USING MONITORING DATA TO IDENTIFY WATER AND SANITATION SERVICE DELIVERY IMPROVEMENT OPPORTUNITIES IN LOW- AND MIDDLE-INCOME COUNTRIES

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ABSTRACT

Ryan D. Cronk: Using monitoring data to identify water and sanitation service delivery improvement opportunities in low- and middle-income countries
(Under the direction of Jamie Bartram)

Universal access to basic sanitation and water services and their progressive improvement are important for human development, health, and human rights; and are recognized in program, national, and international policies such as the Sustainable Development Goals (SDGs). Monitoring data are important for measuring progress toward universal access and improvements in service levels. In the SDG era, substantially more data will become available with new and expanded monitoring. These data can be analyzed beyond their immediate purpose to answer policy-relevant questions. However, these data are underused for service delivery research and there are opportunities to improve the reliability and quality of monitoring. To address these challenges, I analyzed monitoring data to identify opportunities to improve monitoring and water and sanitation service delivery.

Using water supply infrastructure data from sub-Saharan Africa and Central America, Bayesian networks predicted water system functionality and continuity increased by as many as 20 percentage points when best-observed conditions were in place. I systematically compiled health care facility (HCF) datasets to produce the first coverage estimates for 21 indicators of environmental conditions in HCFs in low- and middle-income countries, where 52% of HCFs lack piped water and 30% lack improved sanitation. Statistically significant inequalities in coverage exist between HCFs by urban-rural setting, managing authority, facility type, and

administrative unit. Using frontier analysis, I transformed household monitoring data into indicators of water and sanitation performance. Water and sanitation performance analysis provides policymakers with a new accountability instrument for assessing country progress on meeting full realization of human rights obligations. There are many simple data collection improvement opportunities that do not add substantial cost or burden which would make monitoring data more valuable for service delivery research. Improvement opportunities include the use of: relevant and appropriate survey questions, clear definitions, and quality assurance/quality control measures.

Together, these studies demonstrate substantial, unrealized value that can be derived from monitoring. Monitoring improvements and analysis of these data are major opportunities to make better use of limited resources, inform evidence-based decision-making for better management, policy, programming, and practice, and improve water and sanitation service delivery.

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LIST OF ABBREVIATIONS

BN	Bayesian network
CAPI	Computer assisted personal interviewing
CI	Confidence interval
DHS	Demographic and Health Survey
HCAI	Health care acquired infection
HCF	Health care facility
IRB	Institutional review board
JMP	Joint Monitoring Programme for water supply and sanitation of the World Health Organization and UNICEF
LAC	Latin America and the Caribbean
LGA	Local government area
LMIC	Low- and middle-income country
LSMS	Living Standards Measurement Survey
MICS	Multiple Indicator Cluster Surveys
MST	Mobile survey tool
NGO	Non-Governmental Organization
OR	Odds ratio
PAPI	Paper-and-pencil interviewing
PCS	Post construction support
QA/QC	Quality assurance/quality control
QI	Quality improvement
ROC	Receiver operating characteristic

RCT	Randomized controlled trial
SARA	Service Availability and Readiness Assessment
SDG	Sustainable Development Goals
SIASAR	Sistema de Información de Agua y Saneamiento Rural
SPA	Service Provision Assessment
STROBE	Strengthening the reporting of observational studies in epidemiology
UN	United Nations
UNICEF	United Nations Children's Fund
WaSH	Water, Sanitation, and Hygiene
WHO	World Health Organization

CHAPTER 1: INTRODUCTION

Universal access to basic water and sanitation services and increased delivery and use of safely-managed services have long been recognized as important for human health, well-being, and development (Bartram & Cairncross, 2010). However, more than 2.4 billion people use unimproved sanitation facilities or defecate in the open and 663 million people use an unimproved drinking water source (WHO/UNICEF, 2015b). Many more do not use safely managed water and sanitation services (WHO/UNICEF, 2015a). When accounting for water quality, 1.8 billion people drink from a fecally-contaminated source (Bain, Cronk, Hossain, et al., 2014; Onda, Crocker, Kayser, & Bartram, 2014). Many of these people live in rural areas, use discontinuous services, and/or non-piped water sources that are distant from the home (Bain, Cronk, Wright, et al., 2014; Kumpel & Nelson, 2016; Shields, Bain, Cronk, Wright, & Bartram, 2015). An estimated 4.1 billion people use sanitation facilities where waste is not treated before it is discharged into the environment (Baum, Luh, & Bartram, 2013). More than 842,000 deaths in 2012 were attributable to inadequate drinking water, sanitation, and hygiene (WaSH) in low- and middle-income countries (LMICs) (Pruss-Ustun et al., 2014).

The substantive and well-documented water and sanitation challenges are reflected in program, local, national, and international policies, goals, and targets. In international development policy, water and sanitation service delivery targets are established in the Sustainable Development Goals (SDGs) through Goal 6. It includes targets for universal access to basic WaSH services by 2030 and service level improvements (United Nations General Assembly, 2015; WHO/UNICEF, 2015a). The WHO/UNICEF Joint Monitoring Programme for

Water Supply and Sanitation (JMP) is responsible for defining and measuring the targets of Goal 6. As part of the definition of universal access, the JMP include non-household settings such as health care settings and schools. (Cronk, Slaymaker, & Bartram, 2015; United Nations General Assembly, 2015; WHO/UNICEF, 2016a, 2016b).

Monitoring data are used to identify and report on trends and patterns of water and sanitation services, including measuring progress toward universal access and service improvements. Using information from 77 LMICs, data experts predict that at least US$1 billion will be needed annually for expanded and new country-level monitoring and statistical initiatives to measure overall SDG progress (Espey, 2015). More will be spent annually on water and sanitation-specific project, program, and sub-national monitoring initiatives (One WaSH National Program, 2013; Pena L, 2013; WPDx, 2015).

There are opportunities to improve monitoring – without adding costs or constraints – to make the data more useful for their intended purposes (reporting levels and trends in service levels) and also deliver added value through other means, such as service delivery research (i.e. the analysis of data on water and sanitation systems to improve service delivery).

For example, there are opportunities to increase the quality and reliability of data collection (Royston, 2011; Zachariah et al., 2009). Improved reporting of sample frames used for monitoring increases the generalizability of the findings (Ministry of Water, 2013). Use of specific survey questions leads to better responses and reduces the potential for under- or over-reporting of water and sanitation service conditions (Fisher et al., 2015). Improved reporting of data collection methods, sources of potential bias, and study limitations makes it easier for others to interpret and use data, replicate monitoring, and learn from errors and mistakes (WPDx, 2015).

Service delivery research is increasingly discussed by water and sanitation actors and leaders as a means to identify and overcome service delivery challenges and bottlenecks; and identify improvement opportunities (Bartram et al., 2015; Department for International Development (DFID), 2012; WHO, 2016; World Health Organization and UNICEF, 2015). Evidence from service delivery research helps policymakers, planners, and practitioners make better decisions about water and sanitation management and identify processes that improve the quality and sustainability of services. However, monitoring data are little used for water and sanitation service delivery research. For example, a systematic review on the use of nationally-representative Demographic and Health Surveys (DHS) in research shows that there are few studies that use DHS data to explore water and sanitation service delivery challenges. In contrast, other areas of health and development research have many studies that use DHS monitoring data. These health and development studies reveal important insights for policy, programming, and practice (Fabic, Choi, & Bird, 2012).

Among water and sanitation service delivery research studies that do use available monitoring data, many studies only report descriptive statistics. Modeling tools are infrequently used to examine relationships between service outcomes and explanatory variables (Royston, 2011). Reports of such studies are infrequently published and made public, few undergo peer review which would add rigor and credibility to the findings, and study findings are rarely translated into actionable policy, programming, and practice recommendations (Zachariah et al., 2009).

The fundamental purpose of monitoring is to create information for action to improve matters. More effective and relevant service delivery research could be produced from available data by researchers for decision-makers (e.g. policymakers, program managers, planners, practitioners) if the boundaries between researchers and decision-makers were better managed to produce salient, credible, and legitimate evidence and associated knowledge products. Saliency here refers to relevance to the decision maker, credibility refers to scientific adequacy, and legitimacy refers to fairness and balance of the process and production of the knowledge products (Cash et al., 2003). However, in water and sanitation, boundaries between actors are often poorly defined or actors work in isolation, where researchers may produce scientifically-credible service delivery research with low salience and/or legitimacy; or practitioners may produce salient findings that have low credibility and/or legitimacy (Cash et al., 2003; Kristjanson et al., 2009).

Diverse service delivery research studies describe overlapping purposes and definitions for similar activities and actions. In the health literature, there has been substantial debate and discussion to define types of service delivery research and describe the role of each in improving health systems (Remme et al., 2010). However, there is little equivalent clarification in water and sanitation service delivery. This lack of clarity on types, definitions, and good practices adversely affects the credibility of service delivery research studies. Inconsistencies make it difficult to evaluate and assess their individual and collective value and impedes their legitimacy and salience among decision-makers (Remme et al., 2010; White, Smith, & Currie, 2011).

Dissertation research questions

In response to these challenges and opportunities, my overarching dissertation research questions are: (1) What examples of additional value can be derived from water and sanitation service delivery monitoring through use in service delivery research? And (2) what opportunities are there to improve water and sanitation service delivery monitoring – adding no or minimal costs or constraints – such that it adds value for policy, programming, and practice? I answer these questions using survey-based input-output-outcome monitoring. I use data from three types of surveys: infrastructure surveys (for example, water system level data), non-household facility surveys (for example, health care facility level data), and nationally representative household surveys. Where appropriate, hygiene and environmental health are addressed (Chapter 5 on health care facilities).

In Chapter 2, the literature review, I identify methods of data collection, types of monitoring, and types of service delivery research. Using water and sanitation service delivery studies and literature on general good practice for data collection, I identify opportunities to improve input-output-outcome monitoring collected through surveys and opportunities to improve their analysis and reporting in service delivery research studies. Jamie Bartram and Michael B. Fisher are co-authors.

In Chapters 3 and 4, I analyze water system infrastructure data using regression and Bayesian Networks to explore variables that influence water service availability. There are few studies that use Bayesian networks to quantitatively explore water service availability. Jamie Bartram is a co-author. As of submission of this dissertation, Chapter 3 is under review at Environmental Science & Technology and Chapter 4 is under review at the Journal of Cleaner Production.

In Chapter 5, I use nationally- and sub-nationally representative health care facility data, to produce the first coverage estimates of environmental conditions and standard precautions in HCFs in low- and middle-income countries (LMICs); and explore factors associated with low coverage. Jamie Bartram is a co-author. As of submission of this dissertation, Chapter 5 is under review at the International Journal of Hygiene and Environmental Health.

In Chapter 6, I use frontier analysis to transform nationally representative household survey data into indicators of country performance on water and sanitation to explore which countries are high and low performers on improving water and sanitation services. Jamie Bartram is a co-author.

In Chapter 7, the joint discussion, I synthesize the findings of the preceding chapters and describe their implications for improving monitoring and generating further value through analysis to inform policy, programming, and practice.

CHAPTER 2: LITERATURE REVIEW

Literature review objectives

I conducted a literature review to:

- Identify and document methods of data collection and types of monitoring
- Identify, document, characterize, and clarify types of service delivery research
- Identify examples of water and sanitation service delivery research studies
- Identify literature documenting good practice for data collection
- Use good practices for data collection to identify opportunities to improve: input-output-outcome monitoring collected through surveys; the analysis and reporting of these data in service delivery research studies; and the salience, credibility, and legitimacy of studies

Methods

Literature review of monitoring and service delivery research

A systematic review was not practical because service delivery research is broadly defined and associated terms, such as operational research and implementation science, are inconsistently used in water and sanitation (Datta, 1993; Royston, 2011; White et al., 2011). Literature searches were conducted in PubMed and Google Scholar. The search strategy combined terms associated with monitoring and service delivery research; terms associated with water and sanitation (hygiene studies were not reviewed to reduce the scope), global health, or international development; terms associated with data collection; and low- and middle-income country (for example, “operational research” AND “water” AND “survey” AND “low- and middle-income country”). Global health and international development literature reviews were reviewed (Datta, 1993; Royston, 2011; White et al., 2011; Zachariah et al., 2009). To ensure inclusion of literature published by actors such as governments and external support agencies (e.g. multi-lateral agencies, non-governmental organizations), relevant information repositories were searched such as the knowledge databases of IRCWASH and the Water, Engineering and Development Centre (IRC WASH, 2016; WEDC, 2016).

Types and definitions of monitoring and service delivery research and examples

Methods of data collection, types and definitions of monitoring, and types and definitions of service delivery research employed in the selected studies were compared to explore overlap and interrelationships. Existing definitions from selected studies were used to more clearly define service delivery research and draw boundaries around types for water and sanitation.

Water and sanitation service delivery studies were tabulated. Service delivery research studies were selected if they were:

- About water and sanitation service delivery in LMICs;
- Collected or used monitoring data, observational data (qualitative or quantitative), and/or data for the purpose of improving a process or program; and
- Analyzed these data and used the results to make policy, practice and/or programming recommendations related to service delivery improvements.

Good practices for monitoring, analysis, and reporting of service delivery research

Quality improvement (QI) frameworks are widely used in fields such as manufacturing and health care (Juran & Riley, 1999; Shewhart & Deming, 1939). Generally, steps in a quality improvement framework where good practice (i.e. practices that lead to better quality data and/or evidence) may be applied are "define, measure, analyze, improve, and control" (Borror, 2009). The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) criteria are a checklist of good practice reporting items for cross-sectional observational studies and Hales *et al.* (2016) developed reporting guidelines for implementation and operational research (Hales et al., 2016; Von Elm et al., 2007). Good practice components of the QI framework, STROBE criteria, and implementation and operational research reporting guidelines were used to organize good practices in input-output-outcome monitoring collected through surveys and opportunities to improve the analysis and reporting of these data in service delivery research studies (the frameworks, criteria, and guidelines are described in (Hales et al., 2016; Juran & Riley, 1999; Von Elm et al., 2007)). Good practices were categorized as applicable: before, during, and after data collection. We also identified examples of 'boundary objects' i.e. collaborative knowledge products such as maps and models, which can be used to improve the salience, credibility, and legitimacy of service delivery research products (Cash et al., 2003).

Results and Discussion

First the methods of data collection, types of monitoring, and types of service delivery research were identified; and then the relationships between the three were identified to show opportunities where monitoring data can be used for service delivery research.

Methods of water and sanitation service delivery data collection

There are several methods of water and sanitation service delivery data collection, and these can be used for monitoring or for an expressed purpose such as evaluation ("the systematic and objective assessment of an on-going or completed project, program or policy, its design, implementation and results"(Kusek & Rist, 2004)) or research (defined as "the systematic investigation into and study of materials and sources in order to establish facts and reach new conclusions" (Oxford English Dictionary)). Types include qualitative, surveys (household, non-household facility, and infrastructure surveys), sample collection and testing, and active and passive remote sensing (Table 1).

Qualitative data collection is used for in-depth exploration, for example of the enablers of and barriers to water and sanitation service delivery. Qualitative data collection instruments include interviews, focus groups, mapping, structured observations, and photography. It is useful for developing theories and hypotheses using a small 'n' size population, however these findings cannot necessarily be generalized to larger populations. Findings from qualitative might be tested in large scale quantitative studies (Denzin & Lincoln, 1994).

Surveys are "a research method…to empirically and scientifically study and provide information about people and phenomena" (Lavrakas, 2008a) and they are widely used in global health, international development, and water and sanitation service delivery. Surveys are conducted at the household-level (e.g. The DHS Program's Demographic and Health Survey), non-household (e.g. health care facility, school) facility-level (e.g. WHO's Service Availability and Readiness Assessment), and/or infrastructure-level (e.g. SIASAR, the rural water and sanitation information system for the Latin America and Caribbean region). Household and non-household facility surveys are typically conducted by a data collection actor collecting data from a respondent. Infrastructure-level survey data are typically collected by a data collector making a professional judgement of a water and sanitation system through an inspection or information from the system operator such as a water committee member or service utility. There is overlap between survey types, where facility or household surveys may include an infrastructure observation component.

Surveys are usually conducted using paper and pencil interviewing (PAPI) or computer assisted personal interviewing (CAPI). For PAPI, an interviewer uses paper surveys to record answers from survey respondents (Lavrakas, 2008b). With wide availability of mobile computers, phones, and internet access, computer assisted personal interviewing (CAPI) is now more commonly used than PAPI. CAPI is "survey data collection by an in-person interviewer (i.e. face-to-face interviewing) who uses a computer to administer the questionnaire to the respondent and captures the answers onto the computer" (Olsen, 2008). PAPI is inferior to CAPI in several ways, as survey complexity is limited by PAPI and PAPI increases the potential for data entry errors (e.g. no feedback mechanism if the interviewer records data that are logically inconsistent or impossible) and/or data compilation errors when the data from surveys are aggregated for analysis (MacDonald et al., 2016). CAPI can use mobile survey tools (MSTs) such as SurveyCTO and mWater (mWater, 2017; SurveyCTO, 2017). MSTs and other mobile technologies and their use in water and sanitation are described elsewhere (Fisher, Mann, et al., 2016; Hutchings et al., 2012; MacDonald et al., 2016; Thomson, Hope, & Foster, 2012b)

Sample collection and testing is the collection of environmental samples and testing these in the field or in a laboratory (Bartram & Ballance, 1996). Sample collection and testing can be combined with other data collection methods (e.g. household, facility, or infrastructure surveys) and the associated data are most useful when they are linked to descriptive information (e.g. water infrastructure type; geospatial location).

Active remote data collection systems include crowd-sourcing and fault reporting systems where "end users act as monitoring agents to alert authorities or service providers of operational problems" (Thomson et al., 2012b). Crowdsourcing is "the practice of obtaining needed services, ideas, or content by soliciting contributions from a large group of people and especially from the online community rather than from traditional employees or suppliers" (Merriam-Webster, n.d.). These systems are dependent upon the subset of the population who will report the problem to the service authority. This requires a person to recognize a problem, know that the problem can be reported, and be able to report the problem (e.g. a person has a mobile phone or access to a web service to submit the problem to the service authority).

Remote sensing includes remote sensors, satellites, and drones that use telemetry to collect data about water and sanitation services (Thomson, Hope, & Foster, 2012a; Thomson et al., 2012b). These are useful for collecting real-time, longitudinal data about specific service processes (e.g. handpump use) or variables related to water and sanitation services (e.g. groundwater levels). Remote sensors can be placed in water and sanitation infrastructure and transmit data on outcomes of interest.

Table 1. Methods of water and sanitation service delivery data collection and their characteristics

Method	**Examples of instruments used**	**How data are obtained**	**Representative population**	**Examples from practice**
Qualitative	Interviews, focus groups, mapping exercises, observations, photographs	Data collector obtaining information from respondent	Small population under study	Qualitative study on processes to improve sustainability of community-managed water systems (Behnke N, 2017)
Surveys – household	Computer assisted personal interviewing (CAPI), paper and pencil interviewing (PAPI)	Data collector obtaining information from respondent	Households	USAID's Demographic and Health Surveys (DHS) and UNICEF's Multiple Indicator Cluster Surveys (MICS) (The DHS Program, 2015)
Surveys – non-household facility	CAPI, PAPI	Data collector obtaining information from facility administrator	Non-household facilities	Service Provision Assessment (SPA) for health care facilities) (The DHS Program, 2011)
Surveys - infrastructure	CAPI, PAPI, sanitary inspection	Data collector making a professional judgment about the infrastructure	Water or sanitation infrastructure	SIASAR rural water supply monitoring initiative (Borja-Vega, Pena, & Stip, 2017).
Sample collection and testing	Water quality test kits, environmental swabbing	Environmental samples collected on site and processed using a mobile test kit or transported to a laboratory for processing	Households or water and sanitation infrastructure	Compartment bag test (for water quality measurement) (Gronewold, Sobsey, & McMahan, 2017)
Active remote data collection systems	Crowdsourcing systems, online web portals to report service problems	User reports service conditions to the service delivery authority	Not representative of population	Crowdsourcing water quality data (Borden, Borden, & Mistry, 2016)
Remote sensing	Remote sensors, satellite measurement and imagery	Remote devices collect data about services	Representative of population under study	The Waterpoint Data Transmitter uses a microprocessor, accelerometer and GPS to transmit data about handpump use (Thomson et al., 2012a).

Types and definitions of monitoring related to water and sanitation service delivery

Monitoring is defined as "the task of observing and checking the status, progress, and quality of [water and sanitation services]; and it is a regular, ongoing activity" (Oxford English Dictionary). There are many terms used to describe water and sanitation service delivery monitoring and distinct types include: *quality control, surveillance, and input-output-outcome monitoring* (Table 2).

Quality control is an internal process conducted by a service provider to ensure it is meeting service delivery standards, such as drinking water standards (i.e. the purpose is to demonstrate the absence of sub-standard services) (WHO, 2011). Fault reporting is a type of quality control.

Adapting available definitions in Table 2, *surveillance* in a water and sanitation service delivery context is the *continuous, systematic collection of data related to water and sanitation service delivery by an independent and/or external agency to determine the occurrence and distribution of service delivery problems and identify actions to improve services to minimum standards*. Surveillance is complementary to quality control. The primary distinction is that surveillance is conducted by a separate, independent (oftentimes a government) agency to oversee service provider operations and ensure the reliability and safety of water and sanitation service delivery (Rahman, Crocker, Chang, Khush, & Bartram, 2011).

Input-output-outcome monitoring (sometimes called process or activity monitoring) is the process of measuring water and sanitation service delivery inputs (e.g. human resources, finances), outputs (e.g. number of water committee meetings held in the past six months), and/or outcomes (e.g. percent of the population using safely managed sanitation services) to document status, levels and trends (Kusek & Rist, 2004; Menon, Karl, & Wignaraja, 2009). Information collected through surveillance and input-output-outcome monitoring may be similar, however, the purpose of input-output-outcome monitoring is to observe changes in the population, systems, and/or services under study (i.e. checking whether policy/program targets and objectives are being met or not) without eliciting a response from an external actor. Surveillance may have a predefined risk mitigation plan whereas input-output-outcome monitoring does not. Based on data collection methods currently available, input-output-outcome monitoring is often conducted less frequently than surveillance (Carrel & Rennie, 2008). Impacts ("positive and negative, primary and secondary, long-term effects produced by a development intervention, directly or indirectly, intended or unintended") are sometimes collected as part of input-output-outcome monitoring; however, impacts are typically used for research and evaluation and are therefore beyond the scope of monitoring) per se (Kusek & Rist, 2004; Oxford English Dictionary).

Table 2. Water and sanitation monitoring types and example definitions

Water and sanitation monitoring types	Types from the literature	Example definitions
Surveillance	Public health surveillance	"Public health surveillance is the continuous, systematic collection, analysis and interpretation of health-related data needed for the planning, implementation, and evaluation of public health practice" (WHO, 2017).
	Water supply surveillance	Water supply surveillance is an "investigative activity that is designed to identify faults in water supplies, evaluate their importance to health and identify appropriate actions to improve the water supply" (WHO, 1976) and is conducted by "a surveillance agency responsible for independent (external) surveillance through periodic audit of all aspects of safety and/or verification testing" (WHO, 2011).
Input-output-outcome monitoring	Performance monitoring	"A continuous process of collecting and analyzing data to compare how well a project, program, or policy is being implemented against expected results" (Kusek & Rist, 2004).
	Implementation monitoring	"Implementation monitoring tracks the means and strategies (that is, those inputs, activities, and outputs found in annual or multiyear work plans) used to achieve a given outcome. These means and strategies are supported by the use of management tools, including budgetary resources, staffing, and activity planning" (Kusek & Rist, 2004)
	Process/activity monitoring	"Process/activity monitoring tracks the use of inputs and resources, the progress of activities and the delivery of outputs. It examines how activities are delivered – the efficiency in time and resources." (Kusek & Rist, 2004)
Quality control	Quality control monitoring	"In general, it is the responsibility of the local water authority to ensure that the water it produces meets the quality defined in drinking water standards" (WHO, 1984)
	Operational monitoring	"the conduct of planned observations or measurements to assess whether the control measures in a drinking-water system are operating properly. It is possible to set limits for control measures, monitor those limits and take corrective action in response to a detected deviation before the water becomes unsafe" (WHO, 2011)
	Fault-reporting	"A maintenance concept that increases operational availability and that reduces operating costs through three mechanisms: reduce labor intensive diagnostic evaluation, eliminate diagnostic testing downtime and provide notification to management for degraded operation" (US Navy Operations, n.d.)

Types and definitions of service delivery research

Several types and many definitions of service delivery research are used in global health and international development (Table 3). The principal types are *operational research*, *implementation* research, and *health systems research* (Remme et al., 2010).

Table 3. Service delivery research types and example definitions

Type of service delivery research and audience	**Example term from the literature**	**Definition of the term from the literature**
Operational research *Intended audience: local government, implementing organizations, program managers*	Action research	"disciplined process of inquiry conducted by and for those taking the action. The primary reason for engaging in action research is to assist the "actor" in improving and/or refining his or her actions." (Sagor, 2000)
	Operations research	"The discipline of applying advanced analytical methods, such as mathematical models, to help make better decisions" (Institute for Operations Research and Management Sciences)/
	Operational evaluation	"Examines how effectively programs were implemented and whether there are gaps between planned and realized outcomes" (Khandker, Koolwal, & Samad, 2010)
	Operational research	Uses an existing resource – the data routinely collected by programs – to provide ways of improving program operations and thereby delivering more effective, efficient and equitable care (Hales et al., 2016)
	Operational research	"The search for knowledge on interventions, strategies, or tools that can enhance the quality, effectiveness or coverage of programs" (Zachariah et al., 2009)
	Operational research	"Any type of improvement-oriented investigation into a program's operations" (Royston, 2011)
	Continuous Quality Improvement	"Enlisting an entire organization to work toward a goal of continuous improvement in quality as defined by the needs and wants of the customer [Or end user]" (Kritchevsky & Simmons, 1991).
	Management science	"Interdisciplinary branch of applied mathematics, engineering and sciences that use various scientific research-based principles, strategies, and analytical methods including mathematical modeling, statistics and algorithms to improve an organization's ability to enact rational and meaningful management decisions." (Institute for Operations Research and Management Sciences)
Implementation research *Intended audience: local government, implementing organizations, program managers*	Implementation science	"Study of methods to promote the systematic uptake of research findings into routine clinical practice" (Eccles & Mittman, 2006).
	Implementation research	"Implementation research often focuses on the strategies needed to deliver or implement new interventions called 'implementation strategies', a term used to distinguish them from clinical and public health interventions." (Peters, Tran, & Adam, 2013)
	Process evaluation	"Explore the way in which the intervention under study is implemented, can provide valuable insight into why an intervention fails or has unexpected consequences, or why a successful intervention works and how it can be optimized." (Craig et al., 2008)
	Process evaluation	"An evaluation of the internal dynamics of implementing organizations, their policy instruments, their service delivery mechanisms, their management practices, and the linkages among these" (Kusek & Rist, 2004)
	Process evaluation	"Process evaluation examines how programs operate and focuses on problems of service delivery." (Khandker et al., 2010)
WaSH systems research	Health policy and systems research	"Production of new knowledge to improve how societies organize themselves to achieve health goals." (Bennett, Ghaffar, Mills, Yesudian, & Mandelbaum-Schmidt, 2007)

Intended audience: state, national policy makers	Health services research	"Health services research is the multidisciplinary field of scientific investigation that studies how social factors, financing systems, organizational structures and processes, health technologies, and personal behaviors affect access to health care, the quality and cost of health care, and ultimately our health and well-being. Its research domains are individuals, families, organizations, institutions, communities, and populations." (Lohr & Steinwachs, 2002)
	Health policy and systems research	"Health policy and systems research (HPSR) is an emerging field that seeks to understand and improve how societies organize themselves in achieving collective health goals, and how different actors interact in the policy and implementation processes to contribute to policy outcomes. By nature, it is inter-disciplinary, a blend of economics, sociology, anthropology, political science, public health and epidemiology that together draw a comprehensive picture of how health systems respond and adapt to health policies, and how health policies can shape − and be shaped by − health systems and the broader determinants of health." (Bennett et al., 2007)

The purpose of *operational research* is to use project or program data, or sub-national administrative data (e.g. district, region) to aid decision-making in complex service delivery problems (Remme et al., 2010). Characteristics of operational research include the use of routinely collected data (e.g. monitoring data) and/or data collection related to the program under study; the use of analytical models such as optimization modelling, network modelling, and forecasting to identify performance or operations improvement opportunities (Hales et al., 2016; Institute for Operations Research and Management Sciences; Khandker et al., 2010; Zachariah et al., 2009). Data used in operational research may be quantitative or qualitative (Monks, 2016). Continuous quality improvement, which uses methods such as Lean Six Sigma, is a type of operational research that uses data to identify improvements addressing a problem defined at the outset of each improvement cycle (Breyfogle III, 2003). Operational research sometimes involves collaboration between researchers and practitioners on the design and planning of the data collection; and the analysis and reporting of findings. In some instances, the practitioner and researcher may be the same actor; in other cases, a researcher may analyze secondary data without having contributed to the design of the data collection. Cross-sectional, case-control, and cohort study designs are typically used for operational research, while experimental designs and randomized controlled trials (RCTs) are not (Zachariah et al., 2009).

