.1016/0022-3956\(81\)90011-X](https://doi.org/10.1016/0022-3956(81)90011-X)

*What Eccleston et al. (2001) did:*

- Two raters or coders were two people
- 24 paragraphs = 24 units of analysis
- For each paragraph, proportional overlap =  $\frac{\# \text{ of agreed codes}}{\text{total \# of codes}}$
- Total # of codes = agreed + extra for coder 1 + extra for coder 2
- $P_o = \frac{\text{sum of proportional overlaps}}{\text{total \# of paragraphs}} = 14.61/24 = 0.32$
- $P_e = \frac{\text{sum of all partial agreements for all cases}}{\text{total \# of theme formulations made by both raters for all paragraphs}}$ 
  - o What is a case? What is a theme formulation? They do not define either.
- $P_e = 14.61/46$ 
  - o They do not explain where they get the 46 but I believe it is  $23 \times 2$ .
  - o I think it is  $23 \times 2$  because 23 is the number of paragraphs with codes (one paragraph has "No codes") multiplied by two for the two raters.
    - Apparently this is what they meant by "total # of theme formulations."
    - Issue is that they did not look across *all paragraphs*.
- $K = 0.43$

Replicating Eccleston et al.'s (2001) Table 2

Paragraph	Proportional overlap
1	3 agreed + 0 extra for rater 1 + 3 extra for rater 2 = $3/6 = 0.5$
2 (typo – needs space between 3126 and 3134)	3 agreed + 0 extra + 2 extra = $3/5 = 0.6$
3 (odd because 1111 and 11111 are treated as an agreement)	1 agreed + 2 extra + 0 extra = $1/3 = 0.33$
4	3 agreed + 3 extra + 2 extra = $3/8 = 0.375$
5	0 agreed + 4 extra + 4 extra = $0/8 = 0$
6	2 agreed + 0 extra + 2 extra = $2/4 = 0.5$
7	1 agreed + 0 extra + 0 extra = $1/1 = 1$
8	1 agreed + 0 extra + 1 extra = $1/2 = 0.5$
9	0 agreed + 1 extra + 1 extra = $0/2 = 0$
10 (odd because they called 11211 and 11121 as an agreement)	5 agreed + 0 extra + 0 extra = $5/5 = 1$
11	1 agreed + 0 extra + 0 extra = $1/1 = 1$
12	2 agreed + 2 extra + 0 extra = $2/4 = 0.5$
13	1 agreed + 0 extra + 1 extra = $1/2 = 0.5$
14	1 agreed + 0 extra + 0 extra = $1/1 = 1$
15	1 agreed + 0 extra + 0 extra = $1/1 = 1$
16 (odd because no codes but counted as full agreement)	1 agreed + 0 extra + 0 extra = $1/1 = 1$
17	3 agreed + 6 extra + 0 extra = $3/9 = 0.33$
18	1 agreed + 1 extra + 0 extra = $1/2 = 0.5$
19	2 agreed + 0 extra + 0 extra = $2/2 = 1$
20	2 agreed + 1 extra + 1 extra = $2/4 = 0.5$
21	3 agreed + 1 extra + 0 extra = $3/4 = 0.75$
22	3 agreed + 1 extra + 1 extra = $3/5 = 0.6$
23	1 agreed + 0 extra + 0 extra = $1/1 = 1$
24	1 agreed + 4 extra + 3 extra = $1/8 = 0.125$

What Mezzich et al. (1981) did:

- 30 psychiatrists diagnosing 27 cases
- Each psychiatrist rates 3 cases
- Each case is rated by either 3 or 4 psychiatrists (how the math works out)
  - o Blanks in Mezzich et al.'s Table 1 are not to be seen as agreement “no codes” like in Eccleston et al.'s Table 2
- So “Rater 1” in Mezzich et al.'s Table 1 is not a column for one psychiatrist; it would be better if it were called “Rating 1”
- Diagnoses can be up to three categories or three numbers (this is why [row 1, column 1] is 9, 11 because the first rating labeled case 1 two categories)
- Proportional overlap  $P_o$  is calculated by comparing the “Rating 1” to “Rating 2” to “Rating 3” to “Rating 4” (if applicable) – how much agreement between categories given in each “Rating”
  - o Compare Ratings 1 and 2, 1 and 3, 1, and 4, 2 and 3, 2 and 4, 3 and 4

- Obtained  $2/3 + 1/3 + 1 + 1/4 + 2/3 + 1/3 = 3.25/6$  comparisons = 0.54 average overlap
- Repeat these two steps for all 27 cases
- Sum all 27 proportional overlap numbers and divide by 27 (i.e., average over all 27)
- Chance agreement  $P_c$  (same as  $P_e$  in Eccleston et al. (2001)) is computed by comparing pairs of diagnoses
  - Comparisons are done within raters and across all cases
  - For example, what is agreement between Rater 1 Case 1 and Rater 1 Case 2? Between Rater 1 Case 1 and Rater 2 Case 1? Etc.
  - Can look “within rater” because Rater 1 is not just one person
    - Otherwise it would not make sense to say, “What is the chance that one person agreed with him/herself across two cases?” That would be intracoder reliability, and we are calculating an intercoder statistic.
  - The total number of comparisons is 90 diagnoses choose 2 or 4005
  - Average proportional agreement across 4005 pairs:  $P_c = 0.12$
- $K = (0.36 - 0.12) / (1 - 0.12) = 0.27$

In order for Mezzich’s kappa to be correctly applied to independent coders in qualitative research, one important modification needs to be made to Mezzich’s original calculation, which we describe below.

*What we should do: Modified Mezzich’s kappa*

- We modify Mezzich’s original calculation of  $P_c$  by not looking within the same rater for chance agreement.
  - If there are only two raters like we had and they are two different people: to get the total number of comparisons = paragraphs (or units of analysis)<sup>2</sup>
  - For example, in the case of Eccleston et al. (2001) they had 24 paragraphs so  $24^2 = 576$  comparisons

## Final coding dictionary

Orange highlighting is where the codebook changed the most between the ICR and final analysis.

Table A1. Categories: Water, Sanitation, Hygiene (WASH) infrastructure\*

Name	Definition
Water	Related to drinking water, domestic water, water storage, onboard water (includes recreational vehicle (RV) sinks and holding tanks)
Sanitation	Related to toilets, <b>fecal</b> wastewater management facilities including wastewater disposal sites and Seattle Public Utilities' (SPU's) RV wastewater pump-out program, onboard sanitation (blackwater tanks)  Code general references to "septic tanks" or "onboard tanks" or "tanks" under sanitation
Hygiene	Related to (water used for) personal hygiene, showers, laundry, handwashing, onboard hygiene (RV showers, sinks, greywater tanks)  A note on greywater: Though greywater can be related to personal hygiene and non-personal-hygiene activities (e.g., washing dishes), for our purposes only code under hygiene.
RV-related	Related to the intersection of WASH and RV living; includes mentions of onboard WASH facilities (using them, maintaining them, etc.), water and wastewater storage tanks, SPU's wastewater pump-out program, operating an RV to get to WASH facilities (e.g., traveling to rest stops with RV wastewater dump stations), bale/stopper/valve system for storage tanks; RV parts stores such as Evergreen and Canter RV
Overlapping categories	While water, sanitation, and hygiene are interrelated, for simplicity this codebook attempts to treat them as separate categories. However, there may be instances where a single unit of analysis can be coded under water, sanitation, and/or hygiene. For example, if a participant mentions deciding between bathing and cleaning RV with the little water he/she has, this unit of analysis can be coded under hygiene and water. If a participant mentions blackwater and greywater, this unit of analysis can be coded under sanitation and hygiene.  A negative example: Code as hygiene <b>only</b> if a participant discusses using illegally tapped water for showers in his/her RV in a single unit of analysis.

\*Notes: Water, sanitation, and hygiene *infrastructure* is synonymous with services, resources, and facilities. Infrastructure can be onboard or external to the RV, purchased or free, public or private. In other words, infrastructure is an umbrella term for various types of water, sanitation, and hygiene.

Subcategories: Accessibility, Adequacy, Availability, Quality/Safety, Acceptability, Timescale, Energy, Access to information, Suggestions

The subcategories are based on the Household Water Insecurity Experiences (HWISE) scale<sup>14,248</sup> and Human Rights to Water and Sanitation criteria.<sup>247</sup>

Codes (parent and child):

The codes under each subcategory were derived from preliminary data analysis and literature review. They have both a positive and negative attribute. Examples for each child code are snippets from (longer) units of analysis.

#### Rules about coding:

- Assign entire units of analysis to a code or codes; do not further segment the units of analysis.
- Try to code each unit of analysis as a separate entity.
- A single unit of analysis is allowed to be coded as both the positive and negative attributes of a parent code (e.g., positive attribute assigned to present behavior, negative attribute assigned to past behavior).
- For those parent codes without positive and negative attributes (e.g., How much information), code all positive or negative instances under that one parent code.
- If a parent code has only two child codes (one “non-RV-related” and one “RV-related”), code as only one of the two. If a parent code has more than two child codes, units of analysis can be coded as RV-related and as another child code simultaneously, or as RV-related only, or not RV-related at all.
- The first hypothetical behaviors (i.e., what *would* participants do) that should be coded are those in relation to wastewater disposal practices if the pump-out program were not operating, or in the case where participants have not previously used the pump-out program what they would do if they could not dump their waste as usual. **The second hypothetical behaviors that should be coded are those in relation to leaks (i.e., what participants would do if their tanks needed repairing). Hypotheticals related to RV mobility (i.e., what participants would do if they were mobile) should be coded as the present circumstance (e.g., mobility prohibits using rest area dump stations). Do not code hypothetical situations about water or hygiene (e.g., what participants would do if water taps turned off or shower facilities closed).**
- Do not analyze statements about other people’s behavior or situation.
- A simplified example of “stepping through” the coding process: First ask, “Is what the participant is talking about related to water, sanitation, and/or hygiene?” Then ask, “Is what the participant is talking about related to accessibility, adequacy, and/or availability, etc.?” If it is related to accessibility, for example, then ask, “Is it related to something physical and/or economic, etc.?” If it is related to something physical, for example, then ask, “Is it talking about something that is physically convenient or inconvenient or both?” Then ask, “Is it time or distance, energy, and/or

RV-related?" If time or distance is coded, for example, check again whether or not it is also RV-related.