The purpose of *implementation research* is to use data to explore efficiency, effectiveness, and impact of processes and programs to scale programs or interventions (Remme et al., 2010). Implementation research is sometimes called process evaluation (Centers for Disease Control, 2005). Implementation research studies may include two phases: the first consisting of formative research to explore implementation challenges and a second quantitative, experimental phase (Peters et al., 2013; Remme et al., 2010). Findings from operational research or the formative implementation research might be tested at scale. Data for implementation research studies are usually collected specifically for the research. Like operational research, implementation research usually involves collaboration between practitioners and researchers. Unlike operational research, experimental study designs are often used in implementation science and studies are designed such that results are transferable outside the geographic area of study (Remme et al., 2010).

Health systems research, or for this context, *WaSH systems research*, is broad in utility and is used to examine questions associated with the "enabling environment" such as governance, policy, financing, and human resources factors that influence water and sanitation service delivery (Amjad, Ojomo, Downs, Cronk, & Bartram, 2015; Remme et al., 2010). Studies are usually descriptive and use secondary data, such as monitoring data. Researchers are typically not involved in the design or collection of the data used in systems research. Like operational research, different methods can be used for analysis. Systems research is usually conducted at a larger-scale than other types of service delivery research and may include country comparisons or analysis of national-level data. Because of their scale and the type of data used, systems research study designs are non-experimental (Remme et al., 2010).

Table 4 describes the relationship between data collection methods, monitoring types, and service delivery research types. Figure 1 describes the relationship between operational, implementation, and WaSH systems research.

Table 4. The relationship between data collection methods, monitoring types, and service delivery research types

Data collection method	**Type of monitoring where the data collection method can be used**	**Type of Service Delivery Research where the data collection method can be used**
Qualitative data collection	Input-output-outcome monitoring	Operational research
Surveys – household	Surveillance, Input-output-outcome monitoring	Operational research, implementation research, systems research
Surveys - non-household facility	Surveillance, Input-output-outcome monitoring	Operational research, implementation research, systems research
Surveys - infrastructure	Surveillance, Input-output-outcome monitoring, quality control	Operational research, implementation research, systems research
Active remote data collection systems	Surveillance	Operational research
Remote sensing	Surveillance, Input-output-outcome monitoring, quality control	Operational research, implementation research
Sample collection and testing	Surveillance, Input-output-outcome monitoring, quality control	Operational research, implementation research, systems research

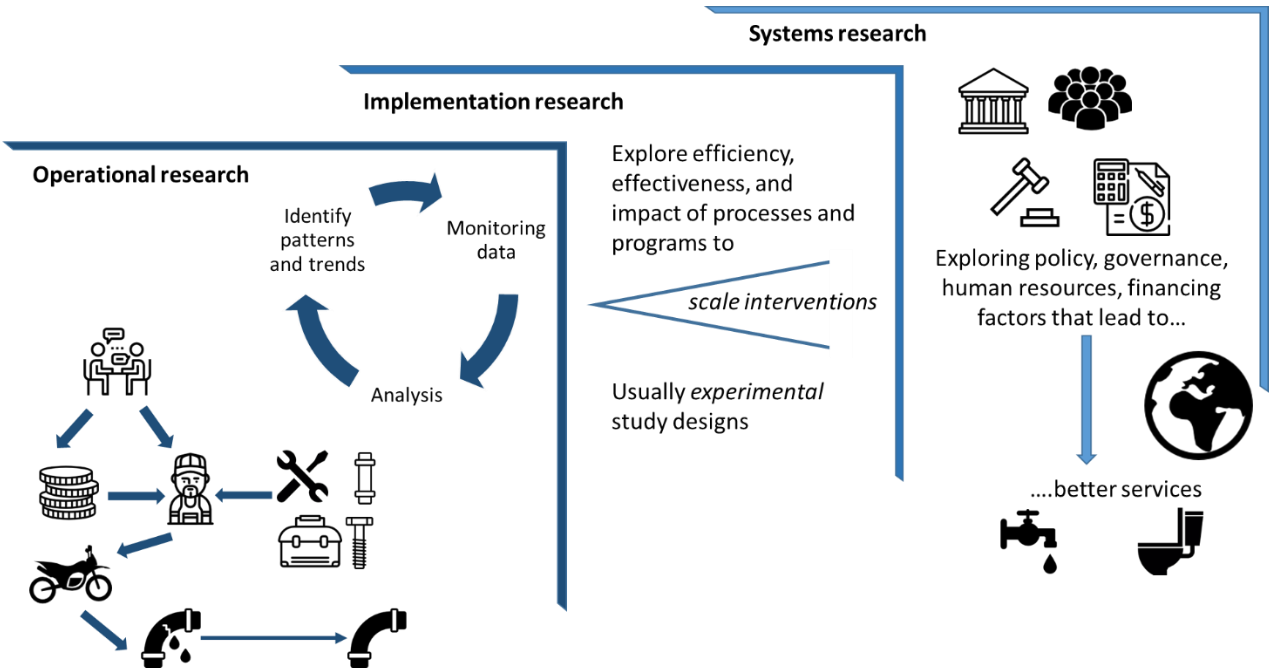

Figure 1. The relationship between operational, implementation and WaSH systems research

Definition and characteristics of water and sanitation service delivery research

Building on available definitions, we define water and sanitation service delivery research as *the collection, use, and analysis of data on water and sanitation systems to improve service delivery*. Data used in water and sanitation service delivery research are obtained from monitoring and/or they are collected for a specific purpose (e.g. evaluation, research). This may include data (such as GIS layers) collected and managed for wholly independent purposes. Data for service delivery research may be quantitative or qualitative. In good practice, data end-users (e.g. researchers, policy makers) work with data collectors early in the data collection design process. Examples of variables related to water and sanitation service delivery include water system functionality, costs of services, availability of safely managed services, use and effectiveness of water safety plans, and failure points and modes of failure of projects and/or programs. Water and sanitation service delivery research typically does not examine health outcomes (though health outcome studies may include a service delivery component), laboratory-based studies lacking a field component (e.g. assessing the effectiveness of a household water filter in removal of viruses in a laboratory setting), perceptions (unless they explicitly relate to service delivery improvements), or any basic research related to water and sanitation. Data analysis can be used to identify improvement pathways and failure modes, for example, exploring the relationship between a service delivery outcome or process and variables hypothesized to have an association with the outcome or process in order to identify patterns and/or test hypotheses (Breyfogle III, 2003).

Examples of water and sanitation service delivery studies

Table 5 presents a selection of water and sanitation service delivery studies (meeting the inclusion criteria described in the methods) that demonstrate the breadth of topics and methods of analysis. Studies listed were conducted in diverse settings such as schools and communities, and in different countries and geographic contexts. The service outcomes examined include water system functionality, the use of shared sanitation facilities, and country performance on drinking water and sanitation. Methods such as Bayesian network modeling, frontier analysis, structural equation modeling (SEM), factor network analysis, and logistic regression were used by study authors to analyze data.

Table 5. Examples of water and sanitation service delivery research studies

Study reference	**Scope of study and country**	**Study topic**	**Service delivery research type**	**Data collection method**	**Analysis method(s) used**	**Main findings of the study**	**Policy and practice recommendations as reported by study authors**
(Alexander et al., 2016)	89 rural primary schools in three Kenyan counties	School WaSH	Operational	Facility survey	Life cycle cost approach	Cost to improve school WaSH to WHO standards were USD 3.03 per student per year	There is a need to increase school budget allocations to WaSH to ensure basic services are provided
(Alexander, Tesfaye, Dreibelbis, Abaire, & Freeman, 2015)	89 water systems in communities in rural Ethiopia	Water system governance and functionality	Operational	Infrastructure survey	Mokken scaling techniques; linear regression	Higher water system functionality was associated with water committee management having good quality records, regular meetings, financial audits, higher monthly fees, having a paid caretaker, and water committees with the capacity to perform minor repairs.	Higher water system functionality is associated with good management characteristics of water committees. External support actors should improve management capacity of water committees.
(Arvai & Post, 2012)	Two rural villages in the Lindi region of southeastern Tanzania	Point of use (POU) water treatment systems	Operational	Qualitative	Structured decision making (SDM)	The SDM process helped communities select the most appropriate POU water treatment that would lead to consistent, daily use.	SDM is a participatory approach to select appropriate technologies for communities which may lead to more sustainable outcomes.
(Atengdem, Gyamfi, & Shahadu, 2013)	190 water systems in East Gonja, Ghana	Water service levels and water system sustainability	Operational	Infrastructure survey	Descriptive statistics	Piped water systems have higher levels of functionality than other source types and most systems in East Gonja do not provide adequate services to people.	Actors should increase budgets for post-construction support; and administrative capacity of water service providers should be improved.

(Barstow, Nagel, Clasen, & Thomas, 2016)	70 of the 96 sectors in the Western province of Rwanda (101,000 households)	Adoption of household water filtration through private financing	Implementation research (process evaluation)	Household survey	Descriptive statistics and process evaluation	Reported use of water filters was higher than 90%; water filter present was observed in 76% of households	Private financing of public health interventions can lead to large scale adoption of high levels of household water filtration
(Chatterley et al., 2014)	16 schools in Meherpur, Bangladesh	Post-implementation management of school sanitation	Operational	Facility survey	Qualitative comparative analysis (QCA)	Characteristics of well-managed school sanitation include quality construction of sanitation, financial support from communities and government, a maintenance plan, and an active management committee.	Financial support and supportive local actors are necessary for well-managed sanitation and may lead to better sanitation-related outcomes in schools.
(Divelbiss, Boccelli, Succop, & Oerther, 2013)	286 households in rural Guatemala	Household water treatment	Operational	Household survey	Structural equation modeling	Personal hygiene practice promotes proper operations and maintenance of household water filters.	There are synergistic effects of operations and maintenance and other household factors on filter quality.
(Fisher et al., 2015)	1,509 water systems in the Greater Afram Plains, Ghana	Water system functionality	Operational	Infrastructure survey	Logistic regression; Bayesian network modeling	Synergistic effects of optimal management and tools substantially increase the likelihood that a water system is functional.	There is a need to improve water system management and repair times to improve pathways to speed the time of repairs.
(Foster, 2013)	National-scale analysis in Liberia, Sierra Leone, and Uganda	Handpump functionality	Operational	Infrastructure survey	Logistic regression	System age, distance from the district capital, and the absence of fee collection were significantly associated with	There is a need to strengthen post-construction support; operations and maintenance; and evaluate alternate water

						handpump non-functionality.	system management models.
(Heijnen, Rosa, Fuller, Eisenberg, & Clasen, 2014)	National-scale analysis in 84 LMICs	Determinants of shared sanitation	Operational	Household survey	Meta-analysis; regression	Shared sanitation is more common in urban areas; results vary geographically; and is more often used by poorer people. Most sanitation facilities are shared with acquaintances rather than the public.	Uniform national policies on shared sanitation may be difficult to implement within different countries due to varied use by economic status and geographically.
(Jordanova et al., 2015)	12 municipalities in Nicaragua	Water and sanitation in schools	Operational	Facility survey	Logistic regression	Coverage of water and sanitation in schools in Nicaragua is low; many water systems and toilets are non-functional.	There are substantial sub-national inequalities in coverage of water and sanitation in schools.
(Kaminsky, 2015)	National-scale analysis in 21 countries	The role of culture in sanitation technology choice	Systems	Household survey	Linear regression	Cultural dimensions of uncertainty avoidance, masculinity-femininity, and individualism-collectivism have statistically significant relationships to sanitation technology choice.	Local culture influences infrastructure choice; it is important to consider local cultural preferences in intervention activities which may lead to greater use and uptake of sanitation.
(Karon A, 2017)	Three provinces in Indonesia	Water and sanitation in schools	Implementation	Facility survey	Logistic regression	Schools with toilet operation and maintenance funds were more likely to have functional toilets; government monitoring data were comparable to	Indonesian government monitoring data may be a reliable source of data for reporting the SDGs.

						independently collected survey data.	
(Katsi, Siwadi, Guzha, Makoni, & Smits, 2007)	Three districts in rural Zimbabwe	Multiple water source use	Operational	Qualitative	Participatory rural appraisal	People need water for productive uses. Use of water for more than drinking is dependent on a number of factors, such as distance to sources, quantity, and quality of water available.	Service providers should consider the water needs of people beyond drinking; to include water for productive uses.
(Luh & Bartram, 2016)	National-scale analysis in 73 countries	Country progress on sanitation and drinking water	Systems	Household survey	Frontier analysis; regression	Most countries are making progress towards universal access to water and sanitation. One-third of countries showed a level of progress that was half the achievable level. Progress was not related to many national indicators.	Water and sanitation progress does not appear to be linked to social and economic characteristics of countries; rather they may be linked to variations in policies and institutional commitment.
(Mellor, Smith, Learmonth, Netshandama, & Dillingham, 2012)	Limpopo province, South Africa	Household water filtration	Operational	Household survey	Agent-based modeling (ABM)	Improved filter maintenance may contribute to higher microbial compliance. Filters are ineffective after three years.	Consistent use and maintenance of household filters are important to maintain the durability of ceramic water filters.
(Nagel, Beach, Iribagiza, & Thomas, 2015)	Three provinces in rural Rwanda	Handpump maintenance models	Operational	Infrasturcture survey; remote sensing	Fractional logit regression	Ambulance and circuit rider models for post-construction support led to higher	Water system asset investment should shift to service delivery

						water system functionality than nominal maintenance models.	models rather than installation models.
(Sandiford, Gorter, Smith, & Pauw, 1989)	Rural Nicaragua	Drinking water quality	Operational	Household survey	Analysis of covariance (ANCOVA)	An association between rainfall and contamination was observed, and an association between community size and water quality was observed.	Community characteristics are a determinant of water quality. Certain water source types provide greater protection from fecal contamination.
(Saunders et al., 2016)	19 households in informal settlement in Suva, Fiji	Water and sanitation marking exchanges	Operational	Qualitative	Participatory action research; systems mapping	The community identified a need for a committee to oversee WaSH activities; sharing of WaSH maps with actors; and including other WaSH actors in a community forum.	Systems mapping of WaSH can empower community-level collective action and planning.
(Walters & Chinowsky, 2016)	Two municipalities in Nicaragua	Rural water service planning	Operational	Qualitative	Factor network analysis	water system sustainability challenges in a district related to water committee management; challenges in another district related to finances and community capacity building by external support.	A complex set of factors interrelate and contribute to the sustainability of water services.

(Neely & Walters, 2016)	Rural village in Timor-Leste	Drivers of sustained functionality in rural water services	Operational	Household surveys and qualitative	System dynamics modeling; causal loop diagramming	Robust, reliable water system technologies have an impact on community satisfaction and water service sustainability.	Incentives are needed to encourage NGO staff to value participatory approaches rather than just building infrastructure.

Opportunities to improve monitoring and reporting of service delivery research studies

Based on the findings from our literature review, we describe opportunities to improve input-output-outcome monitoring *collected through surveys* and the analysis and reporting of service delivery research studies (specifically, operational research and WaSH systems research) using these data (implementation research was not specified as these studies are typically experimental).

Good practices for input-output-outcome monitoring data collection using surveys; and analysis and reporting of studies using these data were identified and categorized in three steps: before, during, and after data collection. Good practices were collated from existing frameworks that were applicable to each step of the monitoring and data analysis process (Hales et al., 2016; Juran & Riley, 1999; Von Elm et al., 2007). The sequential steps for good practice are shown in Figure 2.

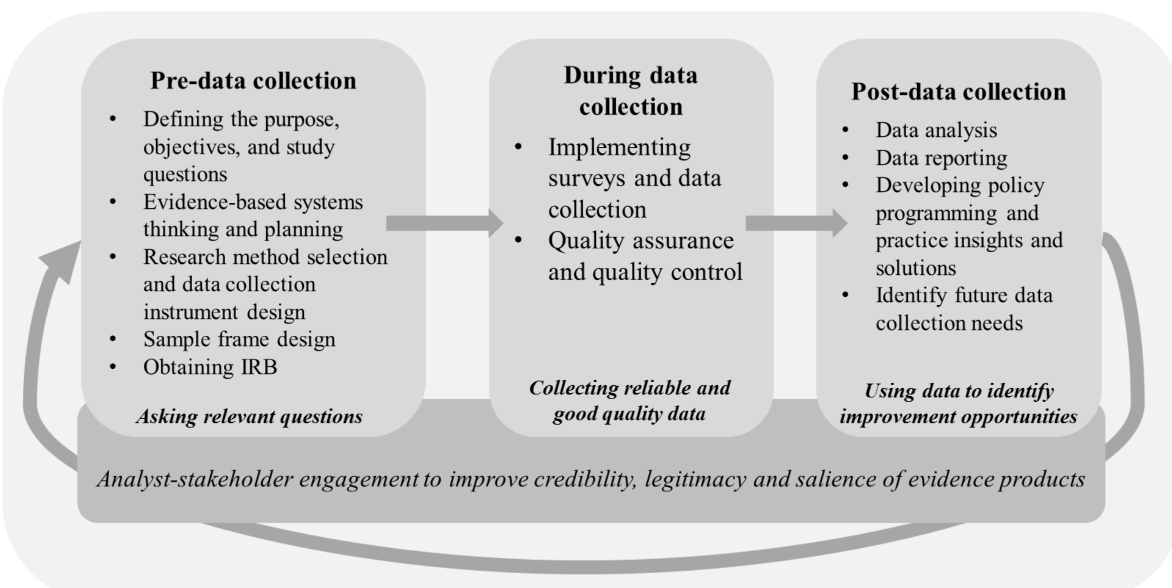

Figure 2. Improving water and sanitation service delivery through monitoring and service delivery research

Considerations before collection

Defining the purpose and objectives of monitoring (including questions to be answered) are fundamental to study design and choice of data collection methods (Eisenhardt, 1989; Eisenhardt & Graebner, 2007). This should precede preparation of data collection approaches including sampling size, sampling frame, and data collection instrument development (Gliner, Morgan, & Leech, 2011).

The purpose, objectives, and questions – as well as the questions and methods used in the data collection instrument – can be developed in part by reviewing evidence. Evidence review serves two purposes: to examine whether new monitoring (and/or new service delivery study) could generate important new information; and to explore whether the questions and methods used in the data collection instrument are policy-relevant and evidence-based (Gliner et al., 2011). The purpose, objectives, questions, and methods can be tailored to the specific context, program, or country of interest and/or to the specific improvements that are desired. Questions might explore, for example, how the effectiveness of water and sanitation interventions varies by setting; what managerial, social, and cultural processes are involved in improving water and sanitation outcomes; and what are the most important factors influencing service delivery outcomes (Hales et al., 2016). Early collaboration between the data collectors, researchers, and the data end-users (decision-makers) through these steps is beneficial to ensure that the data can be appropriately analyzed; and knowledge products are credible, salient, and legitimate (Cash et al., 2003).

Environmental problems and interventions are complex with social, managerial, cultural, environmental, political, and policy variables influencing service delivery outcomes (Pidd, 2009). Systems thinking, defined as the practice of identifying the components of a defined system and tracking the linkages, many of which may not be obvious – is an appropriate analytical approach to address these. Systems thinking has been used in several of the water and sanitation service delivery study examples (Neely & Walters, 2016; Walters & Javernick-Will, 2015).

For surveys, clear definitions of terms used in questions in data collection instruments are needed to assess the status of water and sanitation systems, accurately record variables, reduce bias, and provide data suitable for addressing policy- and program-relevant questions. While survey question evaluation criteria specific to water and sanitation are not available, use of the "SMART" and similar criteria may help improve the quality and reliability of responses to questions (Schwemlein, Cronk, & Bartram, 2016). The SMART acronym stands for specific (i.e. is the question well-defined), measurable (i.e. how much or how many of something), attainable (i.e. is the question realistic), relevant (i.e. is the question worth measuring), and time-bound (i.e. is the question measurable over a specific period) (Doran, 1981). Survey questions need to be scientifically relevant, cost-effective, and designed to minimize bias (Choi & Pak, 2005). In some service delivery studies in Table 5, data were removed from analysis because they did not meet the SMART criteria (Fisher et al., 2015; Foster, 2013; Jordanova et al., 2015). In these studies, the researchers were not involved in the design of the data collection instrument, design of the survey questions, or involved in the data collection. Response fatigue due to long surveys may introduce bias and loss of data. One study on WaSH in schools in Nicaragua had a low number of responses to questions at the end of the survey instrument; this was likely due to response fatigue (Jordanova et al., 2015).

For sample collection and testing (which may be collected as part of surveys), use of good practice standards will improve data quality and reduce bias. For example, for water quality testing, standard procedures from the test manufacturer should be followed or others such as the standard methods for examination of water sources (American Public Health Association, American Water Works Association, Water Pollution Control Federation, & Water Environment Federation, 1915). In a systematic review of fecal contamination of drinking water sources, authors assessed the quality of 319 studies using a 13-point checklist of reporting criteria – which included quality criteria for handling of the sample and description of methods used. Study quality varied greatly, with most studies reporting only half of the minimum reporting criteria (Bain, Cronk, Wright, et al., 2014).

In cases where not all units (e.g. systems, communities, facilities, and/or individuals) of interest can be monitored, a suitable sample frame and sampling approach is necessary to obtain data that are representative of the population of interest (Scheaffer, Mendenhall III, Ott, & Gerow, 2011). Proper sampling and sample design requires several considerations such as obtaining a sample frame, determining the sample size and power needed, determining the method of sampling, and developing replacement strategies for non-responses (this last consideration is done during data collection) (Scheaffer et al., 2011). Among the service delivery studies that relied on secondary monitoring data (Table 5) where researchers were not involved in the data collection, components of sampling were less frequently described (Foster, 2013; Jordanova et al., 2015). This makes it difficult to assess the extent to which the analysis can be generalized to the country of study or to other countries and contexts.

Survey questions programmed into CAPI devices, such as mobile survey tools (MSTs), improve data quality and facilitate data collection and management; and have been demonstrated in examples in Table 5 (Karon A, 2017; MacDonald et al., 2016). Data collected from MSTs can be transmitted to an online database in real-time (though often not) whereas paper surveys take longer to consolidate and process. MSTs facilitate standardized data management and storage, and they facilitate automated data processing (Fisher, Mann, et al., 2016; MacDonald et al., 2016).

If necessary, appropriate ethics approval must be obtained before starting data collection. Typically, infrastructure surveys do not require ethics approval (when no human subjects are involved). For secondary analyses of household surveys and non-household facility surveys, ethics approval is usually obtained by the data collector and the data are anonymized. Ethics approval is usually obtained through Institutional Review Boards (IRBs) which are available from universities, governments, or organizations such as the WHO and UNICEF. University, government, and many large organizations are obliged to obtain ethics approval. A specific challenge for other organizations such as NGOs is that they may have difficulty obtaining ethics approval if they are not affiliated with organizations with IRB access. Some organizations may not require it or may have policies to obtain ethics approval but not enforce them.

Other important pre-data collection considerations include training of field staff (especially for large surveys) and pilot testing of data collection instruments (Fisher, Cronk, et al., 2016). Training field staff improves the likelihood that data will be consistently collected by different people; and piloting ensures that the data collection instruments work properly and are appropriate for the area under study. Data security, confidentiality and privacy concerns must be considered to ensure sensitive information is protected.

Considerations during data collection

To improve the reliability of monitoring data collection, a quality assurance (i.e. quality of processes) and quality control (i.e. quality of products) (QA/QC) plan should be developed, and surveys and data collection instruments should be designed to facilitate QA/QC checks (Environmental Protection Agency (U.S. EPA), 2000; Fisher, Madsen, Karon, et al., 2017; Fisher, Mann, et al., 2016). Examples of QA/QC techniques appropriate for water and sanitation surveys include: photo-verification for direct observation questions such as water source type; re-surveying a subset (e.g. 5-10%) of shortly after data collection to check the accuracy of data for those survey questions that are not expected to vary greatly over short time periods (e.g. number, location, and type of water and sanitation infrastructure); the use of QC such as blanks and duplicates to ensure the validity of water quality sampling and analysis; or using geographic coordinates to ensure sampling locations were visited and data were not fabricated; supervision of field staff; review of QA/QC samples and data; and timestamp verification for survey enumerators using mobile data collection tools (Environmental Protection Agency (U.S. EPA), 2000; Fisher, Madsen, Karon, et al., 2017; Fisher, Mann, et al., 2016). In some studies (Table 5), little to no QA/QC was used and/or reported on the data collection, such as photo verification of water and sanitation facilities and re-surveying facilities, which led the study authors to have to concerns about data reliability (Fisher et al., 2015; Jordanova et al., 2015).

Considerations post-data collection: analysis and reporting

Sustainable water and sanitation service delivery is multi-factorial and nested within complex social, political, technical, and environmental systems (Amjad et al., 2015; Craig et al., 2008). To analyze these complexities, data analysis among studies in Table 5 often drew on methods from engineering, public health, economics, environmental science, public policy, and other fields.

Methods include regression, Bayesian network modeling, frontier analysis, and structural equation modeling. As demonstrated in Table 6, different methods (many of which were used in the studies listed in (Table 5) are appropriate for different data types and contexts. The examples in Table 6 were classified as descriptive (e.g. the type of studies that allow researchers to understand and describe the situation), used to explore associations (e.g. the type of studies that allow researchers to explore potential cause-and-effect relationships), and/or compare decisions (e.g. the type of studies that allow researchers to evaluate alternatives and consequences of one or more policy, program, or management decision). Use of different analytical tools separately and in combination may reveal nuance and insight in the data (Fisher et al., 2015; Royston, 2011). Many of these analysis methods are useful boundary objects between researchers and decision-makers that can be used to facilitate credible, legitimate, and salient information products (Cash et al., 2003). For example, Bayesian Networks are participatory, are relatively easy for non-experts to understand and interpret, and are useful for decision-making (Chen & Pollino, 2012).

Table 6. Examples of methods to analyze monitoring and observational data for water and sanitation service delivery research

Analytical method	Method use (e.g. analysis type)	Description of method	Advantages and disadvantages for water and sanitation service delivery research
Agent-based models (ABM)	Explore associations	ABMs are object-oriented spatial models that can be used to study complex environmental systems (Gilbert, 2008).	Advantages: ABMs can be used to model complex systems and account for many explanatory variables. Disadvantages: ABMs are a deterministic approach, whereas some water and sanitation service delivery challenges are non-deterministic.
Bayesian network (BN) modeling	Explore associations; compare decisions	BN modeling is a network-based framework to analyze and describe systems that involve uncertainty. They allow for causal pathway analysis by incorporating prior probabilities (Cain, 2001; Pearl, 2014).	Advantages: BNs are graphical network representations of environmental problems; they use Bayesian statistics, which better account for relationships between environmental variables; and they can integrate data from multiple sources (e.g. quantitative data; qualitative data; data from expert elicitation).

			Disadvantages: BNs must be directed acyclic graphs (DAGs), meaning they cannot represent systems with feedback loops.
Factor analysis	Explore associations	Factor analysis is used to explore complex relationships that cannot be easily measured by collapsing a large number of variables into a small set of significant factors (Osborne & Costello, 2009).	Advantages: Factor analysis enables researchers to investigate factors associated with services that cannot be easily measured – and they instead use latent variables. Disadvantages: Factor analysis cannot be used to show causality.
Frontier analysis (also known as data envelopment analysis, DEA)	Descriptive	Frontier analysis is a non-parametric method to evaluate the efficiency of different 'units.' In a water and sanitation context, a unit might be a country or district. Frontier analysis can be used to compare the best-in-class performance of units in comparison to their relative size or level of development (Luh, Cronk, & Bartram, 2016; Wilson, 1993).	Advantages: Frontier analysis can be used to measure progressive realization of human rights and it can be used to measure performance of countries or programs. Disadvantages: Frontier analysis requires a large amount of data that are comparable and from multiple time points (Luh et al., 2016).
Life cycle cost approach (LCCA)	Descriptive; compare decisions	LCCA is a quantitative method that can be used to investigate the cost of delivering water and sanitation services over time (Fonseca et al., 2011).	Advantages: LCCA can be used to identify the direct costs of building infrastructure and indirect costs of maintaining infrastructure over time. Disadvantages: It can be time consuming and difficult to collect sufficient data to conduct an LCCA.
Participatory rural appraisal	Descriptive	Participatory rural appraisal is a qualitative method that consists of interviews, focus groups, and observations (Mukherjee, 1993).	Advantages: Participatory rural appraisal is important for theory building and generating hypotheses in a subject area. Disadvantages: Findings from participatory analyses are usually case studies and they are not necessarily generalizable.
Photo Elicitation	Descriptive	Photo elecitation is a method where photographs are taken (or created by respondents) and respondents comment on the photos in discussions (Harper, 2002).	Advantages: Photo elicitation can reduce bias and lead to more valuable qualitative and quantitative data. Disadvantages: Findings from photo elicitation are usually used in a case study context and they are not necessarily generalizable.
Qualitative comparative analysis (QCA)	Descriptive; explore associations	QCA is an analytical method used to generalize findings from a small number of cases(Jordan, Gross, Javernick-Will, & Garvin, 2011; Kaminsky & Jordan, 2017).	Advantages: QCA provides a middle ground between small 'n' and big 'n' research studies. It can be used to identify associations in large qualitative datasets.

			Disadvantages: The findings are usually case studies and they are not necessarily generalizable.
Regression analysis	Explore associations	Regression analysis can be used to model the relationship between outcomes and associated factors. There are many types such as logistic, multinomial logit, linear, and Poisson to model different types of outcomes (Cameron & Trivedi, 2009).	Advantages: Some types of regression, such as linear regression, are relatively simple models and relatively easy for people to understand. Disadvantages: In complex systems, regression cannot always be used to evaluate the impact of multiple variables in combination. In regression, we assume that variables are independent and identically distributed, which is not necessarily the case with many WaSH related analysis problems. Some types of regression are difficult to interpret, such as multinomial logits.
Social Network analysis	Descriptive; explore associations	Social network analysis is used to map the relationships and strengths of relationships between different groups and people (Scott, 2012).	Advantages: Social network analysis is used to explore interactions between groups and people. Disadvantages: Social network analyses can be difficult to generalize and relationships may be subject to bias.
Structural equation modeling	Explore associations	A specialized method made up of several techniques, structural equation modelling is a multivariate analytical method that can be used to conduct causal modeling or path analysis (Ullman & Bentler, 2003).	Advantages: Structural equation modelling uses a graphical modeling interface; it uses flexible assumptions; it can be used to test models with multiple dependent variables; and it can handle difficult data. Disadvantages: Structural equation modelling has high data requirements; it is based on complex theory; and it is a post hoc model production.
Structured decision making	Descriptive; compare decisions	Structured decision making is a risk assessment method that helps people evaluate alternate options and make choices in complex situations by improving transparency of the decision-making process (Gregory et al., 2012).	Advantages: Structured decision making may lead to better outcomes due to better uptake because of the participatory nature of decision making. Disadvantages: Findings from structured decision-making analyses are typically case studies and they are not necessarily generalizable to other contexts.
System Dynamics modeling	Explore associations	System dynamics modeling can be used to explore the complex associations between people, information, states, organization and social information and explore the role that feedback mechanisms play in influencing these variables (Homer & Hirsch, 2006).	Advantages: System dynamics modeling can be used to model complex systems using a graphical modeling interface. Disadvantages: While system dynamics modelling can predict future outcomes, the adequacy of this approach has been challenged.

Systems mapping	Descriptive	Systems mapping exercises are conducted to create collaborative maps produced by community residents that document local resources and knowledge (Parker, 2006).	Advantages: High-quality systems mapping allows communities and researchers to have a detailed understanding of the research context and situation. Disadvantages: Findings are case studies and they are not necessarily generalizable to other contexts.

Harnessing the power of “big data” generated through remote sensing (e.g. satellite imagery) and other techniques may yield cost-effective opportunities to incorporate more variables into service delivery analyses (Christenson et al., 2014; Lu, Nakicenovic, Visbeck, & Stevance, 2015). For example, if geographic coordinates are collected during data collection, spatial and geographic analyses can be conducted. External data sources can be added to the analysis, such as population density, climate zone, poverty levels, and groundwater levels (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006; MacDonald, Bonsor, Dochartaigh, & Taylor, 2012; Nelson, 2008; Schneider, Friedl, & Potere, 2009).

When reporting the findings of water and sanitation service delivery studies, clear, consistent language and definitions enable meaningful comparison of data and results between studies and making them more useful in systematic reviews and meta-analyses (Remme et al., 2010). In reports and publications, clearly reported methods that follow appropriate reporting standards such as the STROBE statement or the World Health Organization (WHO) reporting guidelines for implementation and operational research allow others to replicate the data collection and analysis methods, or adapt the study approach to different settings or contexts (Hales et al., 2016; Von Elm et al., 2007). These reporting standards are updated over time and provide a reference for current understanding of good practice. Good practice reporting includes clear descriptions of data limitations and sources of bias so that others can learn to address these in future data collection efforts. In several studies, data limitations and sources of bias were insufficiently documented (Atengdem et al., 2013; Walters & Chinowsky, 2016).

Policy briefs and other knowledge products that communicate findings in simple, clear language, generalized where appropriate, and communicated to a broad local, national, and/or international audience may help other actors adopt the findings into their projects, programs, or policies and improve credibility, legitimacy, and salience (Brocklehurst, 2013; Cash et al., 2003). For example, a briefing note written about a WHO/UNICEF report on water and sanitation in health care facilities synthesizes the report's findings for policymakers and identifies solutions to address water and sanitation service delivery in health care settings (The Water Institute at UNC, 2015; World Health Organization and UNICEF, 2015).

After finishing a service delivery research study, data should be made publicly available for others to use and analyze (though sensitive information should be removed). In some studies listed in Table 5, data were not publicly available for further analysis (Atengdem et al., 2013). Such data should be accompanied by operational definitions, survey instruments, training manuals, and other instructions and documentation needed to adequately interpret them (Fisher, Madsen, Shields, et al., 2017).

Implications for policy and practice

This is the first article to critically review data collection methods, types of monitoring, types of service delivery research, and the use of input-output-outcome survey-based monitoring data in a water and sanitation service delivery research context. Insight from service delivery studies lead to opportunities to improve coverage and service quality, and to reduce the economic and disease burdens associated with inadequate services. We describe how types, definitions, and methods overlap and interrelate, and propose a definition of service delivery research for use in water and sanitation. We identify examples of water and sanitation service delivery research studies and use these to document examples of good practice and improvement opportunities for service delivery research studies using input-output-outcome survey-based monitoring data. Better use of monitoring data and improvements to data collection lead to more efficient use of the billions of dollars that will be invested in monitoring (Espey, 2015).

This review clarifies data collection methods, types of monitoring, and service delivery research in water and sanitation – which are often poorly defined and inconsistently described in the field of water and sanitation. There are important roles for different types of service delivery research and different types of data collection. Operational research using monitoring data can be used to identify improvement opportunities at the project, program, or sub-national administrative unit-level and aid decision-makers with the assessment of complex service delivery. WaSH systems research using monitoring data can be used to identify enabling environment factors, such as governance, financing, and human resources capacity that influence service delivery. Such studies using monitoring data are useful for developing better theories, policies, and practical guidance to improve service delivery. Analysis of monitoring data can help to better describe water and sanitation services and identify influential variables. They can help to strengthen evidence and theory, and these analyses can be used to shape research questions that may be best answered by experimental study designs that can be used to explore causal relationships (Craig et al., 2008). Implementation research can be used to describe, at scale, why projects or programs fail and/or their characteristics that lead to successful service delivery.

Monitoring data have immediate value to reveal trends, patterns, and levels of water and sanitation services. However, as demonstrated by this review, there are opportunities for water and sanitation actors – such as external support agencies, regulators, practitioners, researchers, and policymakers – to improve water and sanitation service delivery monitoring, adapt good practice, and generate further value through analytic studies. For example, many service delivery research studies are not documented nor published (White et al., 2011; Zachariah et al., 2009). A lack of published examples limits the ability to generate evidence through meta-synthesis, consolidate findings, generate theory, and creates publication bias.

There are opportunities for stronger partnerships to improve the quality of monitoring and service delivery research (Zachariah et al., 2009). Other fields such as agriculture and natural resource management have demonstrated the value of collaboration between researchers and decision-makers and good management of the boundary between them to produce salient, credible, and legitimate evidence and knowledge for sustainable development (Cash et al., 2003; Kristjanson et al., 2009). Applying these principles to water and sanitation service delivery, researchers and practitioners working together early in the design and data collection stages can ensure that water and sanitation monitoring is purpose-driven and accurately reports status and trends. Working together during the analysis and reporting stages, researchers and practitioners can collectively improve the interpretation of findings.

Strong partnerships for monitoring and associated service delivery research may be of interest to communities, local and national governments, and external support actors such as NGOs, Sanitation and Water for All, and the World Health Organization. These actors seek better data, evidence to inform their policy, programming, and practices, and good documentation of their investments in water and sanitation. Donors and funding agencies should include contract stipulations as part of funding requiring monitoring and associated service delivery research studies. Donors and funding agencies should also stipulate that the monitoring is consistent with whatever platform is used by the national/local governments, so that data and analysis are consistent, and data can be aggregated.

More effective monitoring using good practice in data collection, analysis, and reporting increases the potential for insight from studies using these data, and ultimately contributes to improved service delivery and the achievement of universal access to basic water and sanitation services.

CHAPTER 3: FACTORS INFLUENCING WATER SYSTEM FUNCTIONALITY IN NIGERIA AND TANZANIA: A REGRESSION AND BAYESIAN NETWORK ANALYSIS[1]

Introduction

Sufficient, safe and continuously-available water services are important to human development, health, and well-being (Bain, Cronk, Wright, et al., 2014; Bartram & Cairncross, 2010; Lloyd & Bartram, 1991). However, maintaining high levels of water service availability is challenging in many low- and middle-income countries (LMICs) (Lloyd & Bartram, 1991). More than one-third of piped water systems in LMICs are intermittent (Van den Berg & Danilenko, 2011). Across sub-Saharan Africa, 10% to 70% of rural, community-based handpumps are non-functional (where functionality is often defined as water unavailable for users from the water collection point) at a given time (Rural Water Supply Network, 2009).

High levels of water service availability ensure that people have sufficient water for consumption and domestic activities. They may reduce water fetching time and reduce diarrhea prevalence, especially among children under five (Hunter, Zmirou-Navier, & Hartemann, 2009; Pickering & Davis, 2012). Water service availability is reflected in program, local, and national policies as well as the Sustainable Development Goals (SDGs), where Goal Six calls for the "availability and sustainable management of drinking water for all" (United Nations General Assembly, 2015).

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Few studies explore and quantify the relationship between water service availability parameters (such as functionality) and associated factors (such as management arrangements, fees, and geographic conditions). This may be due in part to the complexity of water service provision in LMICs, where social, management, cultural, environmental, and policy factors influence water service delivery outcomes (Amjad et al., 2015; Pidd, 2009).

An appropriate analytical approach to examine water system functionality is Bayesian network (BN) modeling which use Bayes statistics to account for prior probabilities. They are particularly useful in causal assessment of environmental problems for evidence-based policy analysis and decision-making (Carriger, Barron, & Newman, 2016). However, few studies have used BNs to analyze water services in LMICs (Phan, Smart, Capon, Hadwen, & Sahin, 2016).

Most studies on water system functionality concern community-managed handpumps, where community management is a management model common in rural settings in LMICs. Few studies examine other system types (e.g. electrically pumped systems) and management types (e.g. private operators) (Jiménez & Pérez-Foguet, 2011; Whittington et al., 2009). There are also few studies that use publicly-available water system monitoring data. For example, a study using monitoring data from Liberia, Sierra Leone, and Uganda explored factors associated with non-functional community-managed handpumps and found that older systems, systems far from the district capital, and the absence of fee collection were significantly associated with non-functionality (Foster, 2013). Another study using data from Ghana found that newer systems, the presence of a management committee, fee collection, fewer total water systems in the community, and administrative district were associated with handpump functionality (Fisher et al., 2015). Studies comparing diverse system types and management types may provide insight into means to improve water system functionality, and more broadly, water service availability.

We analyzed data from monitoring initiatives in Nigeria and Tanzania using multilevel logistic regression and BNs to explore factors influencing water system functionality. These data were linked to geospatial data from other sources to examine the relationship between water system functionality and: poverty, population density, groundwater availability, and distance to urban centers. We explored the types of management that were associated with higher functionality and examined how functionality varied by system type.

Methods

Survey data sources

Data for Nigeria were collected in 2012 using mobile survey tools (MSTs) as part of the Nigeria MDG Information System (NMIS) water system census. The dataset included enumerator observations of 116,009 water systems in 661 of 774 local government areas (LGAs) (Office of the Senior Special Assistant to the President on MDGs, 2015).

Data for Tanzania were collected in 2011 and 2013 using MSTs as part of a census by the Tanzanian Ministry of Water to inform national water sector planning (Ministry of Water, 2013). The census was intended to be a baseline of water systems in the 132 districts of Tanzania. The data include enumerator observations of 65,535 water system in 123 districts.

For both monitoring initiatives, enumerators were provided training on data collection and the survey instrument. In Nigeria, a pilot was conducted to test and refine the survey instrument (Pokharel et al., 2014). However, due to the scale of data collection in both countries, there is the potential for non-sampling errors such as different enumerator interpretation of survey questions and inaccurate responses. For example, in Tanzania, data collection teams were formed in each district. A report that assessed the Tanzania data suggests that some districts may have used a stricter functionality definition (SeeSaw & Crossflow Consulting, 2014).

Geospatial data sources

ArcGIS 10.2.1 was used to link geospatial variables to each water system observation. Geospatial variable values were linked to water system observations using the point-to-raster tool.

Population density. Population density data, measured as population per 100m square grid, were obtained from WorldPop (Linard, Gilbert, Snow, Noor, & Tatem, 2012).

Urban areas. Data from the Global Rural–Urban Mapping Project were used to define whether systems were in rural or urban areas (Schneider et al., 2009). Rural-urban definitions were determined by satellite imagery of stable anthropogenic night-time light extent and a database of settlement areas (Balk, Pozzi, Yetman, Deichmann, & Nelson, 2005; Balk, Yetman, & de Sherbinin, 2010).

Poverty. Data on the proportion of the population living in poverty were obtained from WorldPop (Tatem AJ, 2013). Poverty estimates were developed using data from household surveys on the proportion of the population living on less than US$1.25 per day.

Groundwater. Groundwater depth, yield, and storage data were used to examine the relationship between groundwater and functionality (MacDonald et al., 2012). Macdonald *et al.* generated groundwater maps using data from a systematic review. Some areas of Africa have little data, therefore there was low confidence in some of the groundwater estimates. Groundwater storage is expressed as the product of the saturated thickness and effective porosity (in millimeters). Macdonald *et al.* discretized storage levels from no storage (0 mm) to very high storage (>50,000 mm). Groundwater productivity was measured in liters per second (l/s) and was discretized from very low (<0.1 l/s) to very high productivity (>20 l/s). Depth to groundwater was measured in meters below ground level (mbgl) and was discretized from very shallow (0-7 mbgl) to very deep (>250 mbgl).

Season. The Koppen-Geiger Climate Classification System was used to explore the relationship between climate zone and functionality. This classification distinguishes climate zones based on precipitation and seasonality of precipitation (Kottek et al., 2006).

Travel time to an urban center of 50,000+ people. Nelson (2008) developed a map of 'remoteness' that estimated distance in minutes to an urban center of greater than 50,000 people (Nelson, 2008). This variable was used to proxy factors not included in the datasets including livelihood zones and the availability of post-construction support (PCS) (e.g. spare parts, maintenance technicians) (Hutchings et al., 2015).

Data analysis: multilevel logistic regression

Data cleaning and regression analysis were conducted using Stata 13.1SE (StataCorp, 2014). Data were cleaned to ensure consistent and meaningful analysis. For example, unlikely values were removed, such as water systems greater than 100 years-old.

In the Nigeria data, water systems were differentiated by their source type (e.g. borehole, protected spring) and system type (e.g. handpump, electric pump). Piped systems were further differentiated by the distance of the outlet (i.e. tap) from the source of water (<100m; 100m-1km; >1km; unknown distance). Manual pumps were distinguished from handpumps in the survey instrument where a manual pump is a human-powered pump using a rope, pully, or wheel. In the Tanzania data, water systems were differentiated by system type and included

Afridev and Nira handpumps. Information on these system types is available from the Rural Water Supply Network (RWSN, 2017a, 2017b). Since the data from both countries were collected at the water collection-point (e.g. tap, handpump spout), there was no information in the datasets on the distance of the water system to households, amount of water used, water storage, or water treatment.

When possible, systems under construction were removed from the dataset. System types with few responses (<90 observations) were consolidated to reduce the number of factors in the analysis and to avoid small cell counts. Since the purpose of this study was to examine the functionality of water system technology types, unimproved water sources such as dams, rivers, and unprotected dug wells were removed. Rainwater harvesting systems were also removed because of the fundamental difference from other system types. Systems were removed when an improved source type or system type (e.g. handpump) was not specified. ArcGIS was used to remove water systems that were not within the boundaries of the country.

Water system functionality was the binary dependent variable in the analysis, where a water system was either functional or non-functional. Other water service availability parameters such as yield and predictability were not available in the survey instruments.

In addition to the linked geospatial data, other independent variables that were used in the analysis were the number of livestock using the source (Nigeria), fee collection (Nigeria and Tanzania), and management type (Tanzania). Categorical variables were created for system age and distance to an urban center. Because of differences in variable measurement, the results between each country cannot be directly compared.

Multilevel, multivariable logistic regression models were developed. Multilevel modeling was conducted to account for potential clustering, where clustering may proxy the availability of operations and maintenance support or local government services that support water service delivery. Administrative units for the multilevel models were selected based on a review of water policies in each country, where the LGA was most appropriate in Nigeria and districts in Tanzania (WaterAid, 2006a, 2006b). In the Nigeria dataset, some LGAs had less than ten water system observations. Sensitivity analyses were conducted to determine if this affected the results of the multilevel model, where LGAs with less than ten systems were removed from the analysis, the model was re-run, and the results were compared. The multilevel models were implemented using the *melogit* Stata package. Independent variables were selected for the multivariable models based on evidence describing their relationship to water system functionality. Regression diagnostics were used to identify multi-collinearity and influential observations (and variables demonstrating multi-collinearity were removed). For all analyses, statistical significance was evaluated with a p-value of 0.05 (95% confidence) using a Wald test.

Data analysis: Bayesian networks

The cleaned datasets were imported into Netica 5.18 to develop graphical Bayesian network (BN) models (Norsys Software Corp., 2014). Variables are represented in the BN as nodes, where each node has different states (i.e. categories). Continuous variables cannot be used in Netica, so the poverty and population density variables were discretized into quintiles. Nodes are connected by arrows which represent a hypothesized causal relationship. BN good practices were followed (Borsuk, Stow, & Reckhow, 2004; Cain, 2001; Chen & Pollino, 2012). The model was developed using available evidence and professional judgement (Chen & Pollino, 2012; Marcot, Steventon, Sutherland, & McCann, 2006).

Sensitivity analysis was conducted to determine which nodes had the most influence on water system functionality. The sensitivity analysis in Netica calculates reductions in Shannon's entropy (Pearl, 2014). The nodes are ranked according to entropy reduction which identifies those with the most influence on the 'objective' node (which, in this study, is functionality). Model evaluations were conducted in Netica where 20% of the data were randomly selected for a test dataset and 80% of the data were used to develop the model. Model evaluations included the receiver operating characteristic (ROC), logarithmic loss, quadradic loss, and spherical payoff (Greiner, Pfeiffer, & Smith, 2000; Marcot et al., 2006).

Alternative water system management scenarios were developed by changing the node states which could be controlled by actors supporting water system implementation and management. Controllable nodes include management, system type, and payment type; uncontrollable nodes include climate zone and population density. Controllable nodes were set to different states in different combinations to determine their influence on water system functionality. Some nodes are not directly controllable but may proxy controllable factors; for example, the variable "distance to an urban center" may proxy the availability of post-construction support (PCS) (e.g. spare parts, maintenance technicians) and other factors. These were also analyzed in management scenarios.

Results

Of the 181,544 water system observations, 18,112 in Nigeria and 9,401 in Tanzania were excluded based on criteria described in the methods. In both countries, many of the water collection-point observations came from the same piped system. It was not possible to cluster water collection-point observations from the same system because a unique piped system identifier was not available; therefore, these were reported in the descriptive statistics but removed from the regression and Bayesian network analyses (40,533 observations of taps from piped systems were removed from Nigeria; 30,995 taps from gravity piped systems were removed from Tanzania). A total of 82,503 systems were analyzed – 57,364 in Nigeria and 25,139 in Tanzania. All systems in Nigeria and most in Tanzania were communal water systems. A text response question in the Tanzania survey suggested that some systems were located at non-household settings, such as schools and clinics, but this information was not consistently reported and data could not be disaggregated.

Functionality varied by water system type. At the time of the survey, 71.8% of water systems in Nigeria were functional. Borehole/tubewells (with unspecified extraction) had the lowest functionality (55.0%) as compared to protected springs (with unspecified extraction) which had the highest (82.7%) (Table 7). In Tanzania, 64.6% of water systems were functional. Play pumps, India Mark III handpumps, and Mono pump systems (a helical rotation pump) had the lowest functionality (35.4%, 48.9% and 48.9%, respectively) while Nira handpumps (74.1%) had the highest. Mono systems on average were the oldest, with an average age of 17.1 years old as compared to Afridev (9.7 years) and Rope pumps (8.9 years) (table in SI).

In univariable and multivariable regression, there was a significant association between system type and functionality. In Nigeria, multivariable logistic regression results suggested that manual pumps (human-powered pumps using a rope, pully, or wheel) (OR:3.1, 95% CI:2.9-3.2) had higher odds of functionality as compared to handpumps (Table 8). The BN predicted that manual pumps had the highest functionality (79.7%) while boreholes (with unspecified extraction) (47.8%) and solar pumping systems (58.1%) had the lowest.

In Tanzania, multivariable logistic regression results (Table 9) suggested that all system types had lower odds of functionality as compared to Nira handpumps. The BN predicted that Nira handpumps had the highest functionality (58.6%) while mono pumps (47.5%) were the lowest.

Table 7. Selected descriptive statistics for all water systems analyzed in Nigeria and Tanzania

Variable	Variable level	n	Percent of total	Functionality rate (%)
Nigeria				
Water extraction type	Piped water outlet within 100 m of source[2]	31,969	32.7	61.8
	Piped water outlet between 100 m and 1 km of source[1]	4,514	4.6	54.2
	Piped water outlet beyond 1 km of source[1]	2,722	2.8	48.1
	Piped water outlet distance unknown[1]	1,328	1.4	37.1
	Hand pump	21,135	21.6	64.3
	Fuel pump	3,541	3.6	65.2
	Electric pump	2,168	2.2	67.9
	Manual pump	19,146	19.6	83
	Solar pump	1,553	1.6	58.7
	Protected spring (other extraction)	241	0.3	86.3
	Borehole tubewell (other extraction)	4,029	4.1	55
	Protected dug well (other extraction)	5,551	5.7	82.9
Payment type	Don't pay for water	88,374	90.27	65.8
	Don't know if pay for water	1,627	1.66	9.3
	Pay for water	7,896	8.07	87.1
Animal use of system	No animals use the system	78,043	79.72	63.2
	10-50 animals use the system	9,329	9.53	83.9
	50-500 animals use the system	7,754	7.92	78.5
	500+ animals use the system	2,003	2.05	74
	Don't know if animals use the system	768	0.78	65.5
Tanzania				
Water Extraction technology	Nira	7,873	14.0	74.1
	Afridev	1,127	2.0	67.2
	Cemo	106	0.2	64.2
	Gravity[1]	30,995	55.2	70.9
	India Mark II	2,620	4.7	65.1
	India Mark III	131	0.2	48.9
	KSB	1,284	2.3	54.1
	Mono	2,528	4.5	48.9
	Play pump	99	0.2	35.4
	Rope pump	572	1.0	68.4

[2] Piped water outlets and gravity piped water systems were removed from the regression models because of potential multicollinearity, where outlets from the same system could not be clustered.

	SWN 81	269	0.5	55.0
	SWN 80	4,302	7.7	62.8
	Submersible	4,228	7.5	61.6
Payment type	Never pay	21,686	38.6	59.5
	Pay annually	4,217	7.5	84.5
	Pay monthly	9,645	17.2	79.5
	Pay per bucket	8,790	15.7	74.7
	Pay when scheme fails	4,100	7.3	71.3
	Other	7,696	13.7	59.7
Age (in years)	0-5 years	9971	17.8	83.1
	5-10 years	11,215	20.0	73.6
	10-15 years	8,883	15.8	74.0
	15-20 years	7,140	12.7	69.5
	20-25 years	4,917	8.8	60.5
	25-30 years	3,384	6.0	61.4
	30+ years	10,624	18.9	47.8
Management type	Village Water committee (VWC)	38,040	67.8	64.4
	private operator	1,665	3.0	82.4
	WUA	2,875	5.1	79.6
	WUG	5,237	9.3	76.3
	Water board	3,627	6.5	83.4
	water authority	786	1.4	69.7
	parastatal	1,666	3.0	72.5
	Other	2,238	4.0	56.7

Table 8. Unadjusted and adjusted multilevel logistic regression results for water system functionality in Nigeria

Explanatory variable	Unadjusted model			Adjusted model			
	OR	CI	p-value	OR	CI	p-value[3]	Wald test p-value[4]
Fuel pump vs. handpump	1.1	(1, 1.2)	0.292	0.9	(0.9, 1)	0.02	<0.001
Electric pump vs. handpump	1.2	(1.1, 1.3)	0.001	1.2	(1, 1.3)	0.098	
Manual pump vs. handpump	2.8	(2.6, 2.9)	<0.001	3.1	(2.9, 3.2)	<0.001	
Solar pump vs. handpump	0.8	(0.8, 0.9)	<0.001	1	(0.9, 1.1)	0.576	
Protected spring (other extraction) vs. handpump	3.6	(2.5, 5.1)	<0.001	3.4	(2.3, 5.1)	<0.001	
Borehole tubewell (other extraction) vs. handpump	0.7	(0.7, 0.8)	<0.001	0.8	(0.7, 0.8)	<0.001	
Protected dug well (other extraction) vs. handpump	2.7	(2.5, 3)	<0.001	3.2	(3, 3.5)	<0.001	
Don't know payment vs. no payment	0.1	(0.1, 0.1)	<0.001	0.1	(0.1, 0.2)	<0.001	<0.001
Payment vs. no payment	2.5	(2.2, 2.8)	<0.001	3.8	(3.3, 4.4)	<0.001	
Between 10 and 50 animals use system vs. none	3.1	(2.9, 3.4)	<0.001	3.3	(3.1, 3.6)	<0.001	<0.001
Between 50 and 500 animals use system vs. none	2.3	(2.2, 2.5)	<0.001	2.7	(2.5, 3)	<0.001	
500+ animals use system vs. none	1.7	(1.5, 2)	<0.001	2.3	(2, 2.6)	<0.001	
Don't know animal use vs. none	1	(0.9, 1.3)	0.925	1.1	(0.9, 1.4)	0.511	
1-2 hours to urban center of 50,000+ vs. 0-1 hours	0.9	(0.9, 0.9)	<0.001	1	(0.9, 1)	0.038	0.0446
2-3 hours to urban center of 50,000+ vs. 0-1 hours	0.9	(0.8, 0.9)	<0.001	1	(0.9, 1.1)	0.051	
3-4 hours to urban center of 50,000+ vs. 0-1 hours	0.9	(0.8, 1)	<0.001	0.9	(0.9, 1)	0.011	
4-5 hours to urban center of 50,000+ vs. 0-1 hours	0.9	(0.8, 1)	0.001	1	(0.9, 1.1)	0.135	
5+ hours to urban center of 50,000+ vs. 0-1 hours	0.8	(0.7, 0.9)	<0.001	0.9	(0.8, 1)	0.002	
Urban vs. rural	1.4	(1.4, 1.5)	<0.001	1.3	(1.2, 1.4)	<0.001	<0.001
Percent of population living on less than US$1.25/day	0.9	(0.8, 1)	0.002	0.6	(0.4, 0.8)	<0.001	<0.001
Population density per 100m square grid	1.1	(1.1, 1.1)	<0.001	1	(1, 1)	<0.001	<0.001
Shallow (7-25 m) depth to groundwater vs. very shallow (0-7 m)	1.1	(1.1, 1.2)	<0.001	1.1	(1.1, 1.2)	0.019	0.001
Shallow-moderate (25-50 m) depth to groundwater vs. very shallow (0-7 m)	1.3	(1.2, 1.3)	<0.001	0.9	(0.9, 1)	0.008	

[3] p-values for each factor or variable from the overall regression output.

[4] Overall p-value for each variable.