Table A.2 Final coding dictionary

Name	Definition for water	Definition for sanitation	Definition for hygiene
<i>Accessibility</i>	Related to having WASH that is able to be accessed <sup>335,336</sup>		
<b>Physical: [convenient/inconvenient]</b>	Convenience of physical water infrastructure	Convenience of physical sanitation infrastructure	Convenience of physical hygiene infrastructure
<p style="text-align: center;">Time or distance</p> <p>Words or phrases such as “nearby,” “close,” “far,” “in the neighborhood,” “over here,” “around here,” “right over there” <b>may</b> indicate time or distance</p> <p>Needs to indicate some sort of distance not just direction (e.g., “up there” is vague unless it is a statement like “all the way up there”)</p>	<p>Distance to water source (or store with water accessories such as filters); time spent traveling to or collecting water</p> <p>Convenient example: “It’s handy because it’s not that far away. Two blocks away” (P 26).</p>	<p>Distance to sanitation facility (or store with sanitation accessories such as buckets, RV parts); time spent managing or disposing of fecal waste</p> <p>Inconvenient example: “Because there is no dump around here. It’s all far...It’s about 35, 40 miles from here. Any dump” (P 10).</p>	<p>Distance to hygiene facility (or store with hygiene-related accessories such as water pumps for handwashing); time spent traveling to or using facility (to take care of personal hygiene); could involve greywater disposal</p> <p>Inconvenient example: “From here you have to go clear down to Rainier beach or go down to Ballard before you find a laundromat. It’s a long ways to go” (P 26).</p>
<p style="text-align: center;">Energy expenditure (effort)</p> <p>Think: Ease</p>	<p>Physical effort needed to obtain water or use water infrastructure (e.g., hauling water)</p> <p><b>Includes physical handicaps (blindness, injuries)</b></p> <p>Convenient example: “I forget the name brand, but it has a handle on it so it’s easy to carry” (P 14).</p>	<p>Physical effort needed to meet sanitation needs or use sanitation infrastructure (e.g., hauling wastewater)</p> <p>Inconvenient example: “But yeah I try to hit a porta potty every time we have we make an effort to go out of our way to hit them” (P 25).</p>	<p>Physical effort needed to obtain water for hygiene or use hygiene infrastructure (e.g., hauling water for hygiene)</p> <p>Inconvenient example: “Something like that. It’s sucks but it’s laziness, they’re there, why can’t I just get up and go and do it. I don’t stink” (P 32).</p>
<p style="text-align: center;">RV-related issues</p>	<p>Physical vehicle-related matters that affect accessing water infrastructure or vehicle-related water infrastructure (includes RV parts stores); includes aspects of vehicle mobility, size, driving, parking, and interior</p>	<p>Physical vehicle-related matters that affect accessing sanitation infrastructure or vehicle-related sanitation infrastructure (includes RV parts stores); includes aspects of RV mobility, size, driving, parking, and interior</p>	<p>Physical vehicle-related matters that affect accessing hygiene infrastructure or vehicle-related hygiene infrastructure (includes RV parts stores); includes aspects of vehicle mobility, size, driving, parking, and interior</p>

	Code “ease of maneuvering RV around city” as effort and RV-related  Inconvenient RV-related example: “Now I know up here there’s a campsite and they have running water for some sinks, but you can’t get your RV to it. It’s only, there’s no vehicle allowed up above” (P 12).	Code “ease of maneuvering RV around city” as effort and RV-related  Convenient time or distance, RV-related example: “I: Okay, so you don’t like us a bucket or okay so then you keep your so you keep your RV here then so that you always are near Fred Meyer? P: Yeah.” (P 1)	Code “ease of maneuvering RV around city” as effort and RV-related  Inconvenient RV-related example: “Yeah I use their laundry as well, so those are two things that if I didn’t have access to using their laundry and their shower it would be really hard for me to do cuz I I don’t I can’t drive” (P 36).
<b>Economic (costs)<sup>14,335</sup>: [inexpensive, affordable/expensive, unaffordable]</b>	Affordability of accessing water infrastructure  Can include expenses from social reciprocity	Affordability of accessing sanitation infrastructure  Can include expenses from social reciprocity	Affordability of accessing hygiene infrastructure  Can include expenses from social reciprocity
Non-RV-related expenses (can be free things)  If participants only say how much something is but it is unclear if the cost is an issue or not, do <b>not</b> code to cost.  If non-RV-related WASH is free or a participant spends no money on it, code as inexpensive.	Cost of obtaining water incurred by participant not water provider; includes travel, service/facility fees  Inexpensive example: “He’s got he’s got an RV dump up there. Six bucks, which is really nothing. You can fill your freshwater tank up too (P 3).	Cost of meeting sanitation needs or using sanitation infrastructure incurred by participant not sanitation provider; includes travel, service/facility fees  Do not code free pump-out program or free enzymes as inexpensive  Expensive example: “It was expensive. Expensive times two, I mean, diapers for one is 30 bucks a month easily” (P 30).	Cost of meeting hygiene needs or using hygiene infrastructure incurred by participant not hygiene provider; includes travel, service/facility fees  Expensive example: I: And what about laundry? P: Constant struggle. Very expensive. (P 27)
RV-related expenses (can be free things)  Includes costs of gas, batteries  If RV-related WASH is free or a participant spends no money on it, code as inexpensive.	RV-related travel costs, maintenance costs, or other issues of affordability associated with obtaining water; includes onboard RV facilities and other RV-related water facilities; rest stop water filling stations are assumed to be free	RV-related travel costs, maintenance costs, dumping costs, or other issues of affordability associated with meeting sanitation needs; includes onboard RV facilities and other RV-related sanitation infrastructure; rest stop dump stations are assumed to be free	RV-related travel costs, maintenance costs, or other issues of affordability associated with meeting hygiene needs; includes onboard RV facilities and other RV-related hygiene infrastructure; rest stop dump stations are assumed to be free

	Expensive RV-related example: “And so I usually have a two-gallon jug that I bought from Fred Meyers and I just go in and refill for 40 cents a gallon instead of 89 cents a gallon. Yeah, it is expensive living this way” (P 2).	Inexpensive RV-related example: “Our option was to drive up to five, because we didn’t know anywhere else to go. It is free there that rest area there that, it’s all free facility” (P 16).	Expensive RV-related example: “But I couldn’t figure out on a legal way to get the blackwater and the greywater pumped out. I found that honey bucket...they cost \$175 a pump out and that’s a large part of my income...” (P 36).
<b>Social: [benefits from or participates in/does not benefit from or participate in]</b>	Influence of social capital or behaviors on water access	Influence of social capital or behaviors on sanitation access	Influence of social capital or behaviors on hygiene access
Sharing  Not letting others use personal WASH resources OR not being able to give or receive shared resources is coded as <b>not</b> sharing	Influence of relational resources such as friends, neighbors, or businesses on water access; includes participants sharing with others  Sharing example: “I was getting it from a friend down the street for a while, he had, I could bring a water thing back and forth. Go down there every few days and he would be sure to have clean water for me” (P 13).	Influence of relational resources such as friends, neighbors, or businesses on sanitation access; includes participants sharing with others; includes getting or asking for mechanical help from others ( <b>not</b> from pump-out program)  Sharing example: “But I have a friend of mine who lives at the bottom of the hill and I go down there all the time to use her bathroom so...” (P 35).	Influence of relational resources such as friends, neighbors, or businesses on hygiene access; includes participants sharing with others; includes getting or asking for mechanical help from others ( <b>not</b> from pump-out program)  Lack of sharing example: “Because it’s low-income housing, and it’s because of COVID you weren’t allowed to have visitors. So that was like a big no go like don’t visit your parents unless you’re outside. So I haven’t been able to use the utilize the restroom. That means like, no showers” (P 5).
Socially reciprocal behaviors	Influence of informal reciprocity on water access (e.g., bribing friends, doing favors or volunteering)  Reciprocity example: “Yeah, but I just don’t want to pass around that allowed me the Ballard Food Bank. They’ve they’ve let me because I’ve volunteered in Ballard helping the homeless so much” (P 12).	Influence of informal reciprocity on sanitation access (e.g., bribing friends, doing favors or volunteering)  Reciprocity example: “Well, I used to fix things, companies, businesses, and I still maintain relationships with a lot of them. And, you know, I pretty much have carte blanche I can go in the	Influence of informal reciprocity on hygiene access (e.g., bribing friends, doing favors or volunteering)  Reciprocity example: “So, before that I’ve, you know, had to bribe friends, to be able to shower...But, you know, gets expensive because usually, you know, usually got to give him like 20 bucks worth of dope or something to do it” (P 19).

		bathroom and dump it down the toilet, especially if I'm taking care of the plumbing anyway" (P 11).	
<p>Community facility or service or donation</p> <p>Does not have to be free and just because it is free does not mean it is a community service</p>	<p>Influence of public or community services or facilities on water access; includes food banks, food stamps, rest areas, state parks, campgrounds, community centers (e.g., Urban Rest Stop, Compass Center)</p> <p>Community service example: "Well, actually the school and the community here provides us with drinking water" (P 11).</p>	<p>Influence of public or community services or facilities on sanitation access; includes food banks, rest areas, state parks, campgrounds, community centers (e.g., Urban Rest Stop, Compass Center), public porta potties (need to be obviously public and not private porta potties); does <b>not</b> include pump-out program because every participant uses it</p> <p>A business such as Starbucks is <b>not</b> a community service even though it may allow non-customers to use their bathrooms for free. The distinction is if the service is meant to be an <i>asset</i> to the local community; Starbucks likely does not see its bathrooms as a <i>feature</i> of its services, compared to, say, rest stops or community centers.</p> <p>Community service example: "I: Where else do you use the bathroom? P: The porta potties at the food bank. (P 19)</p>	<p>Influence of public or community services or facilities on hygiene access; includes food banks, rest areas, state parks, campgrounds, community centers (e.g., Urban Rest Stop, Compass Center); does <b>not</b> include pump-out program because every participant uses it</p> <p>Lack of community service example: "I guess in the community center up here somewhere on Rainer but I can never find it" (P 33).</p>
<p>Status<sup>337</sup></p>	<p>Perceptions of how status (e.g., as an RV resident, homeless person, customer) affects water situation</p> <p>No example</p>	<p>Perceptions of how status (e.g., as a vehicle resident, homeless person, customer) affects sanitation situation</p> <p>Negative status example: "Yeah because, like restaurants won't let you, even if you buy something</p>	<p>Perceptions of how status (e.g., as a vehicle resident, homeless person, customer) affects hygiene situation</p> <p>Positive status example: "But Seattle is definitely pretty good to their homeless people...And the people</p>