Table 9. Unadjusted and adjusted multilevel logistic regression results for water system functionality in Tanzania

Explanatory variable	Unadjusted model			Adjusted model			
	OR	CI	p-value	OR	CI	p-value[5]	Wald test p-value[6]
Afridev vs. Nira	0.6	(0.6, 0.7)	<0.001	0.6	(0.6, 0.7)	<0.001	<0.001
Cemo vs. Nira	0.2	(0.1, 0.3)	<0.001	0.2	(0.1, 0.3)	<0.001	
India Mark II vs. Nira	0.6	(0.5, 0.6)	<0.001	0.6	(0.5, 0.6)	<0.001	
India Mark III vs. Nira	0.4	(0.3, 0.6)	<0.001	0.4	(0.3, 0.6)	<0.001	
KSB vs. Nira	0.2	(0.2, 0.2)	<0.001	0.2	(0.2, 0.2)	<0.001	
Mono vs. Nira	0.3	(0.2, 0.3)	<0.001	0.3	(0.2, 0.3)	<0.001	
Playpump vs. Nira	0.2	(0.1, 0.3)	<0.001	0.2	(0.1, 0.3)	<0.001	
Rope pump vs. Nira	0.6	(0.5, 0.8)	<0.001	0.6	(0.5, 0.8)	<0.001	
SWN81 vs. Nira	0.4	(0.3, 0.5)	<0.001	0.4	(0.3, 0.5)	<0.001	
SWN80 vs. Nira	0.5	(0.5, 0.6)	<0.001	0.5	(0.5, 0.6)	<0.001	
Submersible vs. Nira	0.4	(0.4, 0.5)	<0.001	0.4	(0.4, 0.5)	<0.001	
5-10 vs. 0-5 years	0.6	(0.5, 0.7)	<0.001	0.6	(0.5, 0.7)	<0.001	<0.001
10-15 vs. 0-5 years	0.5	(0.4, 0.5)	<0.001	0.5	(0.4, 0.5)	<0.001	
15-20 vs. 0-5 years	0.5	(0.4, 0.5)	<0.001	0.5	(0.4, 0.5)	<0.001	
20-25 vs. 0-5 years	0.5	(0.4, 0.5)	<0.001	0.5	(0.4, 0.5)	<0.001	
25-30 vs. 0-5 years	0.5	(0.4, 0.5)	<0.001	0.5	(0.4, 0.5)	<0.001	
30+ vs. 0-5 years	0.3	(0.2, 0.3)	<0.001	0.3	(0.2, 0.3)	<0.001	
Pay annually vs. no payment	4.7	(3.9, 5.6)	<0.001	4.7	(3.9, 5.6)	<0.001	<0.001
Pay monthly vs. no payment	2.8	(2.5, 3.1)	<0.001	2.8	(2.5, 3.1)	<0.001	
Pay per bucket vs. no payment	3.7	(3.4, 4.2)	<0.001	3.7	(3.4, 4.2)	<0.001	
Pay when scheme fails vs. no payment	2	(1.8, 2.3)	<0.001	2	(1.8, 2.3)	<0.001	
Other payment type vs. no payment	0.7	(0.6, 0.8)	<0.001	0.7	(0.6, 0.8)	<0.001	

[5] p-values for each factor or variable from the overall regression output

[6] Overall p-value for each variable

Private operator vs. village water committee	3.3	(2.8, 3.9)	<0.001	3.3	(2.8, 3.9)	<0.001	<0.001
WUA vs. village water committee	2	(1.6, 2.6)	<0.001	2	(1.6, 2.6)	<0.001	
WUG vs. village water committee	1.4	(1.2, 1.6)	0.1	1.4	(1.2, 1.6)	0.001	
Water board vs. village water committee	1.9	(1.4, 2.7)	0.1	1.9	(1.4, 2.7)	0.001	
Water authority vs. village water committee	2.6	(1.8, 3.7)	<0.001	2.6	(1.8, 3.7)	<0.001	
Parastatal organization vs. village water committee	1.6	(1.3, 2)	<0.001	1.6	(1.3, 2)	<0.001	
Other vs. village water committee	1.8	(1.4, 2.2)	<0.001	1.8	(1.4, 2.2)	<0.001	
Hold public meeting vs. no	1.3	(1.1, 1.4)	0.1	1.3	(1.1, 1.4)	0.003	<0.001
Don't know if public meeting held vs. no	1.6	(1.3, 1.9)	<0.001	1.6	(1.3, 1.9)	<0.001	
Koppen classification: Arid vs. Tropical	1.1	(0.9, 1.3)	0.6	1.1	(0.9, 1.3)	0.523	<0.004
Koppen classification: Temperate vs. Tropical	1.4	(1.2, 1.7)	0.1	1.4	(1.2, 1.7)	0.001	
1-2 hours to urban center of 50,000+ vs. 0-1 hours	1	(0.9, 1.1)	0.5	1	(0.9, 1.1)	0.466	<0.001
2-3 hours to urban center of 50,000+ vs. 0-1 hours	1.1	(1, 1.2)	0.9	1.1	(1, 1.2)	0.816	
3-4 hours to urban center of 50,000+ vs. 0-1 hours	0.9	(0.8, 1.1)	0.1	0.9	(0.8, 1.1)	0.062	
4-5 hours to urban center of 50,000+ vs. 0-1 hours	1.1	(0.9, 1.2)	0.9	1.1	(0.9, 1.2)	0.886	
5+ hours to urban center of 50,000+ vs. 0-1 hours	0.8	(0.7, 0.9)	<0.001	0.8	(0.7, 0.9)	<0.001	
Urban vs. rural	1.4	(1.1, 1.8)	0.1	1.4	(1.1, 1.8)	0.01	0.01
Percent of population living on less than US$1.25/day	1	(1, 1)	0.1	1	(1, 1)	0.045	0.045
Population density per 100m square grid	1	(1, 1)	0.1	1	(1, 1)	0.028	0.028
Shallow (7-25 m) depth to groundwater vs. very shallow (0-7 m)	1.1	(1.1, 1.2)	0.1	1.1	(1.1, 1.2)	0.049	0.0963
Shallow-moderate (25-50 m) depth to groundwater vs. very shallow (0-7 m)	1	(0.8, 1.2)	0.6	1	(0.8, 1.2)	0.523	
Low moderate groundwater storage vs. moderate storage	1.4	(1.3, 1.6)	<0.001	1.4	(1.3, 1.6)	<0.001	<0.001
Low groundwater storage vs. moderate storage	1.2	(1.1, 1.4)	0.1	1.2	(1.1, 1.4)	0.008	

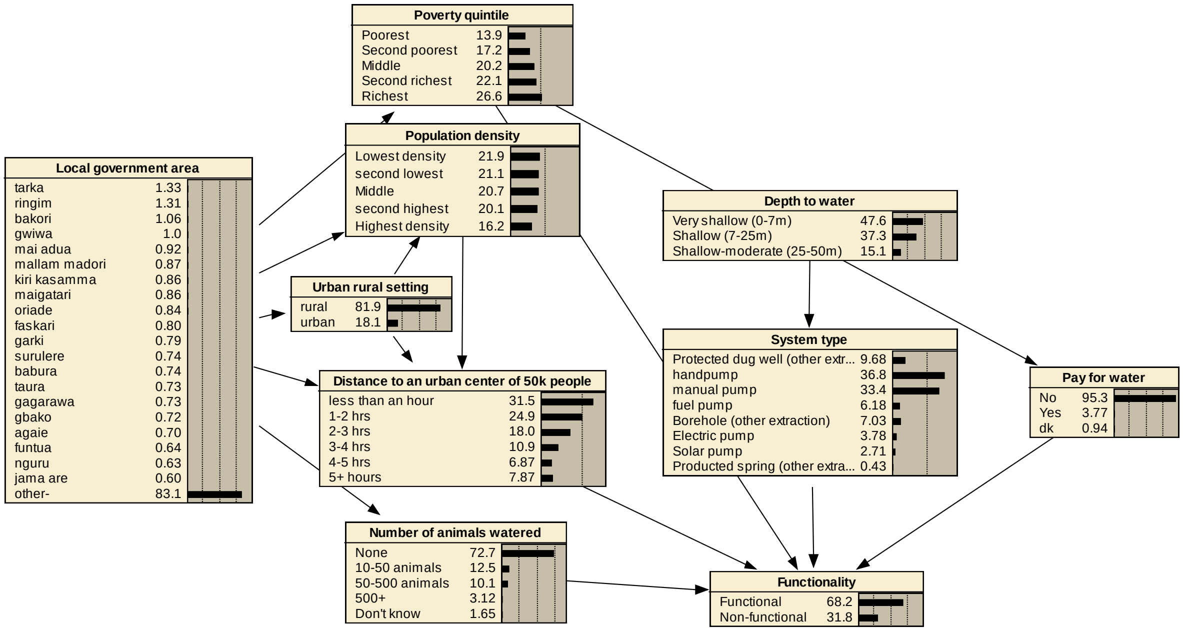

Figure 3. Bayesian network model for Nigeria. Each box represents a node (variable) which is made up of categorical states. The arrows represent a hypothesized causal link between variables.

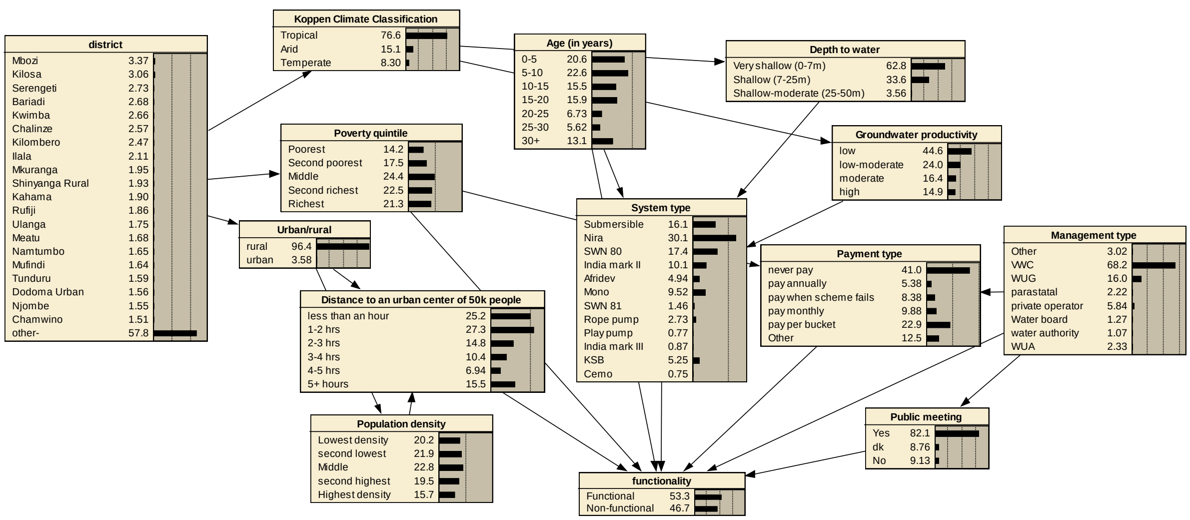

Figure 4. Bayesian network model for Tanzania. Each box represents a node (variable) which is made up of categorical states. The arrows represent a hypothesized causal link between variables.

In Tanzania, functionality was significantly associated with system age, where systems more than 0-5 years old had significantly lower functionality. The BN predicted that functionality varied by 10 percentage points between systems 0-5 years old (56.5%) and systems 30+ years old (46.2%).

In Nigeria, water system functionality was significantly associated with use of the system for animal watering (in addition to use for human consumption). In multivariable regression, systems used to water 10-50 animals had 3.3 times higher odds of functionality than those not used to water animals (95%CI: 3.1-3.6). As compared to systems that were not used to water animals (65.3% functionality), the BN predicted that functionality was 14.4 percentage-points higher for systems used to water 10-50 animals, 10.9 percentage points higher for 50-500, and three percentage-points higher for more than 500 animals.

Water system functionality varied by management and payment factors. In Nigeria, systems where people paid for water had 3.8 times higher odds of functionality as compared to those where people did not pay (95%CI:3.3-4.4). In Tanzania, multivariable regression results suggested that when people made a single annual payment for water, systems had 4.7 times higher odds of functionality as compared to systems where people did not pay (95%CI:3.9-5.6). Systems managed by private operators in Tanzania had 3.3 times higher odds of functionality as compared to those operated by a village water committee (95%CI:2.8-3.9). In the Tanzania data, there was no survey response option for "no system management." Systems in Tanzania where management held a public meeting had 1.3 times higher odds of functionality as compared to those that did not (95%CI:1.1-1.4).

Functionality varied by administrative unit. System functionality varied from 0% to 100% among Nigerian LGAs. Sensitivity analysis revealed that LGAs with less than 10 systems did not influence the multilevel model. Among Nigerian states, functionality ranged from 47.1% (Abia) to 82.1% (Rivers). Among Tanzanian districts, functionality ranged from 0% (Kigoma) to 93.5% (Karatu); and among regions, rates ranged from 44.9% (Geita) to 86.3% (Simiyu).

In univariable and multivariable regression in both countries, systems in urban areas had significantly higher odds of functionality than those in rural areas. Distance to an urban center and population density were significant in both country models, however, in Nigeria the odds ratios were close to the reference value of one. Poverty was significantly associated with functionality in Nigeria, where the odds of functionality decreased as the percentage of people living on less than US$1.25 per day increased (OR:0.6,95%CI:0.4-0.8).

In Nigeria, the odds of functionality were lower for systems with shallow-moderate depth to groundwater as compared to very shallow (OR:0.9,CI:0.9-1.0). In Tanzania, the odds of functionality were higher for systems with low-moderate and low storage as compared to moderate storage.

In BN sensitivity analyses, system type, number of animals, LGA, and payment had the greatest influence on functionality in Nigeria; while system type, age, public meeting, and poverty had the greatest influence on functionality in Tanzania (APPENDIX 1 FOR CHAPTER 3). Best observed conditions for controllable nodes in Nigeria (which included manual pump, less than one hour to an urban center, and used to water 10-50 animals) resulted in a 20.3 percentage-point greater probability of functionality from 68.2% to 88.5%. In Tanzania, best observed conditions for controllable states (which included Nira handpump, monthly water payment, public meeting held, less than one hour to an urban center) resulted in a 14.7 percentage point greater probability of functionality from 53.3% to 68.0%.

Discussion

We explored factors influencing water system functionality in Nigeria and Tanzania by analyzing monitoring data using BNs and regression. We analyzed data for more than 82,000 water systems – one of the largest studies of water system functionality conducted to-date. We found that system type was associated with functionality. In Nigeria, manual pumps had higher functionality than handpumps. In Tanzania, Nira handpumps had higher functionality than KSB and mono pump systems. We also found that functionality varied by administrative unit, poverty level, livestock watering, management structure, climate zone, distance to an urban center, and rural-urban setting.

Consistent with other evidence, systems were more likely to be functional if people paid for water and systems were newer (Fisher et al., 2015; Foster, 2013; Whittington et al., 2009). We included older water systems in our analysis, which may introduce a “denominator problem” where older, non-functional systems may not be included in monitoring datasets because they are abandoned and/or they cannot be identified (Carter & Ross, 2016). This suggests that older systems may appear to have higher functionality in monitoring data as compared to newer systems. However, our data show that older systems have lower functionality and if older abandoned systems were also measured and included in the dataset, functionality may have been even lower.

We modeled functionality using BNs in addition to regression. Regression is a more established modeling tool used for international water analyses. Modeling functionality with BNs is useful to explore complex systems; provide insights that are relatively easy for decision-makers to interpret through the use of graphical models and predicted probabilities (as opposed to odds ratios); and improve transparency (Cain, 2001). Further, the BNs developed for this article demonstrate several improvements achievable through modifiable factors such as payment for water and holding public meetings.

Regression and BN results suggest system use for both human consumption and animal watering was associated with higher functionality; and that functionality declined with high levels of use. People with animals may pay more to use the system, thereby increasing financial resources for repairs. However, in the Nigeria dataset, the ‘pay for water’ variable could not be differentiated by proactive versus reactive payments. These findings may alternatively be explained by an economic imperative to keep the system functional, where the value of livestock may make repair urgent. High levels of use for animal watering (500+ animals) may lead to an increased risk of water unavailability due to parts failure from heavy use or overuse. These results may more generally suggest that multiple source use is important to ensure functional water supplies.

Different types of system management were associated with functionality in Tanzania. The most common management type is the village water committee (VWC) which are part of the Tanzanian village government system. To decentralize water system management, the 2002 Tanzanian National Water Policy promoted the formation of Community-Owned Water Supply Organizations (COWSOs) (rather than VWCs), which are more autonomous and less influenced by village-level politics. The rationale was that COWSOs would establish stronger ownership, set up fee collection, and conduct operations and maintenance. Types of COWSOs include Water User Groups (WUGs), Water User Associations (WUAs), trusts and private operators (WaterAid Tanzania, 2009). We found that management by WUGs, WUAs, and private operators were associated with higher functionality as compared to systems managed by VWCs in Tanzania, suggesting the policy change may have been effective, though this should be interpreted with caution because the detected improvements may be associated with other factors (Haysom, 2006). For example, more organized communities may facilitate system improvements faster. Further, there were no survey questions on the quality of system management which may have yielded additional insight into these relationships.

In Tanzania, prepayment of water fees, such as a single annual payment or monthly payment, was associated with higher functionality, which is consistent with evidence from studies from Liberia and Kenya (Foster, 2013; Foster & Hope). We hypothesize that proactive rather than reactive payment models enable water system managers to have funds available to purchase replacement parts and pay repair technicians.

Functionality varied by administrative unit. Districts and LGAs may proxy the implementation of policies and local capacity to repair water systems. This suggests that local factors, such as district management, local government policies, skill sets of local technicians, and availability of spare parts contribute to higher functionality. Implementers working in different districts may have different community engagement models, training, and system implementation quality. Further, districts and LGAs may proxy other factors such as geographic remoteness, ethnicity, poverty, and other variables that were not fully captured by the variables available to us.

Overall, the odds ratios of groundwater variables were close to one, suggesting these variables have little influence on functionality. Counterintuitively, functionality of systems in Tanzania was higher for low-moderate groundwater storage as compared to moderate storage. This may be explained by low groundwater storage being sufficient to support average annual extraction from boreholes with manual handpumps (three mm per year) (MacDonald et al., 2012). The groundwater dataset has coarse resolution and examination of local hydrogeology would require more detailed maps to explore these relationships further (MacDonald et al., 2012).

The linked geospatial data played an interesting role in our analyses and added explanatory power to both the regression and BN results. Many of these variables were significantly associated with functionality. However, none were particularly influential. The magnitude of the associations in the regression models and the changes in predicted probabilities in the BNs were small.

Study limitations

There are several limitations which may affect the internal and external validity of the findings. Because the data are cross-sectional, it is not possible to establish causal relationships. The analysis was reliant on data available; and there were several potentially important missing variables such as the quality of initial system construction, the role of women in water management, and availability of maintenance technicians. Some data were excluded from the analysis due to inconsistencies, which may have introduced missing data bias. Some associations between variables may be dynamic, however BNs cannot represent systems with feedback loops.

Piped systems were excluded from the regression and BNs because the water collection-points could not be clustered by system. While each water collection-point (i.e. tap) may have a hardware problem preventing water from being available, it is also possible that water is not available because the entire system is non-functional and all the taps from the same system were reported as non-functional. This may bias the analysis, and it is therefore an important methodological consideration for water system mapping initiatives, where taps from the same system must be consistently identified to enable clustering in analysis.

The linked geospatial data added important covariates to the model, however there are limitations to this approach. For example, there was low confidence in some of the groundwater data and limited data available to create estimates (MacDonald et al., 2012). Local groundwater data are necessary to provide more reliable estimates of the relationship between groundwater and functionality.

The poverty measure from the linked geospatial data relates to the population at-large and does not necessarily equate to poverty among those using the water systems. Poorer households in rural areas are more likely to use unimproved water sources, therefore it is difficult to determine whether population-level poverty rates closely correlate with water-system level poverty rates.

Seasonality likely influences system functionality; however, this is difficult to examine with a cross-sectional dataset.

Optimizing water system monitoring

There are opportunities to improve water system monitoring. Many would place limited additional burden on data collectors and would make the data more useful to analysts and stakeholders.

Water system monitoring would benefit from better use of mobile survey tools (MSTs). MSTs can be used to standardize and verify data. Surveys following good practice data collection protocols, including quality control checks, will reduce data errors (Fisher, Mann, et al., 2016). For example, better skip-logic would have reduced data entry errors in both monitoring datasets (e.g. we excluded several misclassified water system types from both datasets).

In Tanzania, qualitative survey responses suggested that some systems may have been at schools and clinics. Functional drinking water services in schools and clinics are an important component of the SDGs; and they are important for preventing disease among children at schools and for the provision of safe patient care in clinics (Bartram & Cairncross, 2010; Cronk et al., 2015; Jasper, Le, & Bartram, 2012). Data disaggregated for schools and clinics are important for SDG reporting. Evidence suggests coverage and functionality in these settings is low and in need of urgent attention in LMICs (Cronk et al., 2015; Jordanova et al., 2015; Karon A, 2017).

The use of clear definitions and survey questions may improve clarity and consistency for data collectors and increase comparability of data over space and time (Schwemlein et al., 2016). Several questions could have been improved, such as the question on management arrangements in Tanzania. The variable should have included an option for ‘no management,’ and the question may have had additional choices such as VWC management with support from a private operator.

Additional questions on other aspects of water service availability (such as predictability of services, flow rate, and service downtime) would add insight and nuance to analysis and reporting; and would provide more useful management objectives for the BN. Other water service parameters such as water safety (e.g. water quality and sanitary risk) are also important for human health and would merit inclusion in surveys to measure progress toward policy targets such as the SDGs (Bain, Cronk, Hossain, et al., 2014; Bain, Cronk, Wright, et al., 2014; Kayser, Moriarty, Fonseca, & Bartram, 2013; Lloyd & Bartram, 1991).

Information for several variables were not collected which may have proved useful in the analysis – these might have replaced questions that had to be removed. For example, there were no questions on the involvement of women in water management, availability of tools for repairs, availability of PCS, the availability of spare parts, and quality of construction (e.g. poor siting, inappropriate materials) – all of which are associated with functionality (Bonsor et al., 2015). Village water committees manage a large proportion of systems in Tanzania, and questions could have been added to differentiate between effective and ineffective committees to better understand the processes that lead to high functioning systems, such as resource mobilization, social capital, and rehabilitation pathways (Behnke N, 2017; Kelly et al., Under review; Klug, 2017).

Practice and programming recommendations

Water service delivery in LMICs is a complex systems challenge requiring improved coordination and action from actors supporting rural water supply. Our findings suggest potential practice and programming improvements are: increased availability of PCS, especially for rural piped systems in Nigeria; improving the quality of water system management (e.g. ensuring fees are collected, public accountability forums are held), and constructing system types that are context appropriate – such that system managers are able to obtain support from maintenance technicians with the appropriate skills to fix the system and spare parts are readily available to fix the specific system type. Government and external support actors should ensure sufficient post-construction support activities (and not simply implementation of new projects), including ‘software’ components such as improved governance and capacity building of staff at the local government level. Further, many people in rural areas of these countries live in extreme poverty. If universal access to basic water services is to be achieved, budgets must account for the fact that many communities may not be able to provide sufficient financial resources to support the water systems over time on their own.

CHAPTER 4: IDENTIFYING OPPORTUNITIES TO IMPROVE PIPED WATER CONTINUITY IN HONDURAS, NICARAGUA, AND PANAMA USING BAYESIAN NETWORKS AND REGRESSION

Introduction

Continuous, sufficient, safe drinking water services are important for human health, human rights, well-being, and development (Bartram & Cairncross, 2010). They are urgently needed in rural areas of low- and middle-income countries (LMICs) of Latin American and the Caribbean (LAC) where water service levels are low. More than 20 million people in rural areas of LAC (16% of the total rural population in LAC) do not use an improved drinking water source and nearly 40.5 million people in rural areas of LAC (32% of the total rural population in LAC) do not use piped drinking water at home (WHO/UNICEF, 2015b).

Many piped water systems in LMICs are discontinuous, providing less than 24-hours of service per day (Kumpel & Nelson, 2016). Systems providing less than 24-hours of service per day are more likely to contain fecal indicator bacteria (Kumpel & Nelson, 2013). An estimated 19% of water sources in LAC contain fecal contamination (Bain, Cronk, Hossain, et al., 2014; Bain, Cronk, Wright, et al., 2014). People with discontinuous services are more likely to store water at home, which is more contaminated than source water (Shields et al., 2015). Inadequate drinking water services are a substantial contributor to global burden of disease (Pruss-Ustun et al., 2014). Piped water discontinuity is associated with disease outbreak, including cholera; and piped water system upgrades to continuous service contributed to a reduction in typhoid (Ercumen et al., 2015; Jeandron et al., 2015). People with discontinuous water services may consume water from unsafe, unimproved sources such as surface water. A modeling study suggested that when people consume water from an unimproved source for a few days per month, health gains from a continuous improved source (such as a piped water supply) are negated (Hunter et al., 2009).

In response, local and national government and external support actors supporting rural water services in LAC collaboratively developed the Sistema de Información de Agua y Saneamiento Rural (SIASAR) – the Rural Water and Sanitation Information System – to monitor rural drinking water services. SIASAR was developed to provide reliable and comprehensive water service data for "better and more efficient priority setting, policy creation, project planning, and budget allocation" (Rodríguez & Weiss, 2016). The World Bank provided loan financing to the governments of Honduras, Nicaragua, and Panama to support this monitoring initiative and to contribute to water service improvements for more than 222,000 people in rural communities (Pena L, 2013).

The objective of SIASAR is to collect and consolidate data on rural water services in four domains: communities, water systems, water committees, and technical assistance providers (Rodríguez & Weiss, 2016). These domains were selected because, in LAC countries, most systems in rural areas are managed by community water committees and committees conduct management (tariff collection, financial accounting) and operations services (day-to-day operations, maintenance). Many committees are volunteer-based and receive post-construction support (PCS) services from technical assistance providers (Rodríguez & Weiss, 2016).

SIASAR was first used in Honduras, Nicaragua and Panama. As of 2017, Bolivia, Brazil, Colombia, the Dominican Republic, Oaxaca state in Mexico, Paraguay, and Peru have adopted SIASAR. Longitudinal data collection is expected (Borja-Vega et al., 2017).

Information on water service outcomes collected through SIASAR include continuity (number of hours of service per day) and water quality (fecal indicator bacteria, chemical contamination, and chlorine residual). This information is useful for decision-makers and is important to document progress of LAC countries toward policy goals and targets such as the Sustainable Development Goals (SDGs). Through a series of targets, SDG six calls for universal access to basic water services in household settings, and in non-household settings such as schools, workplaces, and health care facilities (United Nations General Assembly, 2015). Targets also call for improving service levels to safely managed water services, that is services that are available at all times (i.e. 24 hours per day), on household premises, and free of priority fecal and chemical contamination.

Post-data collection, actors supporting SIASAR combined the data into four metrics that were intended to represent factors associated with water service sustainability in the four domains: communities, water systems, water committees, and technical assistance providers. These four metrics provide a rating for each domain and these were 'A' ("optimal" service level) through 'D' ("lowest" service level). The sustainability metric for each domain comprises 33 community indicators, 37 system-level indicators, 39 water committee indicators, and 44 technical assistance indicators, respectively (Rodríguez & Weiss, 2016).

The SIASAR sustainability metric is one of more than 200 metrics and tools that have been developed to-date with the purpose of assisting actors who support water supply determine water system/project sustainability (Boulenouar, Schweitzer, & Lockwood, 2013). A potential problem with the SIASAR sustainability metric and many other sustainability metrics and tools is that each included variable is weighted equally, suggesting that all variables contribute equally to the sustainability of water services. However, rural water service sustainability is complex, multifactorial, and often-times context dependent; and variables contribute differently to water service sustainability (Amjad et al., 2015). For example, studies from sub-Saharan Africa suggest that variables such as system age, system type, tariff collection, and implementing actor have greater influence on water system sustainability than others such as the availability of alternative water systems and distance to urban centers (Fisher et al., 2015; Foster, 2013).

There are no large studies from LAC that examine variables associated with 24-hour water service availability or related service parameters. Available studies are small and there are no multivariable analyses, meaning they could not report the relative influence (i.e. magnitude of effect) of different variables on water service levels. For example, a study of 60 water systems in El Salvador examined the influence of circuit rider post-construction support (CRPCS) on piped water system quality and sustainability, and found that communities with CRPCS had safer water, higher tariff payment rates, and higher spending for system repairs (Kayser, Moomaw, Portillo, & Griffiths, 2014). A study from the Dominican Republic found high levels of maintenance activities and the availability of savings to be associated with higher water system continuity; however, this study only examined 61 communities and effect sizes were unavailable (Schweitzer & Mihelcic, 2012).

There is an opportunity to gain further insight from SIASAR by using monitoring data to model variables associated with higher water service levels. There are also opportunities to optimize SIASAR monitoring – without adding cost or time burden – such that future data collection will yield even more useful information for government and external support actors supporting rural water systems in LAC and more useful data for analysis in service delivery research. Bayesian Networks (BNs) may reveal opportunities to improve services and these are useful for: examining associations in complex environmental systems, modeling decision-making scenarios, and evidence-based decision making (Cain, 2001; Carriger et al., 2016).

However there is little application of BNs to water systems and services, especially in LMICs (Fisher et al., 2015; Liddle & Fenner, 2017; Phan et al., 2016)

In the largest study of its kind conducted to-date in LAC, we analyzed SIASAR data from Honduras, Nicaragua, and Panama using logistic and linear regression and BN models to explore variables associated with water service continuity. We compared our regression models to the SIASAR sustainability metric to examine goodness of fit.

Methods

Data sources

Data for Honduras, Nicaragua, and Panama were obtained from the online SIASAR database in November 2016 (SIASAR, 2016). These cross-sectional data had been collected by the government agency responsible for rural water service provision in each country. The actors conducting monitoring for SIASAR intended data collection to be a census of all rural piped water systems in these countries. Data quality assurance and quality control (QA/QC) measures varied by country. For example, systems and communities in Honduras were revisited several times to verify data whereas few data checks were conducted in Nicaragua and Panama (Borja-Vega et al., 2017; Pena L, 2013).

For each country, the water system, community, and water committee datasets were combined so that data analysis could occur at the water system level. Technical assistance provider data could not be combined at the system level because they lacked identification codes for the systems serviced.

Water system variables in the dataset included continuity, system age, source type (either surface water or groundwater), supply type (either gravity-piped system or electric pump piped system), sufficient water available in the summer (i.e. the dry season) and winter (i.e. the wet season), watershed condition, and infrastructure condition (for each of: the intake, conduction, storage, and the distribution network). Continuity was measured as the number of hours of service per day. A binary variable “24-hour service” was adopted to represent systems that provide 24-hours of service versus those that do not. Infrastructure condition was reported as a rating: good condition, requires maintenance, and requires rehabilitation. The definitions of the ratings were similar to a sanitary inspection, which is a water system assessment used to identify actual and potential sources of contamination (WHO, 2011). Data for source type were only available for Honduras.

Microbial and chemical water quality data were collected as part of SIASAR monitoring from a sample of the total population of systems under study. Non-sampled systems were not distinguished from those that were contaminated, therefore these data could not be used in the analysis.

Community variables included population served by the system and ethnicity. The ethnicity variable was measured as the majority ethnicity in the community and categories included mestizo and different indigenous ethnicities.

Water committee-related variables included: the legal status of the committee (categorized as not legally established; in process of legalization; or legally established), women included as water committee members, committee procedures and regulations in place, minutes available from the last committee meeting, water committee maintains the watershed, committee held a meeting in the past six months, existence of a bank account (to pay for repairs and services), average monthly household tariff rate (set by the committee), availability of replacement funds for system rehabilitation (i.e. savings), amount of funds available (per household), and availability of funds for preventative repairs.

Operations and maintenance-related variables included the availability of external technical support (e.g. PCS), the availability of "corrective" maintenance support (i.e. support to rehabilitate the system, and availability of preventive maintenance support.

Data analysis: univariable and multivariable linear regression

Data were cleaned and analyzed in Stata IC 13.1. Examples of data cleaning included the removal of water system observations with impossible values (e.g. systems providing more than 24-hours of service per day). Where appropriate, variable categories were combined to avoid small cell counts (e.g. ethnicity was categorized as mestizo or indigenous). Variables with small cell counts where categories could not be meaningfully combined were not included in analyses (e.g. sub-national region was not included in analyses of Panama).

Tariff values were converted from the local currency to United States Dollars (USD) using the average exchange rates from 2015 so that these values could be compared to data on the cost of provision of safely managed water services (i.e. on-plot, continuous, and safe water supply) which were calculated in 2015 USDs (Hutton & Varughese, 2016). Annual capital infrastructure, capital maintenance, and operations costs per person living in rural areas in each country were obtained from the supplementary dataset supporting the 2015 estimates for costs of water services (Hutton & Varughese, 2016). These values were converted to monthly household costs so that these could be compared with the SIASAR data. Average household size in rural areas in each country were obtained from the most recent demographic survey available for each country (with the exception of Panama, where the national average household size was used)

(Contraloría General de la República, 2014; Instituto Nacional de Información de Desarrollo (INIDE) & Ministerio de Salud (MINSA), 2013; Secretaría de Salud - SS/Honduras, Instituto Nacional de Estadística - INE/Honduras, & ICF International, 2013).

Univariable and multivariable linear and logistic regression were used to explore variables associated with water service continuity. Logistic regression using the dependent variable of 24-hour service was conducted since a piped system that is not under constant pressure at all times is subject to risk of contamination (Kumpel & Nelson, 2016). It was also used to compare with the Bayesian network (BN) model, since continuous variables cannot be used in BNs. Independent variables were included in the model if they represented a control, were identified in the literature as a variable associated with water service availability, or represented a plausible theoretical association with water service availability (Alexander et al., 2015; Fisher et al., 2015; Foster, 2013; Kayser et al., 2014; Klug, 2017; Whittington et al., 2009)

Linear regression using the dependent variable of continuity was conducted so that an r-squared value could be generated to compare with the SIASAR sustainability metric (logistic regression outputs only generate pseudo r-squared values). To assess model validity, regression diagnostics were conducted to examine specification errors, goodness-of-fit, multi-collinearity, and influential observations. For all analyses, statistical significance was evaluated with a p-value of 0.05 (95% confidence).

The SIASAR sustainability metric for water systems was analyzed using continuity as the outcome variable in the regression model to compare r-squared values; where the r-squared value is an indicator of model fit that can be used to compare two models.

Data analysis: Bayesian network analysis

The cleaned datasets for each country were exported from Stata and developed into graphical Bayesian network (BN) models using Netica 5.18 (Norsys Software Corp., 2014). In Bayesian networks, variables are represented as nodes. Each node comprises states (category of a variable) and nodes are connected by arrows which represent associations. Predicted probabilities of each state are reported in every node. Cycles and dynamic relationships (feedback loops) cannot be represented. Netica cannot incorporate continuous variables, so all nodes must be categorical. The network comprises 'uncontrollable' nodes, management nodes, and objective nodes. Uncontrollable nodes (e.g. sub-national region and community ethnicity) are those that influence the overall model but cannot be changed by an intervention. Management nodes are those that can be modified (such as availability of preventative maintenance, availability of funds for operations and maintenance). Objective nodes are the nodes under study; and they are influenced by uncontrollable and management nodes. In this study, the objective node under study is 24-hour service. All nodes are causally ordered, where distal nodes are connected to proximate nodes which are connected to the objective node. States of each node can be modified to examine the influence of different states on the objective node. The BN model with all states unmodified is the 'base-case.' For all analyses, good BN practice was followed (Cain, 2001; Chen & Pollino, 2012).

Sensitivity analyses of each BN were conducted to determine which nodes were most influential on 24-hour service. The sensitivity analysis in Netica calculates reductions in Shannon's entropy (Pearl, 2014). Ranking all nodes according to entropy reduction identifies those with the most influence on the objective node of 24-hour service. Model evaluations were conducted, including calculation of the receiver operating characteristic (ROC), logarithmic loss, quadradic loss, and spherical payoff (Marcot et al., 2006; Morgan, Henrion, & Small, 1992). These evaluations are useful for determining the BN model sensitivity and specificity. To conduct the model evaluations, the dataset was randomly split into a dataset to build the model (80% of the original dataset) and a test dataset (20% of the original dataset).

Alternative ‘best case’ and ‘worst case’ scenarios were developed and compared to the ‘base case’ by changing management nodes to their highest (best case) and lowest (worst case) states. To explore the influence of seasonal water availability on system continuity, scenarios were developed where the nodes ‘sufficient water available in the summer and winter’ were set to their best and worst states. Because of the causal structure of the BN, distal nodes may have less influence on the objective node than nodes that are more proximate. Therefore, scenarios were developed where the condition of the conduction and the distribution network were used as objective nodes and the relationships with other nodes explored.

Results

Descriptive and linear regression analysis

Data from 2,946 water systems in Honduras were analyzed (90% gravity-piped systems, 10% electric-pump piped systems), 2,115 in Nicaragua (67% gravity-piped systems, 33% electric-pump piped systems), and 499 in Panama (61% gravity-piped systems, 39% electric-pump piped systems). Tables of descriptive statistics are available in the appendix (APPENDIX 2 FOR CHAPTER 4).

On average, systems in Honduras provided 18 hours of service per day and continuity varied by sub-national region: Lempira region had the highest (22 hours/day) and Valle region had the lowest (6 hours/day). Lempira had the highest proportion of systems providing 24-hour service (82%) and Valle had the lowest (11%). On average, systems in Nicaragua provided 16 hours of service per day and continuity varied by region: RACCN (North Caribbean Coast Autonomous Region) had the highest (21 hrs/day) and Managua region had the lowest (10 hrs/day). RACCN had the highest proportion of systems providing 24-hour service (78%) and Masaya had the lowest (7%). On average, systems in Panama provided 18 hours of service per day and continuity varied by region: Colón region had the highest (21 hrs/day) and Comarca Emberá region had the lowest (12 hours/day). Panamá region had the highest proportion of systems providing 24-hour service (84%) and Comarca Emberá had the lowest (40%).

In all three countries, gravity-piped systems were associated with higher 24-hour service than electric-pump piped systems. In Honduras, systems using groundwater sources were significantly associated with lower 24-hour services as compared to surface water (OR:0.7, 95%CI:0.5, 0.8, $p<0.001$). Source type was removed from the Nicaragua and Panama regressions and BNs due to missing data. In all three countries, sufficient water available in the summer was associated with higher continuity. Regression models for all three countries and BNs for Nicaragua and Panama are available in the appendix (APPENDIX 2).

Nearly half of systems in Panama (47.5%), 22.9% of systems in Nicaragua, and 4.4% of systems in Honduras had no tariff collection (table available in APPENDIX 2). For more than 90% of systems in all three countries, insufficient monthly household water service rates were collected to cover capital infrastructure, operations, and maintenance costs.

In Honduras, the amount of funds available (categorized into quintiles) was not associated with 24-hour service. This variable was not included in the models of Nicaragua and Panama due to missing data for some water systems. For comparison with other analysis of water service availability (e.g. (Fisher et al., 2015; Foster, 2013)), a separate model was developed and the variable for amount of funds available was replaced with a binary tariff collection variable (tariff collected or no tariffs collected). The binary tariff collection variable was not associated with 24-hour service in Honduras.

The Panama multivariable model predicted that water systems with intakes in need of rehabilitation (as compared to those in good condition) were less likely to provide 24-hour service (OR: 0.3, 95% CI: 0.2, 0.7), p=0.0061). In multivariable logistic regression models of Honduras and Nicaragua, systems with a distribution network requiring rehabilitation (as compared to systems with networks in good condition) were significantly associated with lower 24-hour service (Honduras: OR: 0.8; 95% CI: 0.6, 1; p=0.022; Nicaragua: OR: 0.6, 95% CI: 0.4, 0.9; p=0.013).

Some water committee-related variables were significantly associated with 24-hour service, where in Panama, systems were more likely to provide 24-hour service if there were replacement funds available (OR:2; 95%CI: 1.2, 3.5; p= 0.016).

In Honduras, availability of corrective maintenance (i.e. services and skills for system rehabilitation) was associated with higher 24-hour service (OR:2.1; 95% CI: 1.4, 3.4; p=0.002) and in Nicaragua, preventative maintenance was associated with higher 24-hour service (OR: 1.3; 95% CI: 1.1, 1.7; p= 0.047).

In Honduras and Nicaragua, systems serving the largest populations were associated with lower 24-hour service as compared to those serving the smallest (highest population quintile versus the lowest, Honduras OR: 0.3, 95% CI: 0.2-0.4, $p<0.0001$; Nicaragua OR: 0.4, 95% CI: 0.3, 0.6, $p<0.001$).

Regression model fit compared to the SIASAR sustainability metric

We compared our regression model to the SIASAR sustainability metric for water systems. In Honduras, the r-squared value for the continuity multivariable regression model was 0.49. In comparison, the regression model for the water system sustainability metric in Honduras predicted that 'A' rated systems ('optimal' service) had higher continuity than 'B' or 'C' rated systems (none were rated 'D', 'lowest' level service) and the r-squared value was 0.03. Similarly, in Nicaragua, the r-squared value for the continuity model was 0.22 compared to 0.05 for the sustainability metric. In Panama, the r-squared value for the continuity model was 0.33 and 0.08 for the sustainability metric.

Sensitivity analysis and alternative scenarios using Bayesian networks

In model evaluations, the receiver operating characteristic (ROC) in Honduras suggested the model was moderately accurate while Nicaragua and Panama were less accurate (Greiner et al., 2000). In the Honduras BN sensitivity analysis, sufficient water available in the summer (dry season), sufficient water available in the winter (wet season), condition of the storage status, and condition of the distribution network were most influential on the availability of a 24-hour service. In Nicaragua, sufficient water available in the summer, distribution condition, and availability of external technical support were most influential on 24-hour service. In Panama, distribution condition, sufficient water in the summer, storage condition, and sufficient water available in the winter were most influential on 24-hour service (model evaluations and sensitivity analyses are available in APPENDIX 2).

The base-case scenario in Honduras predicted 63% of systems provided 24-hour service. The best-case management scenario of Honduras water systems predicted five percentage point higher 24-hour service from the base-case scenario of 63% to 68% (tables in APPENDIX 2). In the worst-case scenario, 24-hour service was 55%, eight percentage points lower than the base-case. When there was sufficient water available in the summer, 24-hour service for systems in the best-case management was 81%, 18 percentage points higher than the base-case. When there was insufficient water available in the summer, 24-hour service for systems in the worst-case was 39%, 24 percentage points lower than the base-case.

In the best-case BN scenario of Nicaragua water systems, the BN predicted higher 24-hour service from 57% in the base-case to 67% (10 percentage points higher). In the worst-case scenario, 24-hour service was 36% (17 percentage points lower than the base-case). When there was sufficient water available in the summer, 24-hour service in the best-case scenario was 66% (13 percentage-points higher than the base-case) while 24-hour service in the worst-case scenario was 26% (27 percentage-points lower than the base-case).

In the best-case scenario of Panama water systems, the BN predicted higher 24-hour service from 55% in the base-case to 64% (nine percentage points higher). In the worst-case, 24-hour service was 54% (three percentage points lower than the base-case). When there was sufficient water available in the summer, 24-hour service in the best-case was 72% (14 percentage points higher). When there was insufficient water available in the summer, 24-hour service in the worst-case was 47% (ten percentage points lower than the base-case).

We examined the influence of BN nodes on the condition of the storage and the distribution network. For example, in Honduras, when external technical support, corrective maintenance, and preventative maintenance were available, the proportion of systems with good condition distribution was nine percentage points higher (55% to 64%) and the proportion of systems with good condition storage was 13 percentage points higher (58% to 71%). When age was also considered (in addition to the availability of external technical support, corrective maintenance, preventative maintenance, and plumbers), the model predicted that a higher proportion of newer systems (0-5 years) had good condition storage and distribution as compared to the oldest (30+ years). Good condition storage was 31 percentage points lower, from 88% (0-5 years) to 57% (30+ years). Good condition distribution networks were 19 percentage points lower, from 74% (0-5 years) to 55% (30+ years).

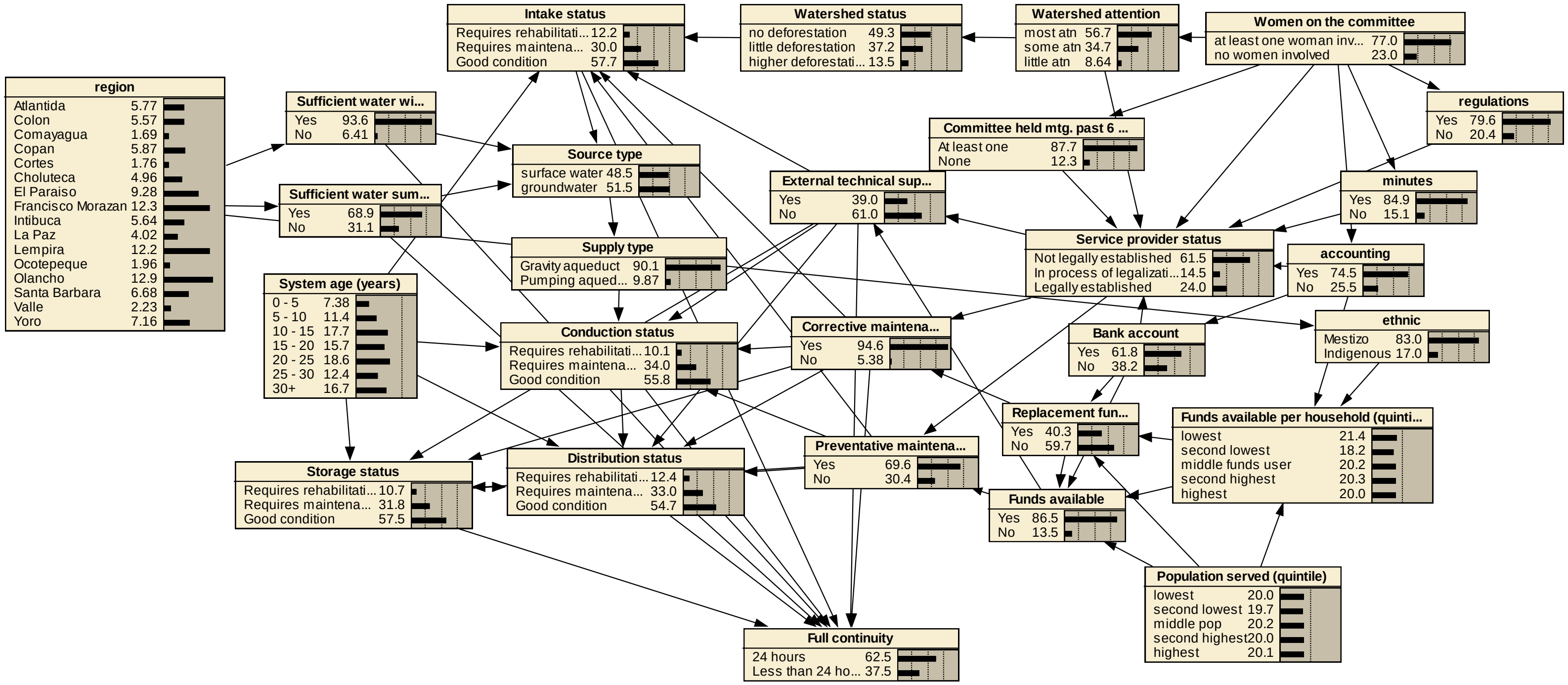

Figure 5. Base-case Bayesian network model for Honduras

Discussion

We used regression and Bayesian networks to analyze the availability of 24-hour piped water services in rural areas of Honduras, Nicaragua, and Panama using data from the SIASAR rural water monitoring system. Data were representative of 5,560 community-based piped water systems. Similar to related studies, we found that 24-hour service availability varied by system type, where gravity-piped systems were more likely to provide 24-hour services than electric-pump piped systems (Fisher et al., 2015; Foster, 2013; Lloyd & Bartram, 1991). We found that water services varied significantly by sub-national region, where in Honduras, the proportion of systems providing 24-hour service spanned 71 percentage points among sub-national regions.

In both the regression and BN models, infrastructure condition (e.g. condition of the distribution network) and seasonal water availability were more influential (i.e. larger regression coefficients; BNs predicted greater change) on 24-hour service than management and operations and maintenance variables such as the availability of external technical support and the availability of funds to rehabilitate the system. The influence of season on water service availability is consistent with other studies from a LMIC context (Foster, 2013). Few studies explore the relationship between infrastructure condition and level of water service availability.

The BNs can be a useful decision tool for actors supporting rural water supply in LAC. The 'best-case' (i.e. good condition infrastructure, corrective maintenance, external technical support) BN scenarios suggest modest improvements in availability of 24-hour service are obtainable (five percentage points higher from the base case of 63% in Honduras; nine percentage points higher in Nicaragua from the base case of 53%; 10 percentage points higher in Panama from the base case of 57%). Sufficient (and insufficient) water availability had a large influence on the best and worst-case scenarios, where in Honduras, there was a 43-percentage point difference in predicted 24-hour service between the best-case scenario with sufficient water available in the summer and the worst-case scenario with insufficient water available.

The relationship between tariff collection and availability of 24-hour service in Honduras was interesting. Similar to related studies, we included a variable in our regression model for tariff collection (and fees paid by system users) versus no tariff collection (Fisher et al., 2015; Foster, 2013). In other studies, tariff collection (versus no tariff collection) was associated with higher water service availability outcomes (e.g. functionality), and these studies (which were conducted using secondary data) assumed that tariffs were monetary. In our regression analysis, there was no significant difference between communities that had a set tariff and records show that at least some people paid and communities that did have a set tariff. This may suggest that communities may contribute resources to the water system though other non-monetary and non-tariff mechanisms, such as mobilization of personal and community assets, community institutions, and community labor; thereby reducing the influence of tariff collection on continuity (Behnke N, 2017). It is also possible that fees are collection in reaction to water system breakdowns.

There were some counterintuitive findings in the multivariable regression models. In Nicaragua, financial accounting was associated with lower availability of 24-hour service and during data analysis, no logical interactions with other variables were identified. The counterintuitive findings may be explained by the fact that associated variables are more distal in the causal chain and may be confounded in the regression. In our BN models, where hypothesized causal associations are better represented, these variables had little or no influence on continuity. This suggests BNs may be better models to assess the complexities of rural water service sustainability. However, Bayesian networks are directed acyclic graphs, meaning relationships represented in the model are unidirectional (rather than dynamic). This presented a problem for some variables, such as availability of technical assistance. Technical assistance providers not only provide support for operations and maintenance and system rehabilitation (as we modeled in our BNs) but they also support water committee activities, such as assisting committees set tariffs, developing accounting records, and setting up accountability procures and processes (Borja-Vega et al., 2017). Therefore, our BN models were unable to assess plausible feedback loops among available variables. Different modelling tools such as system dynamics modelling might be used to represent dynamic relationships (Liddle & Fenner, 2017; Walters & Javernick-Will, 2015).

Study limitations

The SIASAR data were cross-sectional, meaning we were only able to show associations (and not causation) using regression and Bayesian networks.

The quality and reliability of some of the variables may be a problem, where in Honduras, data collection actors conducted substantially more quality control measures (such as revisiting communities to confirm responses) than in Nicaragua and Honduras. Random data collection errors introduced by incorrect survey responses or data management errors due to lack of verification in Nicaragua and Panama likely contributed to a worse model fit than in Honduras in the r-squared values in the regression (Honduras r-squared: 0.49; Nicaragua: 0.22; Panama: 0.33) and the receiver operator characteristic in the BNs (Honduras

ROC: 0.7044; Nicaragua ROC: 0.5982; Panama ROC: 0.6302). Another potential contributor to lower data quality and reliability may be some of the survey questions. Questions such as 'availability of funds for repairs' and 'availability of corrective maintenance' are neither specific nor objective. With other questions such as 'availability of external technical assistance" it was not possible to assess the quality of technical assistance provided or the frequency of support. In this study, misclassification and other errors likely reduce the magnitude of effect of some independent variables; and in some instances, it may have been the reason for counterintuitive associations.

Monitoring implications

SIASAR is an important source of data about water services which can be used to inform evidence-based practice, programming, and policy decision-making by actors in LAC who support rural water services. There are several opportunities to optimize SIASAR without increasing costs or time burden on data collectors and which would increase the value of future data collection.

Many survey questions would be improved by applying good-practice for survey question design – for example, by making questions such as 'availability of funds for repairs' more specific and measurable (Schwemlein et al., 2016). A codebook or table of definitions of terms used in SIASAR would provide greater clarity for data collectors and data analysts.

The SIASAR instrument would benefit from adopting externally prepared standard questions. For example, the infrastructure ratings could be replaced by questions with sanitary inspection forms or water safety plans which were developed by the WHO (WHO, 2011). Many of these standard questions are based on evidence, have been field tested, and are based on good practices. Use of these standard questions enables comparability with other monitoring and datasets conducted in other contexts.

The SIASAR instrument would benefit from additional questions on continuity and water service availability parameters. The current question asks about the number of hours of service per day, but other service delivery durations and patterns have been observed in other contexts, such as regular supply for specific hours of the day, specific days of the week, or unpredictable patterns (Kumpel & Nelson, 2016; Lloyd & Bartram, 1991). Identifying the nuance and patterns in service delivery may provide useful information on the potential influence on comping strategies and health implications for system users.

Some variables in the analysis may have not been associated with 24-hour service availability because they did not represent best-available evidence related to water system sustainability. For example, while SIASAR included a variable for women on the water committee, token involvement of women is insufficient to improve rural water sustainability outcomes (Prokopy, 2004). SIASAR also included a question on availability of preventative and corrective maintenance in the community however community involvement in technical decisions is associated with lower water system sustainability (Marks, Komives, & Davis, 2014). Future SIASAR instruments might include other indicators associated with sustainable water system management including social capital and ownership, resource mobilization, and water system rehabilitation (Behnke N, 2017; Kelly et al., Under review; Klug, 2017; Marks, Onda, & Davis, 2013).

Water quality data (fecal contamination, chemicals, chlorine residual) were collected in all three countries. However, in the datasets, there was no differentiation between systems where water quality results were positive for contamination and those that were not tested.

Further, among systems that were tested, few samples were collected per system. Consequently, these data were not used in our analysis. Simple improvements to data management (e.g. separating data by 'system contains fecal contamination' 'system does not contain fecal contamination' and 'no water quality test conducted') would have yielded additional variables of particular relevance to improving health and reporting policy targets. Similarly, the technical assistance provider data could not be combined with the water system data because there were no identifying codes to link technical assistance providers to the systems they service. This would have yielded greater insight into the role that technical assistance providers play in improving infrastructure condition and water service continuity.

Policy and practice implications

Sustainability tools and metrics are growing in popularity among actors supporting rural water services to assist with resource targeting, eliciting change in behaviors, and identifying improvement opportunities. Many tools, including SIASAR, include many variables and it can be difficult to discern which variables might have the greatest impact on improving sustainability outcomes. Many of these tools are not analyzed for their predictive capabilities. Our results suggest that an optimized sustainability metric that includes a smaller number of variables – primarily those that have the most influence on water service outcomes – may be a more useful tool for stakeholders by showing them which factors are most important for sustainability. Low predictive capability may result in resource allocation to systems that are not in as great of need of support as other systems in need of improvements. Therefore, better use of sustainability tools may enable better targeting of resources to the systems in greatest need – and these resources may contribute to more continuous services, improvements in drinking water quality, and ultimately improved community health. Actors supporting rural water services may benefit from the use of sustainability tools and metrics that have been empirically validated or use evidence-based, statistically-sound methods such as Bayesian networks and regression to analyze monitoring data.

Ensuring sufficient financial resources are available to maintain water services are an important component to ensure sustainable services over time and to achieve universal access to water services (Hutton & Varughese, 2016). Our descriptive analysis of tariffs suggests that most water committees collect insufficient funds to cover operations and maintenance. In each country, insufficient household water tariffs were collected for 90% or more of systems to cover capital, operations, and maintenance costs. Communities, local and government actors, and external support actors should identify opportunities to improve cost-recovery for operations, maintenance, and capital replacement such as modifying tariff structures. Actor should also look for opportunities to improve financial viability by identifying alternative sources of financial viability such as public financing.

Actors supporting rural water services can use monitoring data to target resources to systems with low service levels. The SIASAR data contain community names and geospatial information; therefore, it is possible to identify specific water systems providing low service levels and with seasonal availability. For example, sufficient water availability in the summer had a large influence on water service continuity. This has important health, policy, and practice implications – where households using the system under conditions of low availability may store water in the home or use other potentially unsafe sources. Although water stored from piped systems is safer than water from ‘other improved’ sources such as boreholes and protected dug wells, actors supporting rural water supply should ensure that communities are using good water storage practices and sustaining those practices over time (Shields et al., 2015; Sobsey, Stauber, Casanova, Brown, & Elliott, 2008). Because SIASAR data are a census, actors should use these data to identify which communities may be at highest risk.

Conclusions

Safely managed water services – that provide 24-hour continuous services and drinking water that is free of contamination – are important for human health, well-being, and development. However, in rural areas of LAC we find substantial differences in 24-hour water service delivery between sub-national regions of Honduras, Nicaragua and Panama. Monitoring data are important for identifying systems providing low services to fix them individually. They are also useful to identify trends and patterns of factors associated with low levels of service so that they can be fixed systematically. Water system continuity improvements are imperative to secure health and development benefits. Actors supporting rural water supply could make better use of available data to direct technical and financial resources to systems and communities where service improvements are needed. Our findings provide local and national actors with evidence to make informed policy, programming, and practice decisions.

CHAPTER 5: ENVIRONMENTAL CONDITIONS IN HEALTH CARE FACILITIES IN LOW- AND MIDDLE-INCOME COUNTRIES: COVERAGE AND INEQUALITIES

Introduction

Safe and adequate environmental conditions in health care facilities (HCFs) – including the availability of water, sanitation, hygiene (WaSH), and waste management – and the availability of standard precaution items (e.g. infection prevention items such as disposable gloves) are essential for safe delivery of health care.

In low-income countries, the prevalence of health care acquired infection (HCAI) is estimated to be 16% (Allegranzi et al., 2011). Many HCAIs are attributable to inadequate environmental conditions (Anaissie, Penzak, & Dignani, 2002; Borg, 2009; Galadanci et al., 2011; Leslie, Fink, Nsona, & Kruk, 2016; Li, Abebe, Cronk, & Bartram, 2016). Inadequate environmental conditions in HCFs contribute to infection through contaminated water, hands, fomites, food, medical equipment, inadequate sharps and infectious waste disposal, and unsafe blood transfusions. Associated adverse health outcomes include gastrointestinal, respiratory, surgical site, burn wound, and sharps-related infections (World Health Organization, 2008).