		else restaurants won't let you use the restroom. Because if you have a backpack on, you're homeless. So I have a tendency to travel without a backpack. I got smarter about that because I'm more likely to get a key to a bathroom. It's pretty screwed up" (P 25).	that come around and help out they always give out toiletries" (P 16).
Illegal practices	<p>Engagement in illegal behavior to access water infrastructure</p> <p>Illegal: Stealing water from external taps on buildings or households; assume illegal <b>unless</b> participant explicitly says they have permission</p> <p>If wants to steal but cannot because locks, code as "does not benefit from"</p> <p>Legal example: "I: Do you get like, get your water from any industrial buildings have external taps or anything? P: No, I don't like to mess with tap water cuz it's got chlorine." (P 32)</p>	<p>Engagement in illegal behavior to access sanitation infrastructure</p> <p>Illegal: Throwing away feces that are not in diapers; unauthorized blackwater (e.g., outside on the ground, down stormwater drains, into sewers); open defecation; public urination</p> <p>Do not code throwing away used toilet paper as illegal or legal</p> <p>Unclear: If cannot tell if something like using a porta potty is allowed, do not code here</p> <p>Illegal example: "When the tanks get super full, and I really need to empty them, on occasion I will go to a sewer cover and pull that. And as long as it's one of the standard sewer hole, I dump in there" (P 19).</p>	<p>Engagement in illegal behavior to access hygiene infrastructure</p> <p>Illegal: Stealing clean clothes; unauthorized greywater dumping (e.g., outside on ground, down stormwater drains, into sewers)</p> <p>Illegal example: "So we'll wait till you know 10 o'clock and go to the door code like we're visiting someone, we actually know people there, and then just go there, there are bathrooms on both floors and there's like four of them. Right. And so, all the people that live there, just go into the bathroom, so they don't know who really staying or not. I mean I shower just about every day, if not every other day" (P 25).</p>
RV-related issues	Influence of social benefits or participation on onboard water infrastructure (not the other way around; for example, the use of public park water fountain because participant does not use RV water is <b>not</b> coded as "Social benefits from community service and RV-related,"	Influence of social benefits or participation on onboard sanitation infrastructure (not the other way around; for example, the use of community center bathroom because participant does not use RV toilet is <b>not</b> coded as "Social benefits from community service	Influence of social benefits or participation on onboard hygiene infrastructure (not the other way around; for example, the use of community center shower because participant does not use RV shower is <b>not</b> coded as "Social benefits from community service and RV-related,"

	<p>only “Social benefits from community service”)</p> <p>Sharing, RV-related, example: “So my my friends house I fill up my tank probably every two weeks from there hose. That that’s the hose from their house” (P 36).</p>	<p>and RV-related,” only “Social benefits from community service”)</p> <p>Community service, RV-related example: “No, no because there are the rest stops you can always do that” (P 13).</p>	<p>only “Social benefits from community service”)</p> <p>Legal, RV-related example “I: Ok. Do you do you just sometimes, open the greywater tank and let the water come out? P: No. I: No, ok. P: I can’t do that.” (P 29)</p>
<i>Adequacy</i>	Related to having sufficient WASH to use (think: how much) <sup>248</sup>		
<b>‘Amount’ of facilities: [enough/not enough]</b>	Number of water resources	Number of sanitation resources	Number of hygiene resources
<p>Non-RV-related facilities</p> <p>Ignore comments on sufficiency of explicitly illegal resources</p> <p>If a participant expresses uncertainty about how many facilities there are available to them, code as ‘Amount of facilities’ and ‘Access to information, Not Knowledgeable’ to capture the uncertainty.</p>	<p>‘Amount’ of non-vehicle-related water infrastructure</p> <p>Sufficient example: “You know there’s no problem. You can either buy it, or there’s other places around here, you can get the water” (P 8).</p>	<p>‘Amount’ of non-vehicle-related sanitation infrastructure</p> <p>‘Amount’ of toilet paper is a “Cleanliness” issue not a ‘Amount of facilities’ issue</p> <p>Sufficient example: “A lot of times they’re open, there are so many porta potties around the area they’re easy to find” (P 13).</p>	<p>‘Amount’ of non-vehicle-related hygiene infrastructure</p> <p>Insufficient example: “I’ve noticed Georgetown does not really have like anybody like the urban rest stops or you know, anything like that. Not that I know of” (P 15).</p>
RV-related facilities/services	<p>‘Amount’ of facilities or services that are suitable for accessing and using water in an RV</p> <p>Insufficient example: “So anyway, I think [the pump-out program] is a great, it’s I think it’s a great thing. City of Seattle needs to have a place for people to get water. There’s no place to get fresh water... Well, port of Seattle, Shilshole Marina. The port, they have an area with many different</p>	<p>‘Amount’ of facilities or services that are suitable for accessing and using sanitation in an RV</p> <p>Nothing related to pump-out program will fall under this code</p> <p>Sufficient example: “Yeah, I feel like if the vehicle was working, I could easily drive to like a place that I can pump, there’s plenty of places...” (P 5).</p>	<p>‘Amount’ of facilities or services that are suitable for accessing and using hygiene in an RV</p> <p>Nothing related to pump-out program will fall under this code</p> <p>Insufficient example: “For them to not have a place that we could go and fill up the tanks because everybody’s got one of them tanks on the on their RV if they could fill up their tanks they wouldn’t have a</p>

	buildings with faucets. They should make it so somebody can drive up, put water in their RV and drive away..." (P 12).		water problem at all, they'd be able to shower and everything. See, we can't shower in these RVs because we don't have water in our tanks..." (P 28).
<p style="text-align: center;"><b>Diversification: [mentions diversification]</b></p> <p>Not interested in "no diversification"</p> <p>Consulting multiple people for mechanical help is <b>not</b> diversification; code as "Where" and "Sharing"</p>	<p>Reliance on multiple water infrastructures or practices to meet water needs; can be onboard plus non-onboard; can be legal and illegal or multiple illegal sources; include past and present resources</p> <p>Purchasing different sized water bottles is not diversification, unless it is person buying bottles and using store fill-up station – these are two resources.</p> <p>Do <b>not</b> code if participant drinks water and some other non-water drink. If participants say they use something "usually" or "sometimes" but do not say what else they use then do <b>not</b> code as diversification.</p> <p>Example: "I: Where do you get your drinking water? P: Anywhere I can find it. I: Anywhere? P: Yeah. I: Where is that usually these days? P: Usually in a tap around here, I don't really, the guys usually go and get it for me so. But yet, it's usually in some tap we can find your way around." (P 23)</p>	<p>Reliance on multiple sanitation infrastructures or practices to meet sanitation needs; can be onboard plus non-onboard; can be legal and illegal or multiple illegal sources; include past and present resources</p> <p>Do <b>not</b> code pump-out program as one of sources</p> <p>If participants say they use something "usually" or "sometimes" but do not say what else they use then do <b>not</b> code as diversification.</p> <p>Example: "I: And so which rest areas do you dump your waste off at? P: SeaTac is one place. There's another place Little Rock miles... I: What is it called? P: Little Rock. I'm not sure the real name of it. Two places I could go...another campground. It's about five miles up from the rest area..." (P 31).</p>	<p>Reliance on multiple hygiene infrastructures or practices to meet hygiene needs; can be onboard plus non-onboard; can be legal and illegal or multiple illegal sources; include past and present resources</p> <p>If participants say they use something "usually" or "sometimes" but do not say what else they use then do <b>not</b> code as diversification.</p> <p>Using hand sanitizer and soap counts as diversification, as does hand laundry and laundromat</p> <p>Example: "I have not washed my clothes recently. But when I do my laundry I go to the laundromat, or the urban rest stop or a friend's" (P 15).</p>
<p style="text-align: center;"><b>Consumption: [mentions preservation]</b></p>	Having enough water resources as expressed in terms of consumption (think: saving/conserving water)	Having enough sanitation resources as expressed in terms of consumption (think:	Having enough hygiene resources as expressed in terms of consumption (think:

<p>Not interested in “no preservation”</p> <p>Preservation is <b>not</b> the same as not using something at all</p>		<p>saving/conserving sanitation resources)</p>	<p>saving/conserving water used for hygiene or other hygiene resources)</p>
<p>Non-RV-related issues</p>	<p>Having enough non-vehicle-specific water resources as expressed in terms of consumption</p> <p>Example: “And I save it. I don’t drink any water...” (P 21).</p>	<p>Having enough non-vehicle-specific sanitation resources as expressed in terms of consumption</p> <p>Example: “So diapers for two I mean we were looking at 50, and he would go over to Starbucks more often back then” (P 30).</p>	<p>Having enough non-vehicle-specific hygiene resources as expressed in terms of consumption</p> <p>Example: “I try to do as much as possible. I usually use, more, more alcohol than, than actually getting to wash because you don’t have that much water” (P 23).</p>
<p>RV-related issues</p>	<p>Having enough onboard water as expressed in terms of consumption; includes moderating use of vehicle facilities</p> <p>No examples</p>	<p>Having enough onboard sanitation as expressed in terms of consumption; includes moderating use of vehicle facilities</p> <p>Stopping the use of an onboard toilet because blackwater tank is full is <b>not</b> preservation – code as discontinuous Operation</p> <p>Example: “Well I pee in it I don’t do anything else in it. And there’s no paper, I don’t put anything else in it so that’s all there is in there” (P 13).</p>	<p>Having enough onboard hygiene as expressed in terms of consumption; includes moderating use of vehicle facilities</p> <p>Example: “Yeah I do use my greywater sometimes, not all that much though, I try not to... You can fill your tanks in a month, quick, I filled up my tanks before in a month so I try to keep it down” (P 25).</p>
<p><b>Storage: [enough/not enough]</b></p>	<p>Sufficiency of water storage (think: Is the participant in possession of what he/she considers to be enough water? Can you tell what the participant thinks of his/her storage situation?)</p> <p>Example indications of sufficient storage: If participant comments on</p>	<p>Sufficiency of storage as it relates to sanitation (think: Can the participant store what he/she considers enough wastewater? Can you tell what the participant thinks of his/her storage situation?)</p> <p>Example indications of sufficient storage: “It takes a while to fill the</p>	<p>Sufficiency of storage as it relates to personal hygiene (think: Can the participant store what he/she considers enough wastewater from or water for hygiene activities? Can you tell what the participant thinks of his/her storage situation?)</p>