Adequate hand hygiene, such as handwashing with soap, is the most cost-effective practice for preventing infection in health care settings (World Health Organization, 2008). However, several hundred million patients annually acquire infections arising from poor handwashing practices – which may be due in part to the lack of available handwashing materials and facilities (World Health Organization, 2009). Compliance with handwashing standards among health care providers is often low and health care providers often transmit infection (Erasmus et al., 2010). Because of these deficiencies, HCFs serve as foci for infection and patients seeking treatment fall ill, and potentially die, for the lack of basic elements of a safe and clean environment (Bartram et al., 2015).

Establishing and maintaining a safe health care environment is a fundamental consequence of the Hippocratic oath: *primum non nocere* (first do no harm). It is recognized in international development policy through the Sustainable Development Goals (SDGs). The WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation (JMP) is responsible for monitoring and defining the WaSH-related SDG targets. The JMP define these goals and targets to include both household and non-household settings including schools, workplaces, and health care facilities (Cronk et al., 2015; United Nations General Assembly, 2015; WHO/UNICEF, 2016a). Waste management and WaSH in HCFs are recognized through dedicated targets of SDG 6 which calls for the “availability and sustainable management of water and sanitation for all” (United Nations General Assembly, 2015). SDG target 3.8 calls for “access to quality essential health-care services” for all (United Nations General Assembly, 2015). Stratifying data by important factors (e.g. rural-urban; facility type) and using these data to identify opportunities to progressively reduce inequalities are important components of every SDG and human rights (Meier, Cronk, Luh, de Albuquerque, & Bartram, 2016; United Nations General Assembly, 2015).

The JMP developed a set of harmonized survey questions and indicators for WaSH and waste management in HCFs (WHO/UNICEF, 2016c). These correspond to service levels of basic, limited, and no service. Service levels are used to describe the proportion of HCFs receiving different services and to report progressive improvements.

Baseline estimates of the status of environmental conditions and the availability of standard precaution items in HCFs have yet to be made for the SDGs. Few studies explore inequalities in coverage of environmental conditions in HCFs by factors such as facility type, managing authority, and sub-national administrative area. Baseline estimates and inequality analyses of HCFs are needed to benchmark progress and identify sub-national administrative areas, countries, and world regions in need of financial, technical, management, and human resources to make improvements. Available studies examine maternity settings in a few countries of sub-Saharan Africa; a limited set of indicators of environmental conditions; a limited set of HCF data; and/or a specific facility type (e.g. hospitals) (Benova, Cumming, Gordon, Magoma, & Campbell, 2014; Chawla et al., 2016; Gon et al., 2016; World Health Organization and UNICEF, 2015).

We produced the first coverage estimates of environmental conditions and standard precaution items in HCFs – including the availability of piped water in the facility premises, availability of sterilization equipment, safe storage and disposal of infectious and sharps waste, and the availability of guidelines for standard precautions. We present the most comprehensive estimates compiled to-date for sanitation, handwashing soap, and electricity availability in HCFs. We report the SDG service levels for water, sanitation, hygiene, and waste management – and document sub-national inequalities in coverage with these services. We identify gaps in monitoring to measure and report the SDG service levels and essential environmental health standards in health care settings. We identify opportunities for harmonizing and improving HCF monitoring initiatives so these can be used by actors supporting HCFs to document service coverage challenges, and develop policies and strategies to precision target resources to improve the situation.

Methods

Search strategy

Eighteen data repositories including the Global Health Data Exchange, the International Household Survey Network, the World Bank Data exchange, and the International Health Facility Assessment Network were reviewed for publications, reports, and datasets relevant to environmental conditions and the availability of standard precaution items in health care facilities.

Using a list of LMICs as defined by the World Bank, the following searches were conducted in English using PubMed and Google Scholar: "[country name]" AND "health facility assessment" and "[country name]" AND "health facility survey." Systematic reviews that documented health care facility surveys were reviewed for relevant data (Adair-Rohani et al., 2013; Chawla et al., 2016; Nickerson, Adams, Attaran, Hatcher-Roberts, & Tugwell, 2015).

Further publications, reports, and datasets was obtained from members of the World Health Organization task team on WaSH in health care facilities.

Websites of the Ministry of Health and the National Bureau of Statistics (or equivalent ministries and government agencies) for low- and middle-income countries were searched for relevant reports and datasets.

Data assessment

All identified publications, reports, and datasets were reviewed for data that related to the WHO Essential Environmental Health Standards in Health Care, the WHO standard precautions in health care and/or the SDG-related WaSH in HCFs indicators (Table 10) (WHO, 2007b; WHO/UNICEF, 2016a; World Health Organization, 2008). This article focuses on standard precaution items rather than practices as monitoring instruments collect data on availability of items in HCFs. Standard precaution items comprise materials for hand hygiene, gloves, facial protection (eyes, nose, and mouth), gowns, sharps boxes, items for environmental cleaning, clean linens, waste disposal, and patient care equipment (WHO, 2007b).

Table 10. Guideline topics and definitions in the essential environmental health standards in health care settings and the core indicators for WaSH and waste management in HCF, adapted from (WHO/UNICEF, 2016a; World Health Organization, 2008)

Guideline topic and definitions from the essential environmental health standards in health care settings, adapted from (World Health Organization, 2008)	
Guideline topic	**Definition in the guideline**
Water quality	Water for drinking, cooking, personal hygiene, medical activities, cleaning and laundry is safe for the purpose intended.
Water quantity	Sufficient water is available at all times for drinking, food preparation, personal hygiene, medical activities, cleaning and laundry.
Water facilities and access to water	Sufficient water-collection points and water-use facilities are available in the health-care setting to allow convenient access to, and use of, water for medical activities, drinking, personal hygiene, food preparation, laundry and cleaning.
Excreta Disposal	Adequate, accessible and appropriate toilets are provided for patients, staff and carers.
Wastewater disposal	Wastewater is disposed of rapidly and safely.
Health care waste disposal	Health-care waste is segregated, collected, transported, treated and disposed of safely.
Cleaning and laundry	Laundry and surfaces in the health-care environment are kept clean.
Food storage and preparation	Food for patients, staff and carers is stored and prepared in a way that minimizes the risk of disease transmission.
Building design, construction and management	Buildings are designed, constructed and managed to provide a healthy and comfortable environment for patients, staff and carers.
Control of vector-borne disease	Patients, staff and carers are protected from disease vectors.
Information and hygiene promotion	Correct use of water, sanitation and waste facilities is encouraged by hygiene promotion and by management of staff, patients and carers.
SDG Related WaSH in HCF indicators, adapted from (WHO/UNICEF, 2016c)	
Core indicators for WaSH and waste management in HCF for the SDGs	**Normative definitions of core indicators for basic WaSH and waste management services in health care facilities**
The proportion of health care facilities with basic water supply	Facilities where the main source of water is an improved source, located on premises, from which water is available at the time of the survey, or if not, water is available from an alternative improved source.
The proportion of health care facilities with basic sanitation	Facilities with improved toilets or latrines for patients located on premises, that are functional at the time of visit, with at least one toilet designated for women/girls with facilities to manage menstrual hygiene needs, at least one separated for staff, and at least one meeting the needs of people with limited mobility.
The proportion of health care facilities with basic hand hygiene	Facilities with hand hygiene stations including a basin with water and soap, or alcohol-based hand rubs, present at critical points of care and within 5 m of toilets.
The proportion of health care facilities practicing basic healthcare waste management	Facilities where waste is safely segregated in the consultation area and infectious and sharps wastes are treated and disposed of safely.

Table 11. Comparing the SDG service levels with data available in the SPA surveys. Adapted from (WHO/UNICEF, 2016a)[7]

	Service level	W1	W2	W3	W4	AW1	AW2	AW3	AW4
Water service (W)	Basic Service	Improved source	On premises	Available from main source at time of survey (W3) or water is available from an alternative improved source (W4)		Same as W	Same as W	Year-round availability	Not available
	Limited service	Improved water source	A “No” response for ANY (W2, W3, W4)			Same as W	A "No response for AW2 or AW3		Not available
	Unimproved / No facility	An unimproved or no water source (W1) OR An improved water source (W1) that is more than 500m from the facility (W2)				Same as W			
	Service level	S1	S2	S3	S4	AS1	AS2	AS3	AS4
Sanitation service (S)	Basic Service	Improved facilities located on premises and usable at time of visit	Sex-separated and have facilities to manage menstrual needs	At least one toilet designated for staff	At least one toilet meets the needs of people with limited mobility	Sanitation piped to sewer	Not available	Not available	Not available
	Limited service	Improved facilities but not usable	A “No” response for ANY (S2, S3, S4)			Other improved facility	Not available	Not available	Not available
	Unimproved / No facility	Unimproved or no facilities	Not applicable (N/A)	N/A	N/A	Unimproved or no facilities	N/A	N/A	N/A
	Service level	H1		H2		AH1		AH2	
Hygiene service level (H)	Basic Service	Hand hygiene stations (water and soap or alcohol based hand rub) at points of care		Hand hygiene (water and soap) available within 5m of toilets		Same as H		Not available	
	Limited service	Hand hygiene stations at either points of care (H1) or toilets (H2), but not both				Not available			

[7] W1, W2, S1, etc. correspond to survey questions which are used to measure each service level. Those with ‘A’ (‘alternative’) represent the survey questions available in SPA surveys.

	Unimproved / No facility	No hand hygiene stations available or available but with no soap or water or alcohol based hand rub			No running water and soap NOR alcohol based hand rub			
Waste management service (M)	**Service level**	**M1**	**M2**	**M3**	**AM1**	**AM2**	**AM3**	**AM4**
	Basic Service	Waste safely segregated in consultation room	Infectious waste treated and disposed of safely	Sharps waste treated and disposed of safely	Infectious waste safely stored	Infectious waste safely disposed	Sharps waste safely stored	Sharps waste safely disposed
	Limited service	Bins are in place but not used effectively.	Waste is segregated but either infectious or sharps waste (or both) are not disposed of safely		A 'No' response for one to three of ANY of AM1, AM2, AM3, AM4			
	Unimproved / No facility	There are no bins for sharps and infectious waste	Waste is not safely treated and disposed	Waste is not safely treated and disposed	Infectious and sharps waste are neither safely stored nor safely disposed			

Data extraction and analysis

Estimating coverage. Data were extracted from publications and reports or from datasets if the datasets were publicly available. Indicators of environmental conditions and standard precaution items with comparable data from more than five countries were used to develop coverage estimates.

In some instances, more than one publication, report, and/or dataset was available for a single country. One was selected for each country for coverage estimation based on the following criteria: the most representative country-level data (e.g. selecting a nationally representative dataset when available; in the absence of nationally representative data, a sub-nationally representative dataset with the broadest national coverage was selected); the most comprehensive dataset in terms of indicators reported (e.g. reporting on all or most environmental conditions and standard precautions items); and the most recent dataset (by year). Each country estimate was weighted by facility type and each facility type (e.g. hospital, clinic) was weighted equally.

Data related to the essential environmental health standards, standard precautions items, and/or SDG indicator guidance with comparable data available from less than five countries were extracted and reported separately.

Descriptive analysis of water, sanitation, and hygiene service levels. The SDG service levels (or close approximations of them, as listed in Table 11) for water, sanitation, hygiene, and waste management were compared between countries using publicly-available datasets from the Service Provision Assessment (SPA) surveys available from the DHS Program (The DHS Program, 2011). The SPA datasets that were comparable and could be used to report the SDG service levels (or close approximations) were available from six countries: Bangladesh, Haiti, Malawi, Nepal, Senegal, and Tanzania.

Stata/SE 13.1 was used to perform statistical analysis. The *Svyset* command was used to account for complex survey design. The unit of analysis was the health care facility. Water sources and sanitation facilities were categorized using the JMP improved water source and improved sanitation facility criteria (WHO/UNICEF, 2014). Missing responses, and responses of "other" or "don't know" were categorized as unimproved per procedures applied by the JMP. Microsoft Excel was used to calculate and report service levels.

Country-level analyses. The six SPA country datasets were used to explore factors associated with the availability of basic water services in those countries. The availability of a basic water service was used as the dependent variable in the analysis; where the outcome is binary (where each HCF either had, or did not have a basic water service). Independent variables depended on the country and included rural-urban setting, facility type, and management authority. Facility types included clinics, hospitals, and dispensaries (where a dispensary is a small outpatient facility providing basic primary health services). Management authorities included government, private for-profit, and private not-for-profit (e.g. NGO, faith-based management authority). Univariable logistic regression and multivariable logistic regression were used to analyze associations between the dependent and independent variables.

Results

Search results

Data on environmental conditions and the availability of standard precautions items in HCFs were identified from 78 of 170 LMICs and territories (Table 12). These 78 countries represent 58% of the total population of LMICs. Most data were from sub-Saharan Africa (n=36 countries). According to the World Bank income classification, 27 (35%) were low-income countries, 32 (41%) were lower middle-income countries, and 20 (24%) were upper middle-income countries. Publicly available datasets were available for 14 of 78 countries (18%) in the analysis. For all others, data were extracted from reports. Data from 37 of 78 countries (47%) were nationally representative and 41 were sub-nationally representative (53%).

Table 12. Countries included in a study of environmental conditions and availability of standard precaution items in health care facilities in low- and middle-income countries

World Region	Countries	Number of countries included in this study (percent of this study)	Total countries and territories in each region (percent of countries represented in this study)	Percent of World Region population represented by countries and territories included in this study
Caucasus and Central Asia (CCC)	Azerbaijan (Bradley, 2006), Kyrgyzstan (Domashov I, 2011), Tajikistan (WHO, 2010), Uzbekistan (WHO, 2009)	4 (5%)	8 (50%)	54%
Eastern Asia (EA)	Mongolia (Spiegel et al., 2011)	1 (1%)	6 (17%)	<1%
Latin America and the Caribbean (LAC)	Barbados (MEASURE Evaluation, 2006a), Belize (IHME, 2014a), Bolivia (Goldberg, 2006), Dominica (MEASURE Evaluation, 2006b), Ecuador (Sullivan T, 2000), El Salvador (IHME, 2011), Grenada (MEASURE Evaluation, 2007a), Guatemala (IHME, 2014b), Guyana (Ministry of Health (MOH) [Guyana], 2005), Haiti (Institut Haïtien de l'Enfance (IHE) et ICF International, 2014), Honduras (IHME, 2013), Mexico (Aquil et al., 2010), Nicaragua (MEASURE Evaluation., 2001), Panama (IHME, 2014c), Paraguay (Gustavo Angeles, 1999), Peru (Macro International, 2009), Saint Lucia (MEASURE Evaluation, 2006c), Saint Vincent and Grenadines (MEASURE Evaluation, 2006d), Suriname (MEASURE Evaluation, 2007b)	19 (24%)	46 (41%)	39%
Northern Africa (NA)	Egypt (Ministry of Health and Population, 2005), Libya (El-Zanaty & Associates, 2012), Morocco (WHO, 2007a)	3 (4%)	6 (50%)	70%
Oceania (O)	Papua New Guinea (National Department of Health & Environmental Health Branch (EHB), 2015), Solomon Islands (WaterAid & UNICEF, 2016), Vanuatu (Zurovac et al., 2015)	3 (4%)	20 (15%)	78%
Southern Asia (SA)	Afghanistan (Ministry of Public Health (Islamic Republic of Afghanistan), 2009), Bangladesh (National Institute of Population Research and Training (NIPORT), Associates for Community Population Research (ACPR), & ICF International, 2016), Bhutan (Ministry of Health, 2009), India (National Rural Health Mission (NHRM) India, 2009), Nepal (Ministry of Health, New ERA, Nepal Health Sector Support Program (NHSSP), & ICF International, 2016), Pakistan (Majrooh, Hasnain, Akram, & Siddiqui, 2015), Sri Lanka (Taira et al., 2010)	7 (9%)	9 (78%)	18%
South-East Asia (SEA)	Cambodia (National Center for HIV/AIDS Dermatology and STD (NCHADS, 2009), Indonesia (National Population and Family Planning Board of Indonesia	4 (5%)	11 (36%)	52%

	(BKKBN), Gadjah Mada University (UGM), Hasanuddin University (UNHAS), North Sumatra University (USU), & Johns Hopkins University Bloomberg School of Public Health (JHSPH), 2015), Myanmar (The Republic of the Union of Myanmar & UNICEF, 2014), Timor Leste (Environmental Health Department, 2011)			
Sub-Saharan Africa (SSA)	Angola (Frøystad, Mæstad, & Villamil, 2011), Benin (Ministère de la Santé, 2015), Burkina Faso (Santé., 2014), Cameroon (Cameroon Ministry of Public Health, l'Institut de Formation et de Recherche Démographiques (IFORD), & World Bank, 2013), Chad (Gauthier B, 2004), Cote d'Ivoire (Kombe Gilbert, 2008), Democratic Republic of the Congo (Ministère de la Santé Publique (MSP), 2014), Eritrea (Ghebrehiwe et al., 2008), Ethiopia (Ethiopian Public Health Institute (EPHI), Federal Ministry of Health, & ICF International, 2014), Gambia (Ministry of Health & Social Welfare, United Nations Population Fund, United Nations Children's Fund, World Health Organization, & Averting Maternal Death and Disability Program/Mailman School of Public Health/Columbia University, 2012), Ghana (Institute for Health Metrics and Evaluation (IHME), 2015), Kenya (National Coordinating Agency for Population and Development (NCAPD) [Kenya], 2011), Liberia (Knowlton et al., 2013), Madagascar (Republic of Madagascar Vice Prime Ministry in Charge of Public Health et al., 2010), Malawi (Ministry of Health [Malawi] and ICF International, 2014), Mali (Pays., 2013), Mauritania (Republique Islamique de Mauritanie, 2016), Mozambique (Molina & Martin G, 2016), Namibia (Macro, 2010), Niger (Institut National de la Statistique, UNFPA, The Global Fund, & WHO, 2016), Nigeria (World Bank, 2013a), Republic of the Congo (Ministere de la sante et de la population, World Bank, AMDD, WHO, & UNFPA, 2014), Rwanda (National Institute of Statistics (NIS) [Rwanda], 2008), Senegal (Agence Nationale de la Statistique et de la Démographie (ANSD) [Sénégal] & ICF International, 2012), Sierra Leone (Sanitation., 2012), Somalia (Elkheir et al., 2014), South Africa (Health Systems Trust, 2004), South Sudan (Berendes, Lako, Whitson, Gould, & Valadez, 2014), Sudan (Abdelgader et al., 2012), Swaziland (Ministry of Health and Social Welfare (Kingdom of Swaziland), Ministry of Education (Kingdom of Swaziland), & WHO, 2008), Togo (WHO, 2012a), Uganda (WHO, 2012b), United Republic of Tanzania (Ministry of Health and Social Welfare (MoHSW) [Tanzania Mainland], Ministry of Health (MoH) [Zanzibar], National Bureau of Statistics (NBS), Office of the Chief Government Statistician (OCGS), & ICF International, 2015), Zambia (Ministry of Health, 2010), Zimbabwe (The Ministry of Health and Child Welfare (Zimbabwe), 2012)	36 (46%)	51 (71%)	97%
Western Asia (WA)	Iraq (USAID, 2011)	1 (1%)	13 (8%)	16%
	Total	78	170 (45%)	-

Coverage of environmental conditions in health care facilities

Estimated coverage of 21 indicators of environmental conditions and the availability of standard precaution items in health care facilities is presented in Table 13. Data availability varied by indicator. The most data were available for the indicator "use of an improved water source within 500 meters of the facility" which was representative of 128,155 HCFs. On average, data for 6.8 indicators were available from each country with a median of 5.5.

An estimated 50% of HCFs in LMICs lack a piped water source on premises, 33% lack improved sanitation facilities on premise, 39% lack soap for handwashing, 39% lack adequate infectious waste disposal, 73% lack sterilization equipment, 74% lack guidelines for standard precautions, and 59% lack reliable electricity.

Table 13. Coverage of environmental conditions and availability of standard precautions in health care facilities based on data from 78 low- and middle-income countries

Indicator	Estimated coverage	Number of countries in the estimate	Number of facilities in the estimate	Coverage in low-income countries	Number of low income countries	Coverage in lower middle-income countries	Number of lower middle-income countries	Coverage in upper middle-income countries	Number of upper middle-income countries
Improved water source within 500 meters	70.7%	71	129,557	65.2%	33	70.4%	26	81.0%	29
Piped water source on premises	50.3%	26	52,689	45.7%	11	48.3%	7	100.0%	13
Reliable electricity	41.2%	46	121,381	39.9%	27	40.4%	21	41.6%	17
Client toilet	67.4%	49	123,695	64.6%	27	67.9%	20	75.6%	19
Soap	60.8%	34	85,742	54.1%	14	60.9%	12	74.6%	14
Running water	54.3%	11	69,746	57.4%	7	54.3%	5	57.6%	6
Soap and running water	44.1%	10	66,355	43.2%	6	44.1%	5	50.6%	5
Alcohol-based hand disinfectant	29.5%	9	66,257	28.1%	6	29.5%	5	-	4
Soap and running water or alcohol-based hand disinfectant	62.2%	17	94,676	60.3%	13	62.2%	12	70.2%	5
Sterilization equipment	26.8%	25	71,048	27.7%	11	26.4%	9	22.7%	7
Equipment for high level disinfection	46.1%	6	54,349	-	4	-	4	-	2
Appropriate storage of infectious waste	39.3%	15	85,116	43.2%	12	39.6%	11	-	3
Appropriate disposal of infectious waste	60.9%	14	82,915	54.3%	12	63.7%	11	-	3
Disinfectant (e.g. chlorine solution for decontamination)	63.6%	35	108,022	63.1%	18	63.7%	16	66.4%	11
Latex gloves	76.5%	41	114,086	81.1%	22	76.7%	16	70.2%	15
Appropriate storage of sharps waste (e.g. sharps boxes)	74.7%	39	113,628	76.3%	22	74.7%	16	73.3%	16
Safe disposal of sharps	63.6%	17	91,382	58.7%	14	68.4%	11	80.2%	6
Disposable syringe	85.2%	30	96,218	86.9%	16	85.1%	12	80.6%	9
Guidelines for standard precautions	26.2%	19	95,708	28.6%	16	26.3%	12	22.5%	6
Gowns	43.7%	19	57,989	52.8%	6	44.2%	5	-	3
Eye protection	6.7%	9	55,613	5.3%	5	6.7%	5	-	2

Infrequently used questions related to environmental conditions in HCFs

Indicators for which data were available in less than five countries but are of importance to WaSH, environmental conditions, standard precautions, and the SDGs are presented in Table 14.

Table 14. Infrequently used questions related to environmental conditions and standard precautions in health care facilities

Country	Question topic	Findings
Bangladesh (National Institute of Population Research and Training (NIPORT) et al., 2016)	Separate toilets for men and women	The Bangladesh SPA reported 72% of facilities had access to toilets for clients; however, 26% of facilities had separate toilets for female clients.
El Salvador (IHME, 2011)	Availability of single use towels	11% of facilities had single use towels for hand drying after handwashing.
El Salvador (IHME, 2011)	Water availability	69% of facilities reported having a water source. 41% of facilities with a water source reported a severe shortage or lack of water occurring last year.
Ethiopia (Ethiopian Public Health Institute (EPHI) et al., 2014)	Health care facilities connected to the power grid	5% of health posts were connected to the power grid and 67% of other facility types (e.g. hospitals) were connected to the grid.
Indonesia (National Population and Family Planning Board of Indonesia (BKKBN) et al., 2015)	Handwashing area is near a sanitation facility	13% of facilities had no handwashing facilities. 57% had handwashing facilities but they were not near the sanitation facilities and 30% had handwashing facilities that were near sanitation facilities.
Nepal	Is the toilet disability accessible	93% of facilities did not have a disability accessible toilet.
Nigeria (World Bank, 2013a)	Staff received training in health care waste management	Staff at 28% of facilities have received training in health care waste management; 72% have not.
Pakistan (Majrooh et al., 2015)	Separate toilets for men and women	88% of HCFs had a toilet available; however, only 20% had separate toilets for men and women.
Solomon Islands (WaterAid & UNICEF, 2016)	Some or all of the toilet facilities are accessible to people with disabilities	43% had at least one toilet which was accessible to persons with limited mobility and 57% of facilities did not.

SDG service levels for water, sanitation, hygiene, and waste management

Service levels for water, sanitation, hygiene, and waste management were calculated using SPA survey data from Bangladesh, Haiti, Malawi, Nepal, Senegal, and Tanzania (Figure 6). The service levels closely approximate the SDG service levels developed by the JMP for monitoring of SDG 6 (Table 11). Of these five countries, Senegal had the highest percentage of HCFs with basic water services (61%) while Tanzania had the lowest (30%). Bangladesh had the highest percentage of facilities with sanitation piped to sewer (17%) and Nepal had the lowest (6%). Senegal had the highest availability of handwashing materials (86%) while Nepal had the lowest (55%). Nine percent of HCFs in Bangladesh and Senegal provide all basic WaSH services; the percentages were lower for Malawi (7%), Haiti (5%), Tanzania (4%), and Nepal (3%) with a facility-weighted average of 7% across all six countries. In a facility-weighted average of the six countries, 2% of facilities provide all four of the SDG benchmark (or close approximation) for basic water, sanitation, hygiene and waste management.

Figure 6. SDG service levels for water, sanitation, hygiene, and waste management in Bangladesh, Haiti, Malawi, Senegal, and Tanzania

Differences in availability of basic water services

Using the six SPA country datasets, inequalities in the availability of basic water services at HCFs were tabulated (Table 15). Differences between urban and rural settings were largest in Senegal (30.2%) and smallest in Haiti (14.9%). Differences between administrative units (e.g. districts, regions) were largest in Senegal (66.7%) and smallest in Malawi (8.3%). Differences between managing authorities (e.g. private-for-profit, private not-for-profit, government) were largest in Bangladesh (44.9%) and smallest in Senegal (13.2%). In all five countries, government-managed HCFs had the lowest coverage. Differences between facility types were largest in Senegal (67.1%) and smallest in Haiti (36%). Hospitals had the highest coverage in all five countries. Differences between facilities with inpatient services and those with outpatient services only were largest in Senegal (23.2%) and smallest in Malawi (0.1%).

Table 15. Differences in availability of basic water services in Bangladesh, Haiti, Malawi, Nepal, Senegal, and Tanzania

Unit of comparison	Difference in coverage	Bangladesh	Haiti	Malawi	Nepal	Senegal	Tanzania
Urban and rural settings	Urban	76.6%	45.2%	62.8%	-	80.0%	50.8%
	Rural	46.8%	30.3%	45.1%	-	49.8%	22.2%
	Difference	29.7%	14.9%	17.7%	-	30.2%	28.6%
Sub-national administrative area (e.g. district, region)	With highest coverage	72.8% (Rangpur)	52.9% (Sud)	54.3% (South)	46.6% (Eastern)	82.4% (Louga)	-
	With lowest coverage	35.3% (Barisal)	16.7% (Nord-Ouest)	46.0% (Central)	33.3% (mid-west)	15.7% (Kédougou)	-
	Difference	37.5%	36.2%	8.3%	13.3%	66.7%	-
Managing authorities	With highest coverage	92.0% (Local government)	47.0% (NGO/private not for profit)	76.7% (Company)	73.9% (NGO/private)	72.5% (Private)	57.1% (private for-profit)
	With lowest coverage	47.1% (Government)	28.6% (Government)	43.5% (Government)	39.3% (Government)	59.3% (Government)	20.1% (Parastatal)
	Difference	44.9%	18.4%	33.2%	34.6%	13.2%	37.0%
Facility types	With highest coverage	83.3% (NGO hospital)	56.9% (Hospital)	100% (Central Hospital)	71.0% (Hospital)	95.1% (Hospitals)	62.7% (Private hospitals)
	With lowest coverage	45.2% (Community clinic)	20.9% (Dispensary)	28.8% (Health post)	32.1% (sub-health post)	28.0% (Health clinic, Case de santé)	22.2% (National referral hospital)
	Difference	38.1%	36.0%	71.2%	38.9%	67.1%	40.5%
Inpatient versus outpatient	Inpatient service provided	49.8%	45.8%	50.7%	-	89.4%	28.4%
	Outpatient service only	49.2%	35.6%	50.6%	-	66.2%	30.0%
	Difference	0.6%	10.3%	0.1%	-	23.2%	1.6%

In univariable regression analysis, there was a significant association between the availability of a basic water service and urban-rural setting; in all five countries, HCFs in rural settings had significantly lower odds of having a basic water service as compared to HCFs in urban settings (Table 16). The relationship was significant in the multivariable models of Malawi (OR: 0.53, 95% CI: 0.37-0.75), Senegal (OR: 0.31, 95% CI: 0.17-0.59), and Tanzania (OR: 0.41, 95% CI: 0.25-0.68).

The significance of managing authority differed by country – where in univariable regression in Bangladesh and Haiti, NGO-managed HCFs had significantly higher odds of having a basic water service as compared to government-managed facilities. NGO-managed HCFs in Malawi had significantly higher odds of a basic water service as compared to government facilities in univariable regression but not the multivariable model. Mission and faith-based managed HCFs had significantly higher odds of having a basic water service as compared to government managed HCFs, whereas in univariable and multivariable analyses of Bangladesh and Tanzania, private-for-profit facilities had significantly higher odds of having a basic water service as compared to government-managed facilities.

In univariable and multivariable analyses by facility type in Bangladesh, health and family welfare centers and clinics had significantly lower odds of having a basic water service as compared to hospitals (health and family welfare centers OR: 0.56, 95% CI: 0.32-0.96; clinics OR: 0.48, 95% CI: 0.28-0.81). In univariable and multivariable analyses of Haiti, health centers without beds and dispensaries were significantly less likely to have a basic water service as compared to hospitals (OR: 0.57, 95% CI: 0.36-0.90). In univariable analysis in Malawi, health centers and dispensaries had significantly lower odds of having a basic water service as compared to hospitals. In univariable and multivariable analyses in Senegal, health centers, health posts, and health houses had significantly lower odds of having a basic water service as compared to hospitals. In univariable and multivariable analyses in Tanzania, dispensaries had significantly lower odds of having a basic water service as compared to hospitals (OR: 0.54, 95% CI: 0.35-0.85).

Table 16. Unadjusted and adjusted logistic regression results for factors associated with the availability of basic water services in health care facilities in six countries

Country	Urban vs. rural (reference: urban)			Managing authority (reference: public facility)									Facility type (reference: hospital)									Inpatient vs. no inpatient (reference: inpatient service provided)		
Bangladesh	**Urban vs. rural**			**NGO**			**Local government**			**Private for profit**			**Health and family welfare center**			**Clinic**			**Dispensary**			**Inpatient**		
(N=1165)	OR	CI	p	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value
Crude	0.26	(0.19, 0.38)	**<0.001**	2.7	(1.7, 4.3)	**<0.001**	12.9	(2.5, 66.4)	**0.002**	5.4	(2.76, 10.5)	**<0.001**	0.32	(0.22, 0.47)	**<0.001**	0.3	(0.21, 0.43)	**<0.001**	0.34	(0.22, 0.53)	**<0.001**	0.98	(0.61, 1.58)	0.929
Adjusted	0.66	(0.37, 1.18)	0.16	2.19	(1.13, 4.23)	**0.021**	8.92	(1.56, 51.3)	**0.014**	2.39	(1.10, 5.17)	**0.028**	0.56	(0.32, 0.96)	**0.035**	0.48	(0.28, 0.81)	**0.006**	0.59	(0.33, 1.04)	0.068	1.11	(0.67, 1.85)	0.67
Haiti	**Urban vs. rural**			**NGO**			**Mission/faith-based**			**Private for profit**			**Health center with beds**			**Health center without beds**			**Dispensary**			**Inpatient**		
(N=907)	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value
Crude	0.53	(0.40, 0.69)	**<0.001**	2.21	(1.5, 3.2)	**<0.001**	1.31	(0.89, 1.92)	0.175	1.74	(1.2, 2.5)	**0.003**	0.96	(0.59, 1.58)	0.88	0.61	(0.40, 0.94)	**0.024**	0.24	(0.15, 0.37)	**<0.001**	0.65	(0.36, 1.17)	0.152
Adjusted	0.9	(0.64, 1.26)	0.527	1.99	(1.33, 2.97)	**0.001**	1.29	(0.86, 1.92)	0.215	1.45	(0.99, 2.13)	0.057	0.99	(0.59, 1.67)	0.983	0.57	(0.36, 0.90)	**0.015**	0.26	(0.15, 0.43)	**<0.001**	1.12	(0.58, 2.19)	0.732
Malawi	**Urban vs. rural**			**NGO**			**Faith based**			**Private for profit**			**Health center**			**Clinic**			**Dispensary**			**Inpatient**		
(N=977)	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value
Crude	0.49	(0.37, 0.64)	**<0.001**	2.23	(1.26, 3.94)	**0.006**	1.7	(1.20, 2.44)	**0.003**	1.67	(1.24, 2.25)	**0.001**	0.58	(0.39, 0.88)	**0.01**	0.86	(0.56, 1.33)	0.508	0.39	(0.20, 0.80)	**0.01**	1	(0.43, 2.33)	0.991
Adjusted	0.53	(0.37, 0.75)	**<0.001**	1.71	(0.86, 3.38)	0.12	1.64	(1.13, 2.38)	**0.008**	1.35	(0.84, 2.19)	0.216	0.88	(0.55, 1.39)	0.573	0.78	(0.45, 1.36)	0.385	0.64	(0.31, 1.32)	0.225	0.97	(0.37, 0.75)	0.941
Nepal (N = 992)	**Urban vs. rural**			**NGO/ private for-profit**			**-**			**Private for profit**			**Primary health care center**			**Health post**			**Sub-health post**			**Inpatient**		
	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value
Crude	-	-	-	4.38	(2.41, 7.95)	**<0.001**	-	-	-	4.17	(2.41, 7.23)	**<0.001**	0.46	(0.29, 0.73)	**0.001**	0.29	(0.19, 0.45)	**<0.001**	0.19	(0.11, 0.34)	**<0.001**	-	-	-
Adjusted	-	-	-	2.73	(1.46, 5.09)	**0.002**	-	-	-	1.72	(0.90, 3.30)	0.101	0.57	(0.35, 0.94)	**0.027**	0.45	(0.28, 0.72)	**0.001**	0.3	(0.17, 0.54)	**<0.001**	-	-	-
Senegal	**Urban vs. rural**			**NGO**			**Private religious**			**Private**			**Health center**			**Health post**			**Health house**			**Inpatient***		
(N=438)	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value
Crude	0.25	(0.15, 0.41)	**<0.001**	0.47	(0.05, 4.89)	0.53	1.57	(0.48, 5.15)	0.454	1.81	(0.84- 3.91)	0.129	0.09	(0.02- 0.52)	**0.006**	0.1	(0.02, 0.50)	**0.005**	0.02	(0.01, 0.11)	**<0.001**	0.23	0.06, 0.93)	**0.039**
Adjusted	0.31	(0.17, 0.59)	**<0.001**	1.49	(0.11, 21.1)	0.767	0.89	(0.26, 3.11)	0.857	0.56	(0.22, 1.41)	0.22	0.09	(0.02, 0.49)	**0.005**	0.15	(0.03, 0.75)	**0.021**	0.04	(0.01, 0.24)	**<0.001**	-	-	-
Tanzania	**Urban vs. rural**			**Parastatal**			**Mission/faith-based**			**Private for profit**			**Health centre**			**Clinic**			**Dispensary**			**Inpatient**		
(N = 1200)	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value	OR	CI	p-value
Crude	0.28	(0.18, 0.41)	**<0.001**	0.88	(0.27, 2.83)	0.82	3	(1.77, 5.04)	**<0.001**	4.64	(2.70, 7.98)	**<0.001**	0.65	(0.43, 0.96)	**0.035**	1.03	(0.55, 1.93)	0.919	0.34	(0.23- 0.51)	**<0.001**	1.08	(0.43- 2.70)	0.867
Adjusted	0.41	(0.25, 0.68)	**0.001**	0.64	(0.18, 2.24)	0.48	2.56	(1.46, 4.47)	**0.001**	2.7	(1.31, 5.57)	**0.007**	0.93	(0.60, 1.44)	0.74	0.43	(0.19, 0.98)	**0.046**	0.54	(0.35- 0.85)	**0.007**	1.35	(0.51- 3.59)	0.55

Discussion

This study is the most comprehensive assessment of environmental conditions, WaSH, and availability of standard precautions items in HCFs in LMICs conducted to-date; with 21 different indicators documented, many for the first time. This is the first study to estimate SDG service levels using available monitoring data.

Data on environmental conditions and the availability of standard precaution items in HCFs were available from 78 LMICs and were representative of as many as 129,557 facilities. The data are from countries that represent nearly 60% of the population of all LMICs. Most HCFs in LMICs have inadequate environmental conditions and insufficient availability of standard precaution items: an estimated 50% of HCFs lack piped water on-premise, 33% lack improved sanitation facilities on the facility premises, 39% lack soap for handwashing, 39% lack adequate infectious waste disposal, 73% lack sterilization equipment, 74% lack guidelines for standard precautions, and 59% lack reliable electricity.

Facility-weighted averages of comparable nationally representative facility surveys from Bangladesh, Haiti, Malawi, Senegal, and Tanzania suggest that 7% of health care facilities in these countries provide all of basic water, sanitation, and hygiene; and 3% of health care facilities provide all of basic water, sanitation, hygiene, and waste management. This is similar to household-level coverage of basic WaSH, where a study estimated that combined household-level basic WaSH coverage (as defined by SDG benchmarks) in 25 sub-Saharan Africa countries was 4% (Roche, Bain, & Cumming, 2017).

There is little evidence on the factors associated with low service levels in HCFs. Significant differences in coverage exist between health care facilities in urban and rural settings, at the sub-national level, by managing authority, and by facility type. We found that

HCFs in rural settings had lower services than those in urban settings. This is similar to the situation for water and sanitation use in household settings (Bain, Wright, Christenson, & Bartram, 2014); and is an underlying challenge to provision of safe health care in rural areas (WHO/UNICEF, 2015b). Unsurprisingly, hospitals had consistently higher coverage of basic water services as compared to all other facility types. More resources are likely invested in hospitals as they serve a greater patient volume than smaller facility types (Campbell et al., 2016). Privately-managed facilities consistently had higher levels of basic water coverage than government managed facilities. Facilities managed by NGO and faith-based organizations may receive more external support (e.g. financial, human resources, supplies) than public facilities which may explain why coverage is higher; though there is a need to better understand the policy context and resource limitations in government-managed HCFs (Olivier et al., 2015).

There are many data gaps. Most HCF data concern Sub-Saharan Africa but few were available for Latin America and the Caribbean, Western Asia, South East Asia, and Oceania. Data from these regions are needed to understand the extent and distribution of inadequate coverage – especially in Western and South-East Asia where a substantial proportion of the LMIC population lives.

Because not all LMICs were represented in this study, our estimates may be inaccurate. Inaccuracy is likely to occur due to countries not included in the estimates (due to data unavailability), some large population countries that are excluded (e.g. China), data included in the estimates that are sub-nationally representative (e.g. India), and data included in the estimates that are only representative of specific facility types in a country (e.g. facilities that provide services for HIV/AIDS care). The estimates may also be inaccurate because data from some countries were older than others (e.g. Peru data from 2008). However, our estimates are in broad agreement with previous estimates. For example, as compared to a WHO/UNICEF report on WaSH in health care facilities which represented 66,101 facilities in 54 LMICs, our estimate for "access to an improved source within 500m" is higher compared to the WHO/UNICEF report (62% in the WHO/UNICEF report; 71% in our estimate); sanitation is lower (81% in the WHO/UNICEF report; 67% in our estimate); and soap for handwashing is slightly lower (65% in the WHO/UNICEF report; 61% in our estimate) (World Health Organization and UNICEF, 2015). Our findings are also comparable with a study reporting 66% of hospitals in LMICs as having water available in the facility (Chawla et al., 2016).

Study limitations

Some countries and world regions may have been under-represented because the search strategy was conducted in English. Some data from peer-reviewed studies may have been missed. Government monitoring data are not always publicly available and may have been excluded when this was the case.

The questions used in survey instruments had some small differences. While the design and implementation of the Service Provision Assessment (SPA) and Service Availability and Readiness Assessment (SARA) instruments (two nationally-representative facility surveys implemented by the DHS Program and the World Health Organization, respectively) were coordinated and harmonized to increase data comparability; WaSH, environmental conditions, and the availability of standard precaution items were not the primary purpose of other assessments such as the Emergency Obstetric and Newborn Care

(EmONC) surveys and the WHO Tool for Situational Analysis to Assess Emergency and Essential Surgical Care. In these assessments, questions such as “was running water available” were used instead of the more commonly used water source survey question on “use of an improved water source” (MEASURE Evaluation, 2016; World Health Organization, 2010).

Few datasets were publicly available (13 of 75, 17% total) so many of the data used to generate the coverage estimates were extracted from reports. This meant that much of the data could not be disaggregated beyond that provided in the reports, limiting our reporting of coverage by facility type, managing authority, and other factors. This also meant that we had to weight facilities equally in the coverage estimates despite differences in size and patient volume served.

Fewer data were available for some indicators as compared to others (e.g. data on the availability of alcohol-based hand disinfectant were available from 66,257 facilities versus 85,664 facilities for handwashing soap), which may affect the reliability of coverage estimates.

Implications for monitoring

We reveal important new insights on the situation in HCFs and previously undocumented inequalities. There are several opportunities to increase value from HCF monitoring. Administrators of HCF monitoring initiatives should consider reviewing their monitoring instruments and refining existing questions to maximize value and include questions on essential environmental health standards, the SDG indicators, indicators of service quality, important stratifying factors, and questions that reflect adequacy for infection control. To prevent monitoring instruments from increasing in size, these questions should either replace lower value questions in monitoring instruments or questions on different HCF topics could similarly be refined to reduce the total number of questions. Poor environmental conditions represent a substantial health risk in HCFs and more information on these would inform better decision-making.

Present HCF monitoring instruments do not measure all essential environmental health standards, the SDG indicators, indicators of service quality, and/or important stratifying indicators (WHO, 2007b; WHO/UNICEF, 2016a; World Health Organization, 2008). For example, safely managed water and sanitation are important components of SDG 6 and questions to measure safely managed water and sanitation are recommended in JMP guidelines (Bain, Cronk, Wright, et al., 2014; WHO/UNICEF, 2015b, 2017). However, none of the nationally representative survey instruments such as the SPA or SARA measured water quality or safe disposal of fecal wastes. Quality health care services are an important component of SDG 3 yet no HCF-specific monitoring initiatives include questions on wastewater disposal, cleaning, laundry, or vector control (World Health Organization, 2008).

Disaggregating HCF data by factors such as facility type, accessibility of services by gender and disability status is an important component of the SDGs yet few instruments include these. Data from those that did include these factors suggest substantial inequalities exist. For example, in Pakistan and Bangladesh, many HCFs had toilets available, but few had separate toilets for women (Majrooh et al., 2015; National Institute of Population Research and Training (NIPORT) et al., 2016). In the Solomon Islands, few HCFs had toilets accessible by disabled persons (WaterAid & UNICEF, 2016). Inadequate services disproportionately affect certain types of people, for example, people who receive health care in rural areas, patients who are disabled, patients with limited mobility (e.g. elderly) and expectant mothers (Cronk et al., 2015).

Monitoring instruments should go beyond the SDG indicators and include questions that provide more usable information that reflects adequacy for infection prevention and outbreaks prevention – especially for facilities providing specialized care. For example, a health care facility that has improved, gender-separated, disability-accessible latrines for patients and visitors and a separate dedicated facility for staff would meet the SDG criteria for basic sanitation. “Improved” sanitation facilities, such as ventilated improved pit latrines, are not sufficient for managing infectious fecal wastes. Transmission of infection from waste leakage into the surrounding environment may contribute to larger outbreaks (Cairncross, Blumenthal, Kolsky, Moraes, & Tayeh, 1996; Levine, Khan, D'Souza, & Nalin, 1976). Safe water management is important to prevent nosocomial infection caused by pathogens such as *Pseudomonas aeruginosa* and nontuberculous mycobacteria in piped water in facilities (Anaissie et al., 2002; Li et al., 2016). To mitigate infection, standards should be more stringent for facility types providing intensive patient care with a higher risk of infection (e.g. intensive care unit) and conduct high risk procedures. For example, a hospital with a burn wound unit should have risk management plans in place such as building-level water safety plans (World Health Organization, 2011). Questions in monitoring instruments and service level benchmarks should reflect this.

Aggregating HCFs for coverage estimates is challenging. Facilities are of different sizes, serve different types of patients, and serve different patient volumes. Equal weighting of HCFs in coverage estimates – which was the approach used in every facility survey and in the calculations for this study – distort estimates of human exposure to low levels of service.

Use of facility weights (different from survey sample weights) may better represent the situation. For example, facilities might be weighted by the volume of deliveries (Gon et al., 2016), average daily or weekly patient volume, or number of patient beds available. Data to support such weighting are not available in many survey instruments.

Facilities are classified differently (e.g. clinic, health center, health post) depending on the country and/or survey instrument. There is no internationally-accepted typology for HCFs (WHO/UNICEF, 2016a). A typology and the ability to assign facilities (e.g. health house; health and family welfare center) to a type would facilitate data pooling, sharing, and comparison.

Improvements to monitoring would increase the quality and comparability of data over space and time; inform burden of disease estimates at the sub-national, national, and international levels; enable actors to identify which conditions represent the greatest disease burden; and provide information that can be used to make improvements to environmental conditions in HCFs.

Implications for public health practice and policy

The health consequences of inadequate environmental conditions and the preventable illness and cost savings that could be achieved suggest urgent attention and prioritization of resources are needed to improve the situation in many LMICs. Our estimates suggest that half of HCFs lack piped water on the facility premises. A lack of piped creates challenges for handwashing, performing surgeries, performing safe deliveries, and cleaning (Benova, Cumming, & Campbell, 2014; Benova, Cumming, Gordon, et al., 2014; Velleman et al., 2014; World Health Organization, 2010; World Health Organization and UNICEF, 2015).

Nearly three in five facilities have unreliable electrical supplies. Intermittent electricity can create facility hazards and limit patient care: sterilization equipment cannot be operated, lighting is inadequate to perform procedures at night and in under-illuminated rooms, and electrically-powered tools for procedures cannot be used (Adair-Rohani et al., 2013).

Poor conditions were not exclusive to low-income countries – many lower-middle and upper-middle income countries had comparatively low coverage or less than universal coverage for many indicators. For example, 70% of HCFs in lower-middle income countries and 64% of HCFs in upper-middle income countries had disposable gloves available. This suggests that basic surveys, such as the DHS Program’s Service Provision Assessment, may be relevant in high income countries, especially in rural areas where health care service delivery is a challenge.

National government agencies and external support actors could make better use of monitoring data to target resources and progressively improve services to achieve universal coverage of basic services. In some instances, health care facility censuses were conducted which provide resource targeting opportunities as compared to sample surveys. For example, using censuses conducted in Haiti and Malawi it is possible to identify the specific facilities that have poor conditions and services (Institut Haïtien de l’Enfance (IHE) et ICF International, 2013; Ministry of Health [Malawi] and ICF International, 2014).

Many sub-national and specialized monitoring instruments provide more detail at the facility-level as compared to more general national monitoring instruments such as the SPA and SARA. For example, specialized monitoring instruments such as the EmONC assessment and the WHO Tool for Situational Analysis to Assess Emergency and Essential Surgical Care provide specific data on conditions in units within HCFs (e.g. labor and delivery wards; surgical suites) (MEASURE Evaluation, 2016; World Health Organization, 2010). These can be used to identify improvement opportunities in specific settings within HCFs as this information is rarely available in nationally representative instruments.

Poor data availability is a challenge – where most data on environmental conditions and standard precautions are only available in reports. The datasets used to create the reports are often not publicly available and these could be analyzed beyond their original use. The benefits of data availability and public data repositories are clear for government stakeholders and external support actors responsible for conducing HCF monitoring. Open access data enables sharing for pooling of data, comparison, and learning.

Monitoring data can be used to inform facility-level improvements. Once low coverage areas are identified, facility managers, infection prevention and control practitioners, and program managers might collaborate to identify simple technology and low-cost solutions to improve the situation progressively. For example, Bennett *et al.* (2015) found in Kenya that 15 months after installing low-cost, portable handwashing stations and simple drinking water stations with drinking water treatment, coupled with health care provider training, there was successful adoption and sustained use of the stations, despite the absence of piped water (Bennett et al., 2015).

Government actors may adopt standards higher than the minima sought under the SDGs. Higher levels of service are necessary to protect patients and health care workers. This study shows that many health care facilities rely on water sources that are not safe, on-site or available year-round. Governments and external support agencies (including faith-based should upgrade services to ensure that *all* HCFs have sufficient, continuously-available, safe piped water in the facility. Sanitation facilities that safely manage patient fecal wastes are imperative to prevent infection in the HCF and nearby communities (World Health Organization and UNICEF, 2015).

Bartram *et al.* (2015) note that hardware interventions and the availability of standard precaution items are necessary but not sufficient; and improvements must also include strengthening of the enabling environment and systems that support environmental health in health care facilities. Governments should establish national standards and policies, invest in building human resource capacity, and improve coordination of related health initiatives, such as universal health coverage, infection prevention, and maternal and child health programming. To assist with such efforts, in 2015 the World Health Organization launched an action plan for WaSH and environmental health in health care facilities – aimed at supporting best practice and improving advocacy and leadership; monitoring and evaluation; evidence and operational research; and policy, standards, and facility improvements (WHO/UNICEF, 2015d).

Implications and priorities for research

There are several low-cost opportunities for exploratory research using available data to gain further insight on the status of HCFs and factors associated with low service levels. They include geospatial analysis of inequalities in coverage (and linking these data to other geospatial data to enable more explanatory power); detailed analyses of sub-national regions to better target of resources; use of the data to model regional estimates of coverage (e.g. sub-Saharan Africa; South East Asia); and using the data for exposure estimates for burden of disease modeling.

While we demonstrate that there is substantial data available describing the status of conditions, evidence on effectiveness of approaches and programs for improving environmental health in health care settings in LMICs is urgently needed. At the facility level, there are opportunities for researchers to partner with HCF practitioners to conduct qualitative research, operational research, and continuous quality improvement projects to identify and implement improvement opportunities. Qualitative research would provide insight into enablers and barriers of a safe health care environment and contribute to understanding the motivations influencing health care workers and others to improve services. Operational research could identify which approaches and programs are most effective in reducing infection. Continuous quality improvement projects help identify bottlenecks that prevent adequate environmental conditions and deliver improvement solutions.

Conclusion

Sufficient environmental conditions and the availability of standard precautions in HCFs are critical for human health and safe patient care. Using publicly-available monitoring data, our findings reveal a hidden but fixable crisis – many HCFs in LMICs lack adequate WaSH, environmental conditions, and the most basic standard precaution items to prevent infection. We identified important, previously undocumented inequalities in coverage of services. The analyses in this study are important for actors improving HCF conditions to develop evidence-based policies and efficient programs to target resources to facilities with inadequate services. With leadership from government and external support actors, HCFs can become models of dignified, safe and people-centered care. The maxim *primum non nocere* (first do no harm) – could not be more apposite.

CHAPTER 6: USING MONITORING DATA TO COMPARE COUNTRY PERFORMANCE IN REALIZING UNIVERSAL ACCESS TO DRINKING WATER AND SANITATION

Introduction

Water, sanitation, and hygiene (WaSH) are long-recognized as important for human health, well-being, and development (Bartram & Cairncross, 2010). Global burden of disease estimates show that 842,000 deaths could have been prevented in 2012 through adequate drinking water, sanitation, and hand hygiene (Pruss-Ustun et al., 2014).

Water and sanitation have featured prominently in human development policy. Program, national, and global monitoring of sanitation and drinking water is carried out in response to policy and political prioritization. Monitoring is important to track progress, improve accountability, and demonstrate impact (Bartram et al., 2014).

Water and sanitation are recognized as human rights. The principle of progressive realization requires that each government takes steps “to the maximum of its available resources, with a view to achieving progressively the full realization of the rights” (United Nations General Assembly, 2010). The United Nations (UN) General Assembly’s 2010 Resolution on the Human Right to Water and Sanitation calls upon governments “to scale up efforts to provide safe, clean, accessible and affordable drinking water and sanitation for all” (United Nations General Assembly, 2010).

In September 2015, the UN launched the Sustainable Development Goals (SDGs) (United Nations General Assembly, 2015). Human development and human rights policy converge in the SDGs. SDG targets call for universal access to basic WaSH, WaSH in non-household settings (schools and health care facilities), progressive reduction in inequalities, and improvements in service levels to safely managed water and sanitation (United Nations General Assembly, 2015; WHO/UNICEF, 2015b). For drinking water, elements of safely managed water include a basic improved drinking water source, water available on premises, water available when needed, and compliant with microbial and chemical standards. For safely managed sanitation, elements include a basic sanitation facility that is not shared and excreta are safely disposed or transported and treated off-site (WHO/UNICEF, 2015a).

Monitoring to assess progress toward SDG targets focuses on levels of coverage. Important additional insight would be obtained by complementing coverage with an instrument to measure country performance in improving the use of – and equality of use of – safe water and sanitation and measure progressive realization of the human rights to water and sanitation (Meier et al., 2016).

When comparing drinking water and sanitation coverage among countries, high coverage countries are primarily high-income countries and low coverage countries are primarily low-income, which does not provide meaningful comparison. An alternative approach compares rates of change in coverage. However, countries are at different levels of water and sanitation development. When comparing levels of coverage with rates of change, rates tend to increase at low levels of coverage, plateau at intermediate levels of coverage, and slow as they approach 100% coverage (Luh, Baum, & Bartram, 2013). Fair country comparison compares country rates of change to best-in-class rates at each level of coverage.

Frontier analysis, a method used to study best-in-class performance, enables fair comparison of countries at different levels of water and sanitation development (Luh et al., 2016). It has been used to measure the performance of schools, factories, and hospitals and has been applied to measure human rights realization (Fukuda-Parr, Lawson-Remer, & Randolph, 2009; Luh et al., 2013).

In this article, we use frontier analysis to explore country performance on different indicators of drinking water and sanitation progress. We relate these to country attributes, such as Gross Domestic Product, the level of policy development, and governance effectiveness, to identify underlying determinants of performance.

Methods

Data sources and measures of country progress

The WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation (JMP) compiles internationally comparable data on drinking water and sanitation. For global monitoring and reporting of the water and sanitation SDGs it uses the "improved water source" and "improve sanitation facility" indicators. For water, source types such as piped water and boreholes are considered "improved" while open dug wells and surface waters are considered "unimproved." For sanitation, improved source types are those that separate human waste from human contact. Improved source types include flush toilets, septic tanks, and composting toilets while unimproved source types are pit latrines without slabs, shared sanitation, or open defecation (WHO/UNICEF, 2014).

National-level data on the proportion of the population using improved drinking water and sanitation (coverage points) were obtained from JMP Country Files. These data are compiled from nationally-representative sources including Demographic and Health Surveys (DHS), Multiple Indicator Cluster Survey (MICS), World Health Surveys (WHS), and national censuses (WHO/UNICEF, 2015c).

Assessing country progress requires the use of standard indicators which are collected in many countries over time. Data that meet these requirements are not available to measure all elements of safely managed drinking water and sanitation. Global estimates of water quality have been developed, but these are not representative at the country level or representative of rural and urban areas in each country (Bain, Cronk, Hossain, et al., 2014; Bain, Cronk, Wright, et al., 2014; Onda, LoBuglio, & Bartram, 2012). Estimates of piped water system continuity (a proxy for water service availability) are only available for piped water systems managed by utilities (Kumpel & Nelson, 2016; Van den Berg & Danilenko, 2011). Estimates of the functionality of point sources, such as boreholes with handpumps, are unreliable and global estimates are not available. Global estimates of the use of an improved water source on-premise have been developed, but these estimates are not available from each country over time (Cumming, Elliott, Overbo, & Bartram, 2014). Instead, the best approximation for basic water and sanitation were used based on JMP data availability: use of an improved water source and use of an improved sanitation facility.

Four indicators of country progress were developed: water access performance; water equality performance; sanitation access performance; and sanitation equality performance. Country progress is the rate of change of the proportion of the population using an improved water source or sanitation facility (i.e. coverage). The equality performance indicators use the rate of change of the gap in coverage between rural and urban settings. Countries have a decreasing gap between rural and urban coverage (i.e. increasing equality) or an increasing gap between rural and urban coverage (i.e. decreasing equality).

Calculation of rates of change

The line of best fit between each series of three consecutive coverage points for each country was calculated (i.e., a three-point moving average). Countries have more than one rate if they have four or more coverage points – each corresponding to a different time in their development. When there were multiple coverage points from the same year for a country, data for that year were averaged to generate one coverage point. The country rate of change is the slope of the best-fit line. A three-point moving average was selected rather than the slope of all available coverage points to capture change in rate over time. The performance rankings in this article are based on the most recent three coverage points for each country. This process was performed for each of the components.

Data from 212 countries and territories were reviewed. Country data were excluded if countries achieved 100% coverage for the respective indicator or if there were less than three coverage points.

Calculating the performance frontier and identifying best-in-class performance

Frontier analysis was conducted using the FEAR software package in R version i386 3.1.1 (Wilson, 2008). Frontier analysis best practice was followed and FEAR was used to identify outliers which were removed when defining the performance frontier (Andrews & Pregibon, 1978; Wilson, 1993). The software used the rates of change from all countries to identify performance frontier points, each representing best-in-class performance.

A straight line between the performance frontier points was used to define best-in-class performance values at any level of coverage. Since countries can no longer improve once they reach 100% coverage or eliminate inequality (for a specific indicator, such as improved water), the line defining the performance frontier ended at 100% coverage and 0% rate of change.