	<p>how much water he/she likes to have and if he/she can store that much and seems satisfied.</p> <p>Example indications of insufficient storage: Comments on “not enough water in the tank;” “not much” bottled water can be stored in RV</p>	<p>wastewater tank...”; comment on tank being big; “still has plenty of room every time they come by to pump”</p> <p>Example indications of insufficient storage: Tank filling “too quickly;” if tank is broken and he/she wants to use it; comment on tank being too small</p>	<p>Example indications of sufficient storage: “It takes a while to fill the wastewater tank with greywater...”; comment on tank being big; “still has plenty of room every time they come by to pump”</p> <p>Example indications of insufficient storage and if specifically mention greywater: Tank filling “too quickly;” if tank is broken and he/she wants to use it; comment on tank being too small</p>
<p>Non-RV-/non-tank-related issues</p>	<p>Sufficiency of water as dictated by capacity to store water in or around vehicle, not in an RV tank</p> <p>Sufficient example: “P: Well right now <b><u>I’ve got about fifteen gallons in there.</u></b> Twelve, about twelve gallons in there. I: Okay. That’s the typical you’d like to have? <b><u>P: I like to</u></b> have a four or five gallon, and then you know, one that I’m using. I keep the five gallon down here and I fill up two gallon jugs to carry in.” (P 27).</p>	<p>Sufficiency of sanitation as dictated by capacity to store wastewater (blackwater) in or around vehicle, not in an RV tank</p> <p>No examples</p>	<p>Sufficiency of hygiene as dictated by capacity to store water or greywater in or around vehicle, not in an RV tank</p> <p>No examples</p>
<p>RV-related/tank-related issues</p>	<p>Sufficiency of water as dictated by ability to store water in holding tank; includes sufficiency of storage as dictated by valves on storage tank (i.e., is the tank broken, and does he/she want to use it?); does RV resident use onboard tank, and has he/she commented on it being enough?</p>	<p>Sufficiency of sanitation as dictated by ability to store blackwater in tanks; includes sufficiency of storage as dictated by valves on storage tank (i.e., is the tank broken, and does he/she want to use it?); does RV resident use onboard tank, and has he/she commented on it being enough?</p>	<p>Sufficiency of hygiene as dictated by ability to store water in holding tank needed for hygiene activities or wastewater in greywater tank; includes sufficiency of storage as dictated by valves on storage tank (i.e., is the tank broken, and does he/she want to use it?); does RV resident use storage tank, and has he/she commented on it being enough?</p>

	<p>Insufficient example: “I: Okay, so that you just can't besides the bottles two gallon bottles of water you don't really have storage for water? P: I got <b>a great big one</b> if I can use it but I can't.” (P 1)</p> <p>Even if a participant stores water in his/her RV holding tank, it does not mean he/she has enough water storage</p>	<p>Just because tank fills faster than pump-out program can come or just because tank overflows does not mean insufficient storage.</p> <p>Sufficient example: “Um, it takes a while. I would say every three to four weeks honestly. It <b>takes quite a while</b>” (P 14).</p> <p>This is an example of what <b>NOT</b> to code under storage: “They um, they ask—Are you got any leaks or anything? The answer is no because the toilet never gets that full” (P 8).</p> <p>This is not about storage as there is no evaluation on tank size, sufficiency; “the toilet never gets that full” could be assigned to a number of codes, such as frequency of pump-out program, moderation, not sharing, etc.</p>	<p>Insufficient example: “Because this greywater is the way, the <b>holding tank is pretty small</b>, and that would require this too much water. Probably after I use it for probably dump it out. And I don't do that” (P 29).</p>
<p><i>Availability</i></p> <p><b>Operation<sup>338,339</sup>: [Adequate availability, continuous/inadequate availability, discontinuous]</b></p> <p>Think: When is something available Can participant “count on it?”</p>	<p><b>Related to having facilities that are available when needed<sup>248</sup></b></p> <p>Operational continuity or consistency of water infrastructure</p>	<p>Operational continuity or consistency of sanitation infrastructure</p>	<p>Operational continuity or consistency of hygiene infrastructure</p>

Non-RV-related issues

	<p>Continuity of non-RV-related water infrastructure availability</p> <p>Code as an availability issue if facilities are shut off but were once open and <b>relied on (not just known about)</b> or if a participant <b>explicitly</b> comments on consistency of a water resource as being either good or bad</p> <p>Indications of discontinuous: Participants mentions problems associated with hours of operation; simply because a business is sometimes closed, a charity comes only at certain times, or illegal resources can only be accessed at night does not automatically mean it is unavailable. Water resources participants used to rely on that they no longer can access are discontinuous/not dependable.</p> <p>Indications of continuous: Comments about resource availability being “always open” or “constantly going” so that it is available when needed; only code a charity as dependable if the participant comments on fixed interval being an asset</p> <p>Do not code as an availability issue if participant says he/she uses some place like a grocery store but says nothing about store hours. Phrases such as “I go whenever possible” are too ambiguous to automatically</p>	<p>Continuity of non-RV-related sanitation infrastructure availability</p> <p>Code as an availability issue if facilities are shut off but were once open and <b>relied on (not just known about)</b> or if a participant <b>explicitly</b> comments on consistency of a water resource as being either good or bad</p> <p>Indications of discontinuous: Participants mentions problems associated with hours of operation; simply because a business is sometimes closed, a charity comes only at certain times, or illegal resources can only be accessed at night does not automatically mean it is unavailable. Sanitation resources participants used to rely on that they no longer can access are discontinuous/not dependable.</p> <p>Indications of continuous: Comments about resource availability being “always open” or “constantly going” so that it is available when needed only code a charity as dependable if the participant comments on fixed interval being an asset</p> <p>Do not code as an availability issue if participant says he/she uses some place like a grocery store but says nothing about store hours. Phrases such as “I go whenever possible” are too ambiguous to</p>	<p>Continuity of non-RV-related hygiene infrastructure availability</p> <p>Code as an availability issue if facilities are shut off but were once open and <b>relied on (not just known about)</b> or if a participant <b>explicitly</b> comments on consistency of a hygiene resource as being either good or bad</p> <p>Indications of discontinuous: Participants mentions problems associated with hours of operation; simply because a business is sometimes closed, a charity comes only at certain times, or illegal resources can only be accessed at night does not automatically mean it is unavailable. Hygiene resources participants used to rely on that they no longer can access are discontinuous/not dependable.</p> <p>Indications of continuous: Comments about resource availability being “always open” or “constantly going” so that it is available when needed; only code a charity as dependable if the participant comments on fixed interval being an asset</p> <p>Do not code as an availability issue if participant says he/she uses some place like a grocery store but says nothing about store hours. Phrases such as “I go whenever possible” are too ambiguous to automatically signal an availability issue on their</p>
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	<p>signal an availability issue on their own. Just because participants say they use something “usually” or “sometimes” is not automatically an availability issue.</p> <p>Comments “24-7” availability: If something is available 24-7 (all the time), it is automatically coded as “continuous.” If something is not open 24-7 and participants indicate they would like it to be, code as “discontinuous.”</p> <p>Continuous example: “164<sup>th</sup> at the spring. Yeah, there’s like a well that’s constantly going” (P 15).</p>	<p>automatically signal an availability issue on their own. Just because participants say they use something “usually” or “sometimes” is not automatically an availability issue.</p> <p>Comments “24-7” availability: If something is available 24-7 (all the time), it is automatically coded as “continuous.” If something is not open 24-7 and participants indicate they would like it to be, code as “discontinuous.”</p> <p>Discontinuous example: “But there’s nowhere 24 hour to go. So, the nearest 24 hour location to go is going to be the subway way up on the fast food strip” (P 30).</p>	<p>own. Just because participants say they use something “usually” or “sometimes” is not automatically an availability issue.</p> <p>Comments “24-7” availability: If something is available 24-7 (all the time), it is automatically coded as “continuous.” If something is not open 24-7 and participants indicate they would like it to be, code as “discontinuous.”</p> <p>Continuous example: “Best place is the in North City, 175<sup>th</sup> and 15<sup>th</sup> northeast, there’s a laundromat 24 hour up there” (P 16).</p>
<p>RV-related issues</p>	<p>Continuity of use of onboard water and access to RV-related water resources used to fill RV holding tanks</p> <p>Code as an availability issue if facilities are shut off but were once open and <b>relied on (not just known about)</b> or if a participant <b>explicitly</b> comments on consistency of a water resource as being either good or bad</p> <p>Stopping the use of an onboard water is discontinuous operation (if they never used it, probably not an availability issue)</p>	<p>Continuity of use of onboard sanitation and access to RV-related sanitation resources for dumping blackwater; <b>includes frequency of pump-out program</b></p> <p>Code as an availability issue if facilities are shut off but were once open and <b>relied on (not just known about)</b> or if a participant <b>explicitly</b> comments on consistency of a water resource as being either good or bad</p> <p><b>Whether or not pump-out truck can extract wastewater (e.g., problems with equipment needed to connect truck to RV) may be coded under</b></p>	<p>Continuity of use of onboard hygiene and access to RV-related hygiene resources for dumping greywater; <b>includes frequency of pump-out program from the perspective of greywater disposal</b></p> <p>Code as an availability issue if facilities are shut off but were once open and <b>relied on (not just known about)</b> or if a participant <b>explicitly</b> comments on consistency of a hygiene resource as being either good or bad</p> <p><b>Whether or not pump-out truck can extract greywater (e.g., problems with equipment needed to connect</b></p>

	<p>Indications of not discontinuous: Participants mentions <b>problems</b> associated with hours of operation; simply because a business is sometimes closed, a charity comes only at certain times, or illegal resources can only be accessed at night does not automatically mean it is unavailable. Water resources participants used to rely on that they no longer can access are discontinuous/not dependable.</p> <p>Indications of dependable/continuous: Comments about resource availability being “always open” or “constantly going” so that it is available when needed; only code a charity as dependable if the participant comments on fixed interval being an asset</p> <p>Discontinuous example: “P: Well, I fill the onboard tank usually at businesses that have a exterior faucet. I: And you do that at night too? P: Yeah.” (P 19)</p>	<p>“Acceptability” or “Technical quality”</p> <p>Just because “tank is full” does <b>not</b> mean it is an Availability issue (e.g., P 8, P 19); participant needs to be explicit about stopping use of their blackwater tank because it is full. There are participants who use it still when it is full (e.g., P 5, P 7).</p> <p>A broken tank is “Technical quality” and “Availability” if participant used tank before and it is clear he/she has stopped using it. If onboard gauges are broken but it does not stop participant from using facility, do not code as unavailable – just code to low technical Quality.</p> <p>Indications of not discontinuous: Participants mentions problems associated with hours of operation; simply because a business is sometimes closed, a charity comes only at certain times, or illegal resources can only be accessed at night does not automatically mean it is unavailable. Sanitation resources participants used to rely on that they no longer can access are discontinuous/not dependable.</p> <p>Indications of dependable/continuous: Comments about resource availability being “always open” or “constantly going” so that it is available when needed;</p>	<p>truck to RV) may be coded under “Acceptability” or “Technical quality”</p> <p>Just because “greywater tank is full” does <b>not</b> mean it is an Availability issue; participant needs to be explicit about stopping use of their greywater tank because it is full.</p> <p>A broken greywater tank is “Technical quality” and “Availability” if participant used tank before and it is clear he/she has stopped using it. If onboard gauges are broken but it does not stop participant from using facility, do not code as unavailable – just code to low technical Quality.</p> <p>Indications of not discontinuous: Participants mentions problems associated with hours of operation; simply because a business is sometimes closed, a charity comes only at certain times, or illegal resources can only be accessed at night does not automatically mean it is unavailable. Hygiene resources participants used to rely on that they no longer can access are discontinuous/not dependable.</p> <p>Indications of dependable/continuous: Comments about resource availability being “always open” or “constantly going” so that it is available when needed; only code a charity as dependable if the participant comments on fixed interval being an asset</p>
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		<p>only code a charity as dependable if the participant comments on fixed interval being an asset</p> <p>Inadequate example: “I just stop using the bathroom that’s it I lock it and until I get money” (P 10).</p> <p>Adequate example: “They um, they ask – Are you got any leaks or anything? The answer is no because the toilet never gets that full...You know because they’re doing it monthly, and that’s a really big help. You know, so I appreciate that too” (P 8).</p>	<p>Adequate example: “...I, I have it a good situation where my friend lets me take showers in their house so because I’m able to shower at their place my greywater tank doesn’t fill up, whereas if I had a shower in my in my home, then I would be having a lot more issues or be having to try and figure out how to off load the greywater more often but because of that having them come once a month or every six weeks it’s perfectly fine for me. And it’s yeah but if I had a shower in my own place that wouldn’t be doable” (P 36).</p>
<p><b>Competition<sup>340,341</sup>: [competition/no competition]</b></p> <p>Think: Is competition a concern? Is there tension?</p> <p>The competition can actually exist OR the participant can be concerned competition (and therefore not share resources, for example). No competition would be if competition does not exist AND participant is not concerned.</p>	<p>Variable access to shared, public, or common-pool water infrastructure due to overcrowding, overuse, or misuse by others</p>	<p>Variable access to shared, public, or common-pool sanitation infrastructure due to overcrowding, overuse, or misuse by others</p>	<p>Variable access to shared, public, or common-pool hygiene infrastructure due to overcrowding, overuse, or misuse by others</p>
<p>Number of users</p> <p>The participant needs to say how the amount of users influences WASH. It is not enough to just mention the amount of users (e.g., P 26 mentioning two RVs used Dick’s restaurant supply is not a number of users issue but it is a behavior issue</p>	<p>Influence of number of users of water infrastructure on availability</p> <p>No competition example: “We’ve told other people about it but we don’t know if they will go down there. We’ve never bumped into anybody else down there. They’ve</p>	<p>Influence of number of users of sanitation infrastructure on availability</p> <p>Competition example: “Yeah there is. Sometimes you go there and you gotta wait because people are in there using it, when you gotta go you gotta go sometimes...” (P 2).</p>	<p>Influence of number of users of hygiene infrastructure on availability</p> <p>Competition example: “When I sometimes is when it’s not too many people at Green Lake, at the community center, I go in there” (P 29).</p>

<p>because it is the RVs' behavior that influenced water supply).</p>	<p>never taken the handle off of this spigot either, so..." (P 16).</p>		
<p>Behavior of users</p>	<p>Influence of the behavior of others on water infrastructure availability</p> <p>Other people stealing water-related resources from participants is an example of competition (e.g., P 23's water containers being stolen)</p> <p>Competition example: "Yeah they were okay with it before everybody started. Trashing sh*t around here. Taking advantage of it. Ivers used to let us get water there late at night before they closed" (P 3).</p>	<p>Influence of the behavior of others on sanitation infrastructure availability</p> <p>Other people stealing sanitation resources from participants is an example of competition</p> <p>Competition example: "You know, the porta potties near Fred Meyer, you know, and then like I was telling him, there's a woman living over here in this porta potty, you know, everybody's got to go at night, it's pretty much she's not getting out" (P 34).</p>	<p>Influence of the behavior of others on hygiene infrastructure availability</p> <p>Other people stealing hygiene resources from participants is an example of competition</p> <p>Competition example: Yeah they closed them both down because somebody was going in there and making a big mess, like huge mess and they just wouldn't stop. So they ended up closing the bathrooms, which is really sad, because we really need those bathrooms badly, Because they have hot water in there. Yeah, it's something that I love, when there's hot water...For showers or coffee or whatever. Wash your face, hands...(P 23).</p>
<p>RV-related issues</p>	<p>Variable access to shared, public, or common-pool vehicle-suitable water infrastructure due to overcrowding, overuse, or misuse by others</p> <p>For this code it is not about onboard RV facilities but about RV-related resources shared by multiple RV residents</p> <p>Behavior of users, RV-related example: "But a couple of motorhomes went in and filled up their 250-gallon tank. They [building owners] put a padlock on it" (P 26).</p>	<p>Variable access to shared, public, or common-pool vehicle-suitable sanitation infrastructure due to overcrowding, overuse, or misuse by others</p> <p>For this code it is not about onboard RV facilities but about RV-related resources shared by multiple RV residents</p> <p>Behavior of users, RV-related example: "I: I want to ask you about that. So here at [person's name] RV you guys would fill up containers with waste and then the pump out program would come...?"</p>	<p>Variable access to shared, public, or common-pool vehicle-suitable hygiene infrastructure due to overcrowding, overuse, or misuse by others</p> <p>For this code it is not about onboard RV facilities themselves but about RV-related resources shared by multiple RV residents</p> <p>Number of users, RV-related example: "About a month and a half. Depends on how many showers I take (laughs). Twice a week so you know it adds up. But again, if I had more water, freshwater capability of</p>

		P: Yeah they had one out here, but somebody stole it.” (P 31)	getting it easily...Yeah, I go someplace but I want everybody to know because the, the place that does it would be overloaded and I don't want to lose my source of water...” (P 12).
<i>Quality/Safety</i> <sup>248</sup>	Related to having facilities that are fit-for-use, function as they were designed to, and do not pose dangers to physical health <sup>336</sup>		
<b>Hygienic safety: [adequate, safe/inadequate, unsafe]</b>	Cleanliness of drinking and domestic water (think: water quality)	Cleanliness of sanitation facilities or practices (think: how well is participant separated from waste?)	Cleanliness of hygiene facilities or practices (think: how well can participant maintain personal hygiene?)
Treatment  Includes filtration, chlorination  Even if participant perceives resource to be safe, consider actual situation from an engineering perspective	<p>Treatment of water at its source or at point-of-use; codes may overlap between water and hygiene; not the same as “treating” the RV system (tanks, pipes) – see “Cleanliness”</p> <p>Inadequate: Drinking or otherwise using non-potable water from spigots/faucets on sides of buildings or houses</p> <p>Adequate: Drinking treated water or filtering/boiling water before use</p> <p>Adequate example: “I: So remember you don't have to answer like any questions you're not comfortable with but where do you get your drinking water? P: I buy it over at the store. I: From Fred Meyer? P: Yeah.” (P 1)</p>	<p>Opportunities for waste or wastewater to be treated upon disposal; does <b>not</b> include leaking tanks; codes may overlap between sanitation and hygiene; not the same as “treating” the RV system (tanks, pipes) – see “Cleanliness”</p> <p>Do <b>not</b> code use of pump-out program as adequate, since everybody in sample uses it</p> <p>Inadequate treatment: Open defecation; public urination; dumping blackwater, or urine outside or down stormwater drain; throwing away feces; selling RV with tank full (no opportunity for waste to be treated)</p> <p>Adequate: Dumping waste into a sewer manhole (illegal, but waste will be treated); dumping waste into porta potty or using a porta potty; blackwater, or urine going into sanitary sewer (e.g., participant</p>	<p>Treatment of water at its source or at point-of-use prior to its use for hygiene; treatment of greywater produced from hygiene activities; codes may overlap between water and hygiene and between sanitation and hygiene; not the same as “treating” the RV system (tanks, pipes) – see “Cleanliness”</p> <p>Do <b>not</b> code use of pump-out program as adequate, since everybody in sample uses it</p> <p>Inadequate: Dumping greywater outside or down stormwater drain; using untreated water for hygiene purposes; assume solar showers do not allow for greywater to be treated</p> <p>Adequate: Dumping greywater into sewer manhole (illegal, but waste will be treated); greywater going into sanitary sewer (e.g., participant uses shower at friend's house)</p>

		<p>uses toilet or shower at friend's house)</p> <p>Inadequate example: "I: Just a few more questions. Have you ever tell me more about where you've dumped your waste before you got connected with Chris? P: Well I find me a big grate and I'd throw it down there." (P 11)</p>	<p>Inadequate example: "Well, I know that if wastewater is held at all for any period of time, it cannot be dumped out, like, on the street or in the grass...the other day I took a shower... And, you know, I wasn't too worried about it because, you know, they don't have the valves, but it the water wasn't getting held at all, it just was going straight down..." (P 19).</p>
Risk of disease	<p>Actual risk of disease due to water; if a participant does not drink enough water do not code here (not a hygienic safety issue)</p> <p>Inadequate: Drinking from exterior taps; drinking water from RV holding tank, even if tank is cleaned; getting sick from drinking dirty water; using untreated water for cooking, doing dishes</p> <p>Adequate: Drinking bottled water or water from rest stop or dump station filling station; filtering water before use; <b>not</b> drinking dirty water; using treated water (could be from RV holding tank) for cooking, doing dishes; using untreated water for cleaning RV; rainwater is assumed to be fine</p> <p>Unclear risk: If it is unclear where water is from, do not code</p> <p>Inadequate example: "I: Where do you get your water for other things like cleaning, cooking, showering?"</p>	<p>Actual risk of disease due to sanitation</p> <p>Do <b>not</b> code use of pump-out program as adequate, since everybody in sample uses it.</p> <p>Inadequate: <b>Storing</b> blackwater in buckets; leaks or overflow; open defecation; public urination; dumping blackwater, urine outside on the ground or down stormwater drains</p> <p>Adequate: No leaks or overflow from blackwater tanks; no open defecation; no public urination; not dumping blackwater, urine on ground or down stormwater drain; wastewater is going into sanitary sewer or porta potty (e.g., participant using toilet or shower at friend's house); defecating in a bag and throwing it away</p> <p>Unclear risk: Do not code if blackwater sits in the tanks for a long time or if participant sells or</p>	<p>Actual risk of disease due to hygiene conditions</p> <p>Do <b>not</b> code use of pump-out program as adequate, since everybody in sample uses it.</p> <p>Inadequate: Using untreated water or water from exterior taps for personal hygiene; not showering every day; not doing laundry often or changing into new clothes but not washing them; not washing hands often (e.g., "I wash my hands when I can."); dumping greywater outside on the ground or down stormwater drain; using hand sanitizer more than washing hands with soap and water</p> <p>Just because use RV holding tank for showers does not automatically mean risk of disease.</p> <p>Adequate: Using treated water for personal hygiene; washing hands often (e.g., "I wash my hands before I eat and after I go to the bathroom."); using water from rest</p>

	<p>P: Faucets. I: Like on sides of buildings? P: Yeah.” (P 17)</p>	<p>purchases the vehicle with its wastewater tanks full</p> <p>Adequate example: “I: Do you ever have to go to the bathroom outside? P: No, I can’t do that. I don’t feel comfortable to do that. Myself. I don’t feel comfortable. I: Ok. I know some people have to go to the bathroom in a bag and then they tie it up and throw it away. P: Oh, no no no.” (P 29)</p>	<p>stop or dump station filling station for personal hygiene; greywater going into sanitary sewer (e.g., participant showering at friend’s house); rainwater is assumed to be fine</p> <p>Unclear risk: If it is unclear how often handwashes or showers, do not code (e.g., “Yeah I wash my hands.”); if it is unclear where water is from, do not code; do not code if greywater sits in tank for long time or if participant sells or purchases the vehicle with its greywater tanks full</p> <p>Inadequate example: “Yeah, I mean, you know, if I don’t have money what I supposed to do. I just sprayed with some detergent and that is. Right now it has been about a month two months I don’t wash” (P 10).</p>
<p>Cleanliness</p>	<p>Issues of cleanliness of water infrastructure that are <b>not</b> treatment related; includes cleanliness of RV water tanks (which is RV-related and cleanliness), other storage containers/behaviors, hoses, evidence of water facilities being orderly/well-maintained (e.g., area surrounding the water source is free of garbage)</p> <p>Inadequate example: “They’ll probably close that one pretty soon. I forgot all about it. I was meant to pick up, somebody like ate some canned soup and stuff. They’re like three cans bunch of garbage sitting there right next to the water spigot. I</p>	<p>Issues of cleanliness of sanitation infrastructure that are <b>not</b> wastewater treatment related; includes cleanliness of RV blackwater tanks (which is RV-related and cleanliness), evidence of sanitation facilities being orderly/well-maintained (e.g., toilet paper in porta potties, participant mentions cleaning RV bathroom or keeping public restrooms clean)</p> <p>Adequate example: “Yeah I think they’re fine. Yeah, I mean they keep them clean all the time. They’re always serviced all the time” (P 32).</p>	<p>Issues of cleanliness of hygiene infrastructure that are <b>not</b> water or wastewater treatment related; includes cleanliness of RV greywater tanks (which is RV-related and cleanliness), evidence of hygiene facilities being orderly/well-maintained (e.g., showers are clean)</p> <p><b>Not bodily cleanliness – with respect to laundry, hand hygiene, showering (code bodily cleanliness under “Risk of disease” if clearly bad or good)</b></p> <p>Only one Inadequate, RV-related Cleanliness example: “It’s just a pain in the b*tt, because we have to like, set up the shower stall take out the</p>

	don't know if that's gonna affect it or not..." (P 7).		pee buckets, clean everything out so it's not you know it's big to do to get clean" (P 30).
RV-related issues	<p>Hygienic safety of onboard water facilities; includes issues of stored tank water quality and cleaning and maintaining onboard system</p> <p>Physical mess in RV that prevents use of onboard water facilities: inadequate cleanliness, RV-related</p> <p>Concerns about bacteria build-up or bleach contamination in tank: inadequate cleanliness, high risk of disease, RV-related</p> <p>If participant uses tank and needs to clean water tank and "treat system" but has NOT done so: unsafe cleanliness, high risk of disease, RV-related</p> <p>If participant uses tank and has "treated system" (at some point): safe cleanliness, high risk of disease, RV-related</p> <p>Inadequate risk of disease, RV-related example: "It's a yeah it's more about how how to store the water so that it remains drinkable so like I was saying it's it's the tanks that are built into the system it's the possibility that water is either going to be contaminated by bacteria or an antibacterial agent" (P 36).</p>	<p>Hygienic safety of onboard sanitation facilities and of blackwater dumping practices; includes onboard sanitation facility or tank maintenance and cleaning; includes issues of leaking/overflowing tanks</p> <p>If only know that participant does not illegally dump but it is not clear what they do with their waste from one unit of analysis, just code as "Adequate Risk of disease, RV-related," not "Treatment."</p> <p>Do <b>not</b> code use of pump-out program as adequate, since everybody in sample uses it</p> <p>Includes physical mess in RV that prevents use of onboard sanitation facilities</p> <p>Adequate cleanliness, RV-related example: "P: Oh no I cleaned it, I sterilized it. Everything. Yeah, water and the sewage oh yeah it'd been sitting for 10 years, it only has 60,000 miles it's a 1994. I: What do you mean by sterilize? P: Bleach and (?) soak. Pressure washed, down in through the toilet. Get all the nooks and crannies, and</p>	<p>Hygienic safety of onboard hygiene facilities and of greywater dumping practices; includes onboard hygiene facility or greywater tank maintenance and cleaning; includes issues of leaking/overflowing greywater tanks</p> <p>Quality of water put <b>into vehicle tank</b> used for hygiene purposes will also be coded here</p> <p>Do <b>not</b> code use of pump-out program as adequate, since everybody in sample uses it</p> <p>Includes physical mess in RV that prevents use of onboard hygiene facilities</p> <p>Inadequate treatment, RV-related example: "Oh yeah, there's a storm drain like right here. I would be comfortable with greywater but I wouldn't do that with black water" (P 14).</p>

		then went up to Evergreen RV and dumped. I did that twice” (P 12).	
<p><b>Technical quality: [high quality/low quality]</b></p> <p>Even if participant perceives resource to be high technical quality, consider actual situation from an engineering perspective.</p>	<p>Technical quality of water infrastructure as it relates to functioning/mechanical quality (think: is it functioning as it should be?)</p>	<p>Technical quality of sanitation infrastructure as it relates to functioning/mechanical quality (think: is it functioning as it should be?)</p>	<p>Technical quality of hygiene infrastructure as it relates to functioning/mechanical quality (think: is it functioning as it should be?)</p>
<p>Non-RV-related issues</p>	<p>Technical quality of water infrastructure external to vehicle (can include accessories such as filters or pumps) as it relates to functioning/mechanical quality</p> <p>Do <b>not</b> code whether or not pliers or water faucet keys work for illegally tapping water</p> <p>If anyone is satisfied with an accessory and says why or describes an accessory as working well, code here</p> <p>Adequate example: “I actually, I have a friend that works for, they used to work for water, and he brought me a pump to sit on top of the five gallon jugs, it’s a lifesaver because my back the way it is it would not be an easy task” (P 34).</p>	<p>Technical quality of sanitation infrastructure external to vehicle (can include accessories) as it relates to functioning/mechanical quality</p> <p>If anyone is satisfied with an accessory and says why or describes an accessory as working well, code here</p> <p>Adequate example: “Well, that’s usually what I do I just haven’t been able to go over and get one lately but Yeah, almost every time I usually go and buy one from over there. It’s just a, it’s just lid, it sits on a five gallon bucket and and fits on there it snaps on just perfect. Yeah, it’s got a lid to it and a seat. That way it doesn’t hurt ya” (P 23).</p>	<p>Technical quality of hygiene infrastructure external to vehicle (can include accessories) as it relates to functioning/mechanical quality</p> <p>If anyone is satisfied with an accessory and says why or describes an accessory as working well, code here</p> <p>A hygiene accessory can be soap and its effectiveness (can reflect a personal preference, too, e.g., P 19)</p> <p>Low quality example: “P: Yeah we even have a washer. I: Oh, tell me about that. P: It’s like a RV washer. It hooks up to the generator and you put water in it and it...It has a piece broken right now.” (P 16)</p>

<p style="text-align: center;">RV-related issues</p> <p>Does <b>not</b> include other non-WASH vehicle maintenance such as oil changes</p>	<p>Technical quality of onboard water facilities (think mechanical failures: leaks and broken parts)</p> <p>Adequate example: "I: Okay. And do you use like the water tanks in your RV? P: I used to, not so much anymore. But everything works still. I'm probably going to start using all that stuff again here soon." (P 23)</p>	<p>Technical quality of onboard sanitation facilities (think mechanical failures: leaks, broken parts, clogs); includes mechanics of pump-out program (e.g., pump-out truck fittings to connect to RVs)</p> <p>High quality: Using enzymes improves technical quality of blackwater tanks</p> <p>Low quality: All leaks from onboard tanks even from overfilling; not using enzymes</p> <p>Inadequate example: "I: Is Chris able to help you with that? P: No, he's helping me with this sewer line, getting that part fixed on it. I: Oh, okay, that's good. Is it is it broken. P: Yeah." (P 13)</p>	<p>Technical quality of onboard hygiene facilities (think mechanical failures: leaks and broken parts)</p> <p>High quality: Using enzymes improves technical quality of greywater tank</p> <p>Low quality: All leaks even from overfilling</p> <p>Adequate example: "...Oh yeah, so you're asking about the greywater tank and the black water tank. Yeah, I don't have any plans to do any maintenance on those. I: Ok so they're not... they're not actively leaking now? P: No, there's no leaking. There's no issues with them. I: And that's great so when you bought the RV... P: Oh, yeah everything worked on the RV. Yeah." (P 14)</p>
<p><i>Acceptability</i></p>	<p>Related to having facilities that are culturally palatable and comfortable to the user (think: satisfaction with infrastructure)</p>		
<p><b>Cultural perceptions<sup>342</sup>: [appropriate/inappropriate]</b></p> <p>Do <b>not</b> code how acceptable participants think illegal behavior is (their behavior or others), even if they cite "their rights." Do not code norms around behaviors such as open defecation that are illegal. Sometimes a norm is mentioned about something related to illegal activity but not to activity itself (e.g., P 7 embarrassed about smelling like diarrhea after</p>	<p>Social or cultural norms associated with water; includes norms associated with when and how the user accesses or uses water</p>	<p>Social or cultural norms associated with sanitation; includes norms associated with when and how the user accesses or uses sanitation facility</p>	<p>Social or cultural norms associated with personal hygiene; includes norms associated with when and how the user accesses or uses hygiene facility</p>

defecating behind a dumpster). Not interested in privacy or gender norms with respect to urinating outside.			
Gender norms	<p>Social or cultural norms influencing the relationship between gender and water; includes collection responsibilities</p> <p>No examples</p>	<p>Social or cultural norms influencing the relationship between gender and sanitation; includes issue of public urination</p> <p>Inappropriate example: “Na, just that sometimes it’s not like there’s a whole lot of cover, you know, being female be nice if there’s some where we can have some cover” (P 23).</p>	<p>Social or cultural norms influencing the relationship between gender and hygiene; includes standards of cleanliness</p> <p>Appropriate example: “Where over here for the men it’s an open shower kind of like jail, you know what I mean, open shower and all the men are there” (P 28).</p>
Privacy norms	<p>Social or cultural norms influencing the relationship between privacy and water; includes issues of public attention and water access or use</p> <p>No examples</p>	<p>Social or cultural norms influencing the relationship between privacy and sanitation; also includes issue of public urination/open defecation</p> <p>Inappropriate example: “We have a usable toilet in here. But sometimes, sometimes he’s either using it or I’m using it. And if it’s late at night, and we and like his brother is here or something. Um, neither one of us really comfortable going in the bathroom in front of him or he he’ll walk down to the boat ramp where the honey bucket is” (P 3).</p>	<p>Social or cultural norms influencing the relationship between privacy and hygiene; includes issue of shared showers</p> <p>Appropriate example: “But Urban Rest Stop is one of the major ones that we use because they’re a little bit nicer than the other ones, you get a private shower there. Where over here for the men it’s an open shower kind of like jail, you know what I mean, open shower and all the men are there. But urban rest stop is different they give you a private shower for 15 minutes” (P 28).</p>
Other social norms	<p>Social or cultural norms other than those related to gender or privacy and water; includes norms related to homelessness</p> <p>Participants may reference a social norm by commenting on other people’s behavior.</p>	<p>Social or cultural norms other than those related to gender or privacy and sanitation; includes norms related to homelessness; includes feelings of shame due to perceptions of breaking social norms (e.g., smell of feces on clothes)</p>	<p>Social or cultural norms other than those related to gender or privacy and hygiene; includes norms related to homelessness</p> <p>Participants may reference a social norm by commenting on other people’s behavior.</p>

	<p>No examples</p>	<p>Participants may reference a social norm by commenting on other people's behavior.</p> <p>Inappropriate example: "Yeah. But I have no vehicle now and thank * for wastewater. I don't think the bus driver would be to take too kindly taking my sh*ts on there (laughs). Bad enough they don't want what propane tanks, even if they're empty on there" (P 11).</p>	<p>Statements such as "I wash my hands like I would in an apartment" or "like anyone else would" are too neutral to be coded.</p> <p>Code participants "wearing out their welcome" showering at friends' place as inappropriate (possibly indicative of some unwritten rule).</p> <p>Inappropriate example: "I: But you don't, you don't really go through a lot of water washing your hands or...? P: You won't find many homeless people that do in a lot of places. Some people have really dirty hands, it does kind of distinguish you out from a lot of people." (P 25)</p>
<p>RV-related issues</p>	<p>Social or cultural norms related to the use of onboard water facilities or other RV-related water infrastructure</p> <p>No examples</p>	<p>Social or cultural norms related to the use of onboard sanitation facilities or other RV-related sanitation infrastructure</p> <p>Inappropriate privacy norms, RV-related example: "Yeah yeah. And I mean it still kinda sucks cuz you know if I have to go to the bathroom it smells you know I have the vents open and everything and I'm kind of funny about when I do it not a busy time of day stuff like that. I: Sure. I guess that's something else to consider like you the first person that's mentioned that have, you know just yeah, just privacy.</p>	<p>Social or cultural norms related to the use of onboard hygiene facilities or other RV-related hygiene infrastructure</p> <p>Appropriate other social norms, RV-related example: "Um, just as if I was living in an apartment, I wash my hands whenever I'm gonna need it before or after eating, cooking, going to the bathroom, I wash my hands" (P 14).</p>

		P: Yeah. And more than that I don't want to offend anybody walking by." (P 34).	
<p><b>Personal preferences: [satisfactory/unsatisfactory]</b></p> <p>Cleanliness can be coded as both a Quality/Safety issue and Acceptability issue</p> <p>Do <b>not</b> code preferences around illegal resources</p>	<p>Personal preferences and user experience during water access or use</p>	<p>Personal preferences and user experience during sanitation access or use</p>	<p>Personal preferences and user experience during hygiene facility access or use</p>
<p>Non-organoleptic experiences</p>	<p>Non-organoleptic preferences or experiences during water access or use (that are separate from social norms)</p> <p>Do <b>not</b> code opinions that do not explain <i>why or attribute to anything specific</i>, such as if a participant simply says, "I'm uncomfortable" or "It's nice."</p> <p>Satisfactory example: "Not much, whatever, you know, jugs we have like the jug there, there's like a jug there and then there's sometimes we have the five gallon jugs, but for some reason people like to steal those. So yeah, I don't have I don't have one right now, which is really crappy because those are the best ones to have, it'd be nice if we had more. The easiest to store" (P 23).</p>	<p>Non-organoleptic preferences or experiences during sanitation access or use (that are separate from social norms); includes feelings of comfort , or cleanliness/dirtiness around toileting, toilet ergonomics; satisfaction with pump-out program is coded as non-organoleptic and RV-related</p> <p>Do <b>not</b> code opinions that do not explain <i>why or attribute to anything specific</i>, such as if a participant simply says, "I'm uncomfortable" or "It's nice."</p> <p>Unsatisfactory example: "The Safeway are bad people too, they don't keep the bathroom clean, they kick us out, they close the doors..." (P 10).</p> <p>Satisfactory example: "Yep, yep, okay, with a pool noodle around, so it's cushion for your butt. You gotta have comfort you know?" (P 16).</p>	<p>Non-organoleptic preferences or experiences during hygiene facility access or use (that are separate from social norms); includes feelings of comfort, quality of hygiene product, amount of time for shower, frequency of shower, feelings of cleanliness/dirtiness around hygiene; satisfaction with pump-out program is coded as non-organoleptic and RV-related</p> <p>Do <b>not</b> code opinions that do not explain <i>why or attribute to anything specific</i>, such as if a participant simply says, "I'm uncomfortable" or "It's nice."</p> <p>Unsatisfactory example: "I have too much sexual abuse, trauma, I mean I would shower in a community center if I had to, but I've had sexual trauma to be around a lot of people like that so I prefer to go to my friend's house where I feel safe" (P 35).</p>

<p>Organoleptic experiences</p>	<p>Includes issues of water odor, taste, color, temperature, look (sight)</p> <p>Needs to have some indication of good or bad (e.g., not enough to just mention hot water)</p> <p>Satisfactory example: “P: So they ended up closing the bathrooms, which is really sad, because we really need those bathrooms badly, Because they have hot water in there. Yeah, it’s something that I love, when there’s hot water. I: What do you what do you do now for hot water? P: Now I just have to boil it. I: And what do you like to use the hot water for? P: For showers or coffee or whatever. Wash your face, hands.” (P 23)</p>	<p>Includes issues of sanitation facility odor</p> <p>Just because something does not have a smell does not make it satisfactory unless participant is clearly satisfied (P 15 is unclear while P 12 is satisfied)</p> <p>Unsatisfactory: Code bad smells; smells originating from vehicle are organoleptic and RV-related</p> <p>Unsatisfactory example: “You know, you got to use the bathroom I said here you go over here, here’s a bucket. You know. Cuz nobody wants to smell urine, especially somebody else’s (laughs)” (P 11).</p>	<p>Issues of hygiene facility odor, temperature of water used for personal hygiene; dry skin (an organ)</p> <p>Satisfactory example: “Well they’ve got a community center over here, and uh, I go to the community center and take a nice hot shower” (P 8).</p>
<p>RV-related issues</p>	<p>Comfort of and preferences around use of onboard water facilities</p> <p>Satisfactory organoleptic, RV-related example: “And the water tastes fine but I’m a little nervous about if I don’t flush the lines with something antibacterial that I might...” (P 36).</p>	<p>Comfort of and preferences around use of onboard sanitation facilities; satisfaction with pump-out program (its performance, customer service, etc.); includes acceptability of sharing onboard toilet</p> <p>Satisfactory non-organoleptic, RV-related example: “They’ve been great when they come out. You know, there’s been one time that they came out... where the truck didn’t have the right adapter for the RV that I used to have. That was the one time that, you know, it didn’t work out. But otherwise, it’s been great” (P 19).</p>	<p>Comfort of and preferences around use of onboard hygiene facilities</p> <p>Unsatisfactory non-organoleptic, RV-related example: “I: Okay. How was it, can I ask, what was it like taking a shower in there, was it really difficult? P: Honestly like it was super stressful, because, first of all there, there’s not enough water in the tank. You know, I had to run out. Or someone ran out, put more water into the thing. And it’s kind of a waste of time, really, to do that.” (P 15)</p>

<u>Timescale</u>	Related to the influence of a specific period of time on WASH		
<p><b>Seasons<sup>343</sup>: [mentions seasons or weather]</b></p>	<p>Effects of seasons or weather on water access or use</p> <p>Example: “So when it rains I got buckets down here. Catch the rainwater and I wash my dishes and stuff in the rainwater” (P 26).</p>	<p>Effects of seasons or weather on sanitation access or use</p> <p>No examples</p>	<p>Effects of seasons or weather on hygiene facility access or use</p> <p>Example: “Showering, we have a solar shower during the summer, and we heat water in a big soup pot on the stove during the winter. So just depends on the weather, we don’t shower a ton, but we do shower” (P 30).</p>
<p><b>Pandemic: [mentions pandemic]</b></p>	<p>Influence of COVID-19 on water</p> <p>No examples</p>	<p>Influence of COVID-19 on sanitation</p> <p>Adequacy, pandemic example: “I know that it’s very nice of them to come because things would be so worse if they didn’t come, cuz there’s no, really since all the bathrooms have closed, just about everywhere they want to go the bathroom you know like it would be before the pandemic” (P 24).</p>	<p>Influence of COVID-19 on hygiene</p> <p>Accessibility, pandemic example: “I usually go to my parents, but they ended up moving. So because they moved they actually are in a place that I can’t go into. Because it’s low-income housing, and it’s because of COVID you weren’t allowed to have visitors. So that was like a big no go like don’t visit your parents unless you’re outside. So I haven’t been able to use the utilize the restroom. That means like, no showers” (P 5).</p>
<u>Energy</u>	Related to association between energy and WASH		
<p><b>Energy: [mentions energy]</b></p> <p>Includes RV gas, batteries</p> <p>Not interested in non-WASH-related energy issues (e.g., energy needed to charge cell phone)</p>	<p>Relationship between energy and water; includes boiling water, heating water with propane</p> <p>Example: “I have my extra, my water tank is full, but I can’t use it because don’t have electricity to run the pump” (P 13).</p>	<p>Relationship between energy and sanitation</p> <p>Example: “Sometimes I’ll run a fan for a couple minutes” (P 14).</p>	<p>Relationship between energy and hygiene</p> <p>Includes solar energy (e.g., solar showers)</p> <p>Example: “So I guess I’ll just get water. Bird bath here in cold water or I now got a little cook stove now that someone gave me, and I put little propane tanks in it when I have the extra cash for it. And I use that for</p>

			heating so every three days I'll heat up some water and do a thorough bird bath in some nice warm water" (P 13).
<u>Access to information (a type of infrastructure)</u>	Related to how residents obtain information/knowledge and how much they know (or think they know)		
<p><b>Where: [mentions source]</b></p> <p>Not "where to go" but "where is information from?"</p> <p>Why do participants know something or why don't they?</p>	<p>Source of information about water-related matters; includes experience as a source of information</p> <p>Example: "Well, I've got some of it, back when I used to camp with my parents. My mother ended up developing Crohn's disease...So and then, you know, I like watching a lot of history YouTubes..." (P 19).</p>	<p>Source of information about sanitation-related matters; includes experience as a source of information; includes pump-out program</p> <p>If participants have not learned anything from pump-out program and/or they are willing to learn from the pump-out program, code as "Where"</p> <p>If participant does not have or does not know where to go to get information, still code as "Where"</p> <p>Not having experience dumping (never doing it) is "Where"</p> <p>Example: "We'd probably have to do it ourselves. We used to have a book on just about everything it's a really good RV book about how to fix, about anything on it, but we loaned it to somebody and it never back. But you know, Google it or something" (P 7).</p>	<p>Source of information about hygiene-related matters; includes experience as a source of information and pump-out program (if greywater is mentioned)</p> <p>Example: "And that's when I started doing some online research and just trying to figure out if there were any more you know any other programs and that's when I found a research paper about the SPU program but there wasn't any online resources at the time for it" (P 36).</p>
<p><b>How much: [knowledgeable/not knowledgeable]</b></p>	<p>Depth of knowledge about water-related matters; includes knowledge about water laws, regulations, where water comes from, RV-related water facility or holding tank</p>	<p>Depth of knowledge about sanitation-related matters; includes knowledge about pump-out program, sanitation laws, regulations, <b>possible contamination of water bodies</b></p>	<p>Depth of knowledge about hygiene-related matters; includes knowledge about pump-out program (if greywater is mentioned), hygiene laws, regulations, RV-related hygiene facility or greywater tank</p>

<p>Not knowledgeable does not always mean incorrect, and knowledgeable does not always mean correct.</p> <p>Situation where most interested in participant being incorrect: If participant is wrong about safety of WASH source (e.g., P 16 water) or practice (e.g., P 19 dumping greywater)), code as not knowledgeable, only if he/she explicitly says something incorrect (not just the fact that they drink water from non-potable water source)</p> <p>In terms of illegal behavior, if participants express some sort of “insider knowledge” or “street smarts” in terms of accessing illegal source that goes beyond just saying they do something illegal, then also code as knowledgeable. Not knowledgeable if clear lack of “insider knowledge” (e.g., P 4). Having the code to an illegal source is not enough to count as access to information.</p>	<p>maintenance, water-related diseases</p> <p>Do they know of all the resources available to them? This may be clearest when the participant says “I’m not sure if there is _____” or “As far as I know” (some expression of uncertainty). <b>The participant may be correct but just may not be confident.</b></p> <p>Do <b>not</b> code “knowledge of a leak or no leak”, “knowledge of tank fill time”, or “knowledge of tank size” as knowledge.</p> <p>Not knowledgeable example: “I haven’t figured out how to use it like the tanks inside but every time I’ve ever tried to fill one it either leaked out inside the RV or I’m not doing it right or I don’t know how. So, other than that the ones I fill up from out here, and the water that I buy. No, I don’t store it nowhere else” (P 24).</p>	<p><b>with wastewater</b>, RV-related sanitation facility or blackwater tank <b>maintenance</b> (includes knowledge about resources for RV parts or maintenance), poor sanitation-related diseases</p> <p>If participant can do any maintenance on his/her RV tanks, code as “knowledgeable.”</p> <p>Do they know of all the resources available to them? This may be clearest when the participant says “I’m not sure if there is _____” or “As far as I know” (some expression of uncertainty). <b>The participant may be correct but just may not be confident.</b></p> <p>For knowledge about pump-out program question <b>ONLY</b> (in response to the interview question “What do you know about the pump-out program?”): Code as knowledgeable if participant knows the truck pumps out waste <b>AND two or more facts</b> from the following (it is ok if they do not specifically say truck pumps out waste and just list facts):</p> <ul style="list-style-type: none"> <li>• The frequency of pump-outs</li> <li>• Chris/SPU and St Vincent de Paul/distribution team</li> <li>• Funding cuts and stationary pump-out service</li> </ul>	<p>maintenance, poor hygiene-related diseases, where greywater goes</p> <p>Do they know of all the resources available to them? This may be clearest when the participant says “I’m not sure if there is _____” or “As far as I know” (some expression of uncertainty). <b>The participant may be correct but just may not be confident.</b></p> <p>Do <b>not</b> code “knowledge of a leak or no leak”, “knowledge of tank fill time”, or “knowledge of tank size” as knowledge.</p> <p>Not knowledgeable example: “Yeah, Yeah and I mean there has to be an easier way to do it you know like transfer it. But I wouldn’t know” (P 15).</p>
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		<ul style="list-style-type: none"> <li>• Communication method – texts, flyers</li> <li>• Where program pumps out (in city)</li> </ul> <p>Code as not knowledgeable if participant does not answer the question or if participant only knows they pump out waste, only knows one fact from list, or cannot give any details about program.</p> <p>Other times throughout an interview that participants mention one-off facts about the program (i.e., If the participant is not answering the question “What do you know about the pump-out program?”) do <b>not</b> code as “Access to information.”</p> <p>Do <b>not</b> code “knowledge of a leak or no leak”, “knowledge of tank fill time”, or “knowledge of tank size” as knowledge.</p> <p>Knowledgeable example: “Yeah. I fixed the leaks it had when those I got it” (P 1).</p>	
<i>Suggestions</i>	Recommendations from participants on how to improve their WASH situation or how to improve the interview		
<b>Suggestions</b>	<p>Recommendations from participants on how to improve their water situation or recommendations on how to improve interview (e.g., water-related questions that should have been asked)</p> <p>Example: “Well, port of Seattle, Shilshole Marina. The port, they</p>	<p>Recommendations from participants on how to improve their sanitation situation or recommendations on how to improve interview (e.g., sanitation-related questions that should have been asked)</p>	<p>Recommendations from participants on how to improve their hygiene situation or recommendations on how to improve interview (e.g., hygiene-related questions that should have been asked)</p>

	<p>have an area with many different buildings with faucets. They should make it so somebody can drive up, put water in their RV and drive away" (P 12).</p>	<p>Example: "A lot of the little encampments and stuff whether they're vehicles or tents, if they would just put a dumpster and a couple porta potties it would just make just so much difference. It would make a huge difference" (P 7).</p>	<p>Example: "Well, I know that the Union Gospel Mission. They have a portable shower system that they drag around, be nice if somebody could maybe help us out with something like that, you know, even if they came twice a week" (P 11).</p>
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## Final coding dictionary outline

(45 child codes x 2 for positive and negative x 3 for water, sanitation, hygiene)

### Accessibility (WASH that is able to be accessed)

#### **Physical: [convenient/inconvenient]**

Time or distance

Energy expenditure (effort)

RV-related issues

#### **Economic: [inexpensive, affordable/expensive, unaffordable]**

Non-RV-related costs (can be free things)

RV-related costs (can be free things)

#### **Social: [benefits from or participates in/does not benefit from or participate in]**

Sharing

Socially reciprocal behaviors

Community facility or service

Status

Illegal practices

RV-related issues

### Adequacy (sufficiency of WASH to use)

#### **“Amount” of facilities: [enough/not enough]**

Non-RV-related facilities

RV-related facilities

#### **Diversification: [mentions diversification] – not interested in no diversification**

#### **Consumption: [mentions preservation] – not interested in does not preserve**

Non-RV-related issues

RV-related issues

#### **Storage: [enough/not enough]**

Non-RV/non-tank-related issues

RV-related/tank-related issues

Availability (WASH is available when needed)

**Operation: [adequate, continuous/inadequate, discontinuous]**

Non-RV-related issues

RV-related issues

**Competition: [competition/no competition]**

Number of users

Behavior of users

RV-related issues

Quality/Safety (fit-for-use infrastructure)

**Hygienic safety: [adequate, safe/inadequate, unsafe]**

Treatment

Risk of disease

Cleanliness

RV-related issues

**Technical quality: [high quality/low quality]**

Non-RV-related issues

RV-related issues

Acceptability (comfort and satisfaction around infrastructure)

**Cultural perceptions: [appropriate/inappropriate]**

Gender norms

Privacy norms

Other social norms

RV-related issues

**Personal preferences: [satisfactory/unsatisfactory]**

Non-organoleptic experiences

Organoleptic experiences

RV-related issues

Timescale (influence of specific time period on WASH)

**Pandemic: [mentions pandemic influences]**

**Seasons: [mentions seasons or weather]**

Energy (influence of energy on WASH)

**Energy: [mentions energy]**

Access to information (a type of infrastructure)

**Where: [mentions source]**

**How much: [knowledgeable/not knowledgeable]**

Suggestions (recommendations from participants on improving WASH or interview)