Comparing country performance and best-in-class performance

To generate a value for each indicator of country progress that enables country comparison, each country rate was divided by the best-in-class country rate. This compares country rates to best-in-class performance and generates a value between -1 and 1, enabling fair comparison between countries. Values between 0 and 1 represent progress while values between 0 and -1 represent retrogression. Values of 1 lie along the performance frontier, reflecting best-in-class performance. Outliers were manually assigned a value of either 1 or -1. This process was repeated for each country and each of the performance indicators.

Comparing trends in performance

The values for country performance change over time. Trends in these values show whether country performance is improving or deteriorating. To examine trends in performance, the slopes of all available performance values from each country were calculated. For all countries where slopes could be calculated, three groups were calculated: either improving, unchanged or deteriorating. Countries with only one value for any given performance indicator were not categorized (listed as “N/A”). Countries with positive values (between 0 and 1) were grouped and countries with negative values (with values between -1 and 0) were grouped. Trends should be interpreted alongside performance values because, for example, a country might have a positive trend but negative performance value or vice versa.

Correlations between country performance and country indicators

Associations between country performance and country indicators were examined using linear regression to explore potential underlying drivers of performance (Table 17). Country characteristics and governance indicators, representing the enabling environment, were used from publicly available datasets (World Bank, 2013b, 2014). The enabling environment is "a favorable culture of internal coordination and communication; policy and institutional behavior that guides the behavior of water and sanitation service providers with clear and enforceable service standards, and resources to provide effective water and sanitation services" (Amjad et al., 2015).

Table 17. Country characteristic and governance attributes

Indicator	Indicator description
Source: World Development Indicators (2013) (World Bank, 2013b)	
Gross domestic product (GDP) per capita (in 2013 USD)	GDP per capita reflects the amount of resources available for investment (in 2013 United States Dollars).
Gross National Income (GNI) per capita	GNI is defined as "the sum of value added by all producers who are residents in a nation, plus any product taxes (minus subsidies) not included in the output, plus income received from abroad such as employee compensation and property income."
Under-five mortality rate	Under-5 mortality rate is defined as "the probability per 1,000 that a newborn baby will die before reaching age five."
Primary education	Primary education is defined as the number of primary education years completed by the population.
Urban population (% of total)	"Urban population refers to people living in urban areas as defined by national statistical offices. It is calculated using World Bank population estimates and urban ratios from the United Nations World Urbanization Prospects."
World region	World region as classified by the World Bank. Regions are Africa, East Asia and Pacific, Europe and Central Asia, Latin America and the Caribbean, Middle East and North Africa, and South Asia.
World Bank income classification	Classification defined by GNI per capita in 2013. Classifications are: Low-income (less than $1,045), middle-income ($1,045 to 12,746), and high-income ($12,746 or more). Lower-middle-income and upper-middle income economies are separated at a GNI per capita of $4,125.
Source: Worldwide Governance Indicators (2014) (World Bank, 2014)	
Control of corruption	Control of corruption "captures perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as capture of the state by elites and private interests."
Voice and accountability	Voice and accountability "captures perceptions of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media."
Political stability and absence of violence	Political stability and absence of violence "measures perceptions of the likelihood of political instability and/or politically motivated violence, including terrorism."
Governance effectiveness	Government Effectiveness (GE) reflects government commitment and effectiveness in implementing programs.
Regulatory quality	Regulatory quality "captures perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development."
Rule of law	Rule of law "captures perceptions of the extent to which agents have confidence in and abide by the rules of society and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence."

Results and Discussion

Country performance in improving water access

Values for water access performance were calculated for 138 countries. Figure 7 depicts the values (details in APPENDIX 3).

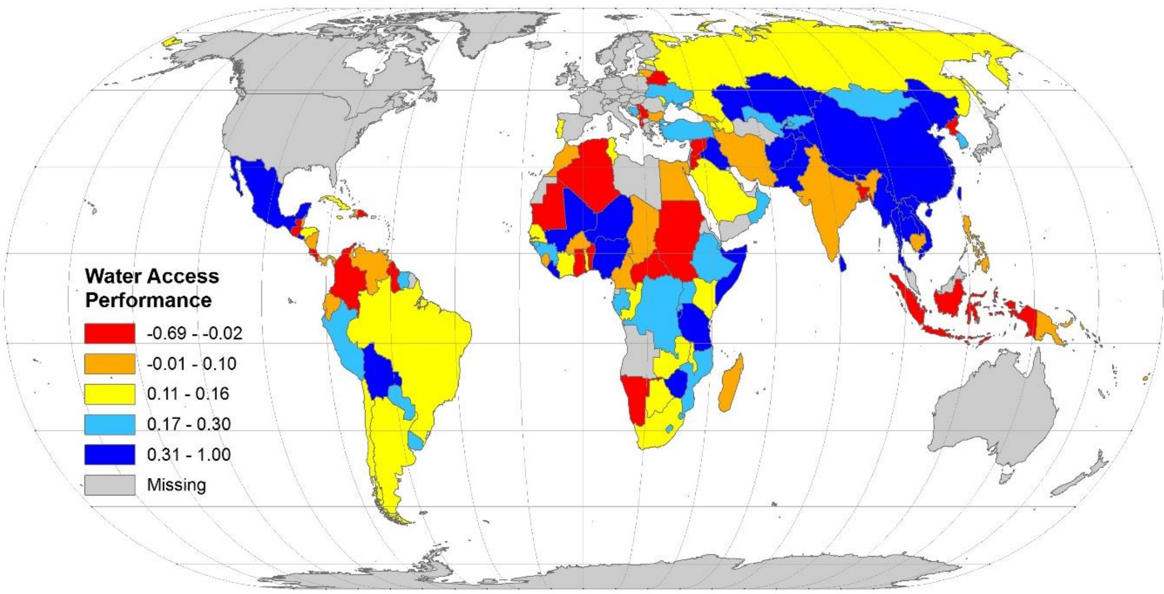

Figure 7. Water access performance: component values by country

In contrast, Figure 8 shows water coverage. Despite persistently being the region with the lowest water coverage in the world, water access performance among countries in Sub-Saharan Africa varies widely, with both high and low performers. South East Asia has higher performance despite low coverage, while South America has higher coverage but lower performance.

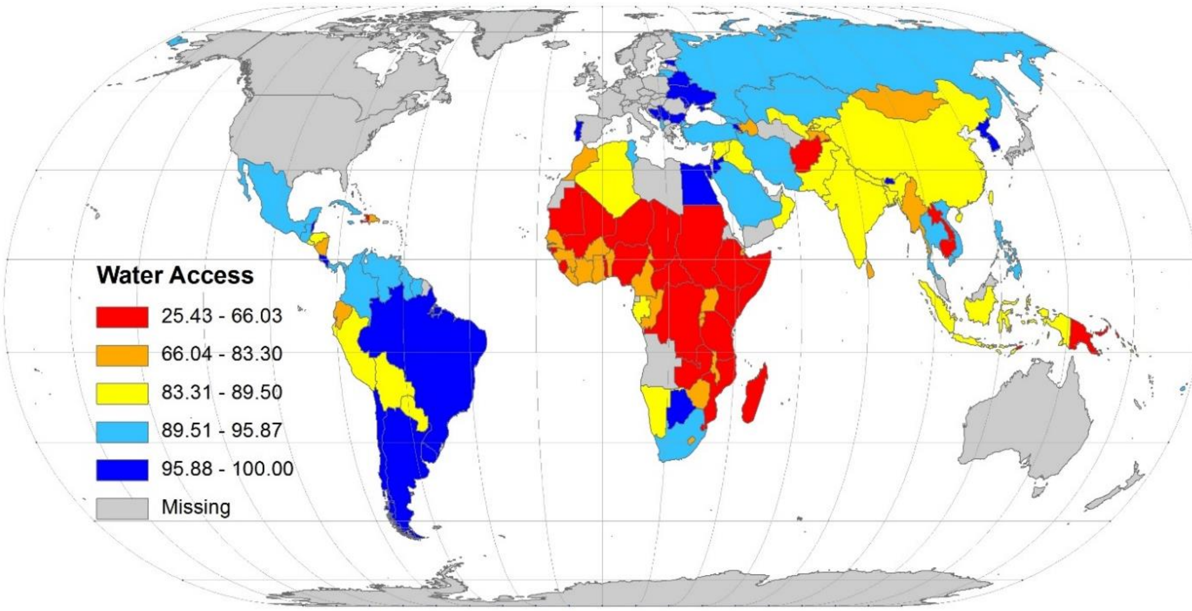

Figure 8. Global water coverage by country (percentage)

Figure 9 shows all the rates of change used in defining the performance frontier for water access. Points defining the performance frontier were: Ethiopia (1998), Cambodia (1998), Malawi (1997), Cambodia (2009), Namibia (2001), El Salvador (2007), Armenia (2005), Armenia (2008), and Belarus (2009).

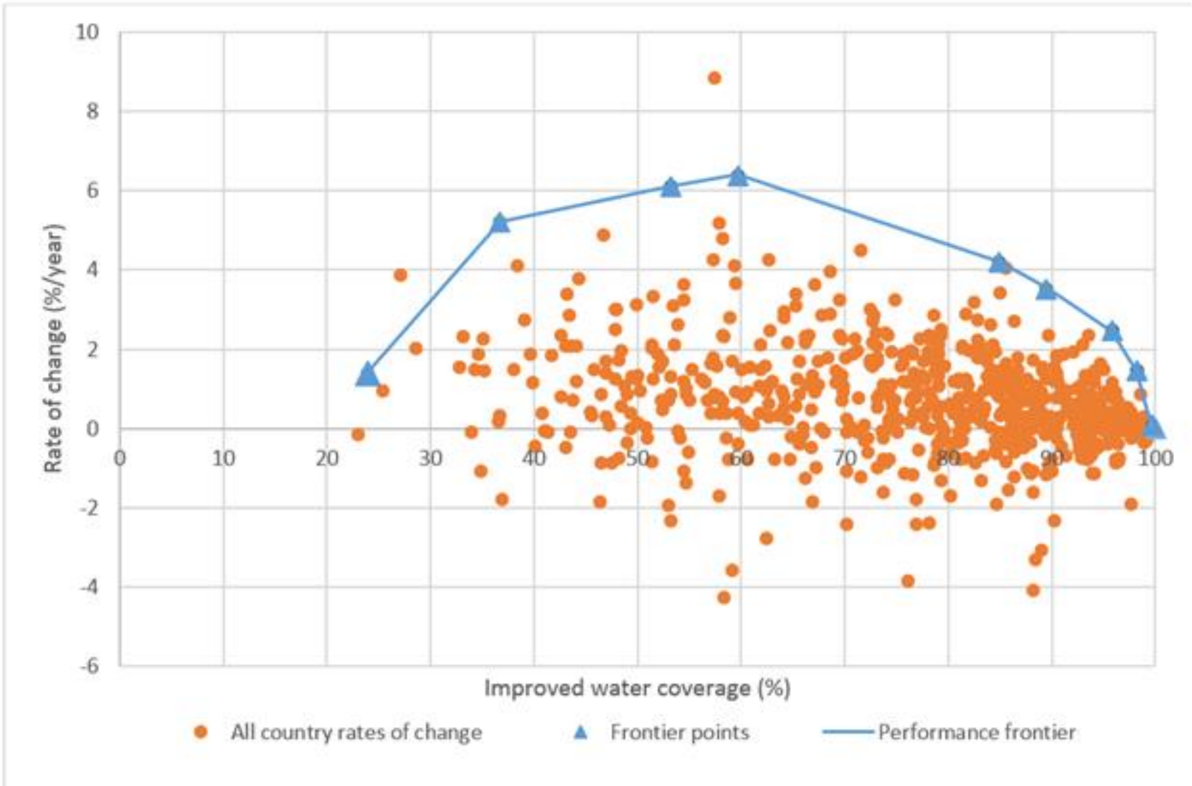

Figure 9. Performance frontier for water access based on rates of change from all countries and all times

High and low performing countries

High performing countries for water access performance were El Salvador, Mali, Tajikistan, Nepal, Liberia, Nigeria, Sri Lanka, Lao PDR, Maldives, and Thailand. Low performing countries are Namibia, Mauritania, the Dominican Republic, Costa Rica, North Korea, Belarus, Ghana, Jordan, the Solomon Islands, and Colombia.

Mali, a high performing country, has rapidly increased coverage. In 1987, coverage was 26%, passing 40% in the early 2000s and reaching 72% in 2010. Another example is Tajikistan. Despite stagnant coverage from 1999 (61%) to 2003 (62%), Tajikistan has increased access to improved water sources from 62% in 2003 to 77% in 2012.

In contrast, the Dominican Republic has experienced slippage in coverage. From 1996 to 2000, coverage was near 90%. Coverage fell to 85% in 2003 and 79% in both 2007 and 2010.

Namibia is experiencing stagnation. While Namibia experienced a rapid increase in access from the early 1990s to the mid-2000s, with coverage increasing from 65% to nearly 90%, in more recent years slipped to 86% in 2004 and 2007 and further down to 82% in 2010.

Among the most populated countries in the world, Nigeria, Pakistan, and Mexico were among high performers while India, Bangladesh, and Indonesia were among the low performers. Alphabetical lists of countries with values for all components and trends are available in the Appendix.

Correlations

Country performance in improving water access is significantly and positively associated with the South Asia region, suggesting countries from this region have been performing better as compared to other regions. Country performance in improving water access is negatively associated with GDP per capita, though the regression model suggests that changes in GDP are associated with little change in performance.

There were no other significant associations among country characteristics examined. No governance indicators were associated with water access performance.

Trends in performance

Table 18 shows the trend in country values for water access performance. The trends suggest countries with a positive value vary in whether they improved over time, with a roughly even number of countries improving, unchanged, or deteriorating. Conversely, the majority (60%) of countries with a negative 2015 value deteriorated over time. This suggests, for water access performance, that deterioration is a long-term phenomenon – meaning that countries with negative values continue to deteriorate over time.

Table 18. Trends in country values of water access performance

Water access performance countries (n = 138)				
Water access component value	Trend	n	% total water access	% of total positive or negative
Positive value	Total positive values	108	78%	-
	↑	35	25%	32%
	→	33	24%	31%
	↓	20	14%	19%
	N/A	20	14%	19%
Negative value	Total negative values	30	22%	-
	↑	3	2%	10%
	→	5	4%	17%
	↓	18	13%	60%
	N/A	4	3%	13%

Country performance in improving water equality

Country rates of change (progression or retrogression, percent per year) in equality of access to water were compared to the performance frontier (best-in-class performance) to generate a country value for performance in improving water equality. We used the gap in rural and urban coverage as our indicator of equality. Values for country performance in improving water equality were calculated for 129 countries. Figure 10 summarizes the values by country.

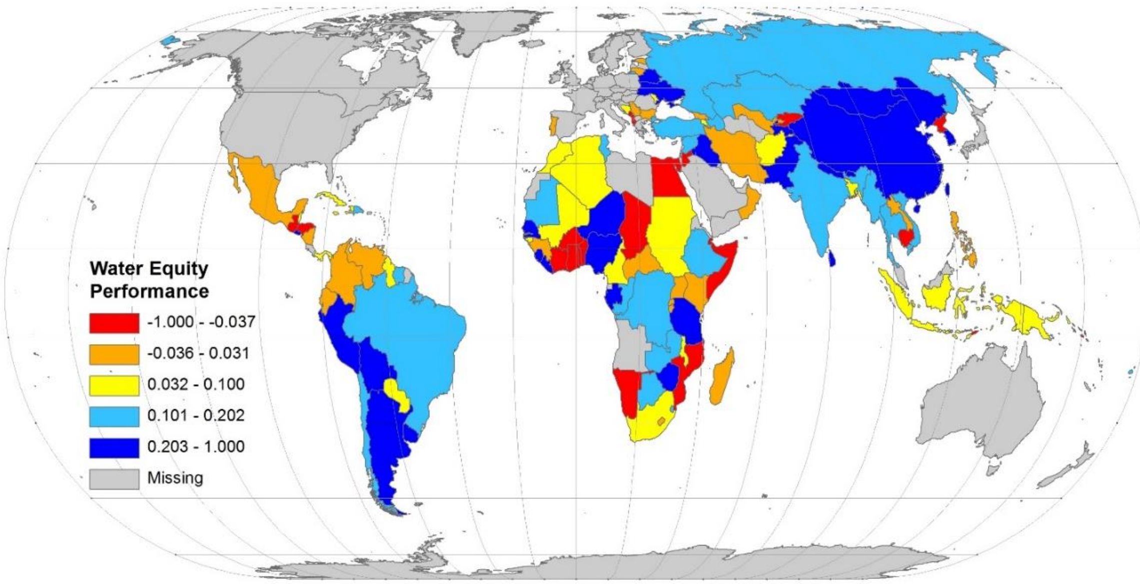

Figure 10. Water equality performance: component values by country

Figure 11 shows all of the rates of change used in defining the performance frontier for water equality. Points defining the performance frontier were Ethiopia (2001), Mauritania (1995), Bolivia (2000), Uruguay (2007), and Belarus (2011).

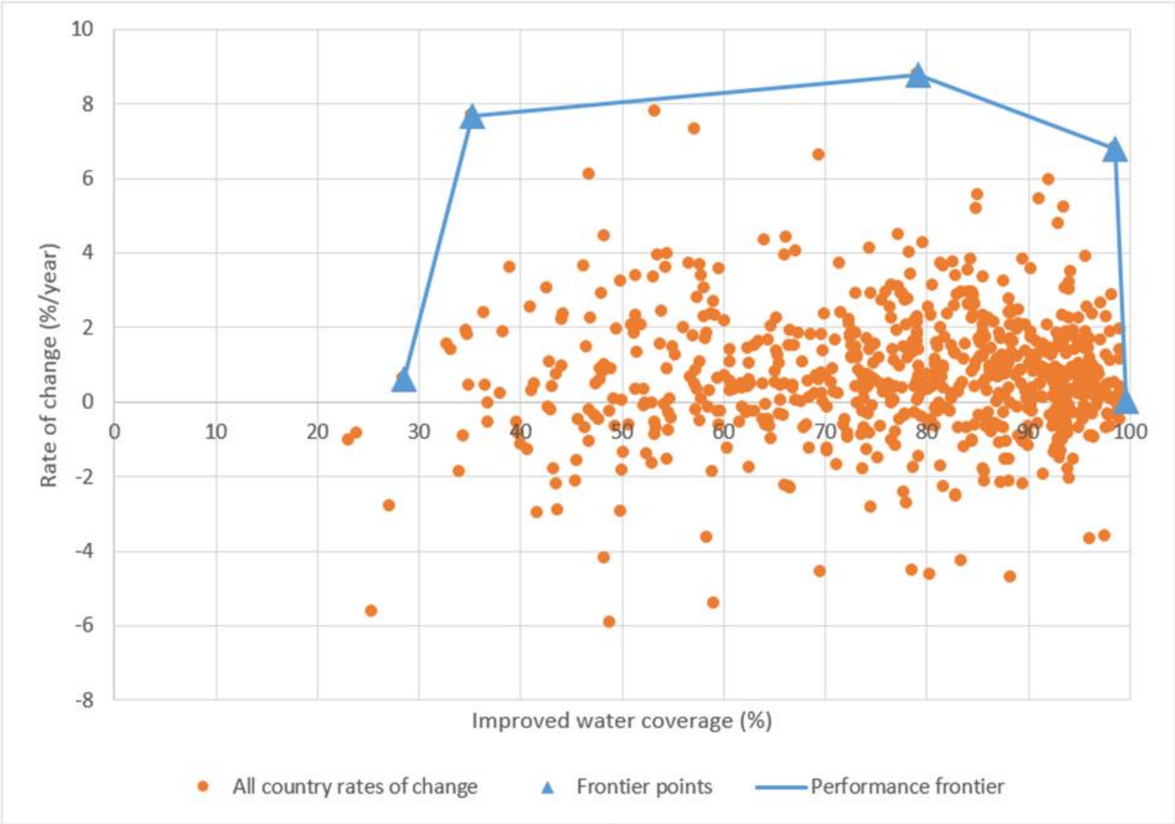

Figure 11. Performance frontier for water equality based on rates of change from all countries and all times

High and low performing countries

High performing countries for performance in improving water equality are Belarus, Sierra Leone, Liberia, Niger, Zimbabwe, El Salvador, Tanzania, Tajikistan, Mongolia, and Uruguay. Low performing countries are Burkina Faso, Honduras, Namibia, Costa Rica, Jordan, Kyrgyzstan, Mozambique, Gambia, Timor-Leste, Cape Verde, and Djibouti.

Among the most populated countries in the world, Pakistan, Nigeria, and China were among high performers while Bangladesh, Philippines, and Mexico were among the low performers.

Correlations

County performance in improving water equality is not significantly associated with any of the governance indicators or country characteristics, including GDP per capita (Figure 12). In contrast, there is a positive association between GDP per capita and the gap in coverage (Figure 13). This suggests the water equality performance is a fair comparison between countries at different levels of coverage.

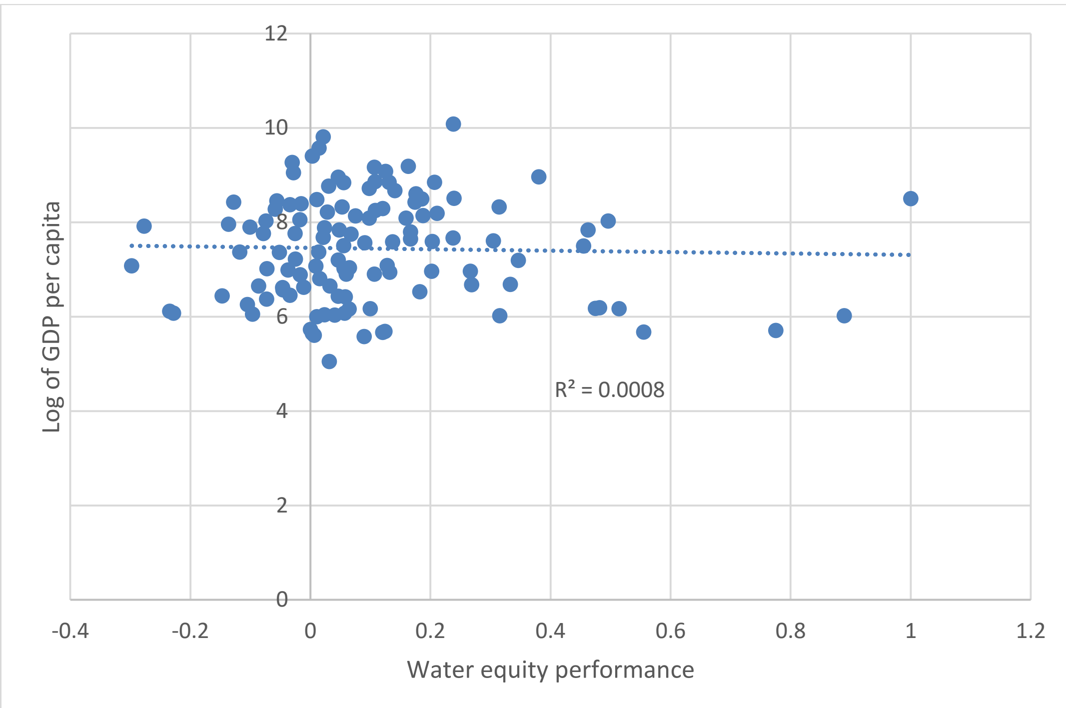

Figure 12. Water equality performance versus GDP per capita (log)

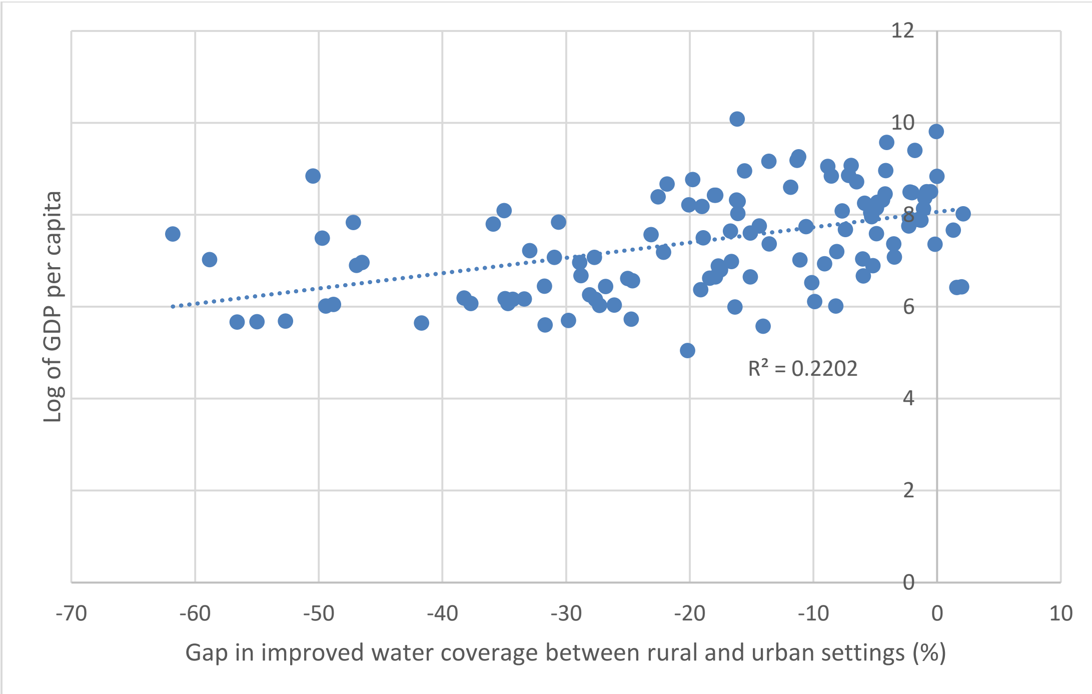

Figure 13. Water coverage equality versus GDP per capita (log)

Trends in performance

Table 19 shows the trend in country values for water equality performance. The trends suggest countries with a positive value are more likely to have improved over time (35%) rather than deteriorate. Conversely, 47% of countries with a negative value deteriorated over time rather than improved. This suggests, for water equality performance, that improvement and deterioration are long-term phenomena – suggesting that countries with positive values continue to improve over time while countries with negative values continue to deteriorate over time.

Table 19. Trends in country values of water equality performance

Water equality performance countries (n = 129)				
Water equality component value	Trend	n	% of total water equality	% of total positive or negative
Positive value	Total positive values	93	72%	-
	↑	33	26%	35%
	→	26	20%	28%
	↓	21	16%	23%
	N/A	13	10%	14%
Negative value	Total negative values	36	28%	-
	↑	4	3%	11%
	→	10	8%	28%
	↓	17	13%	47%
	N/A	5	4%	14%

Country performance in improving sanitation access

Country rates of change (progression or retrogression, percent per year) in access to sanitation were compared to the performance frontier (best-in-class performance) to generate a country value for performance in improving sanitation access. Values for sanitation access performance were calculated for 133 countries. Figure 14 summarizes the values. Figure 15 shows sanitation coverage by country.

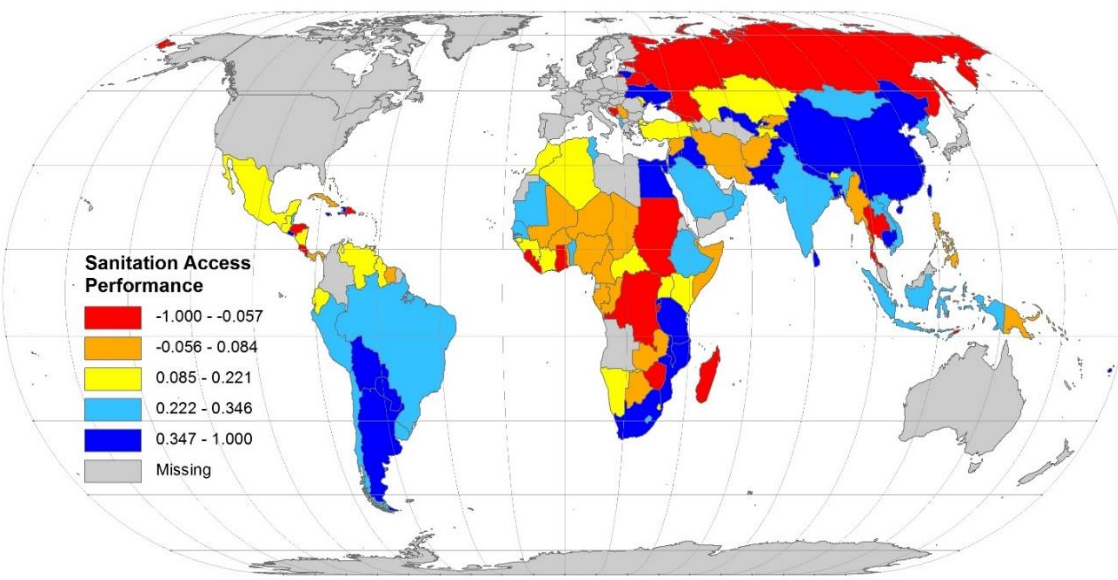

Figure 14. Sanitation access performance: component values by country

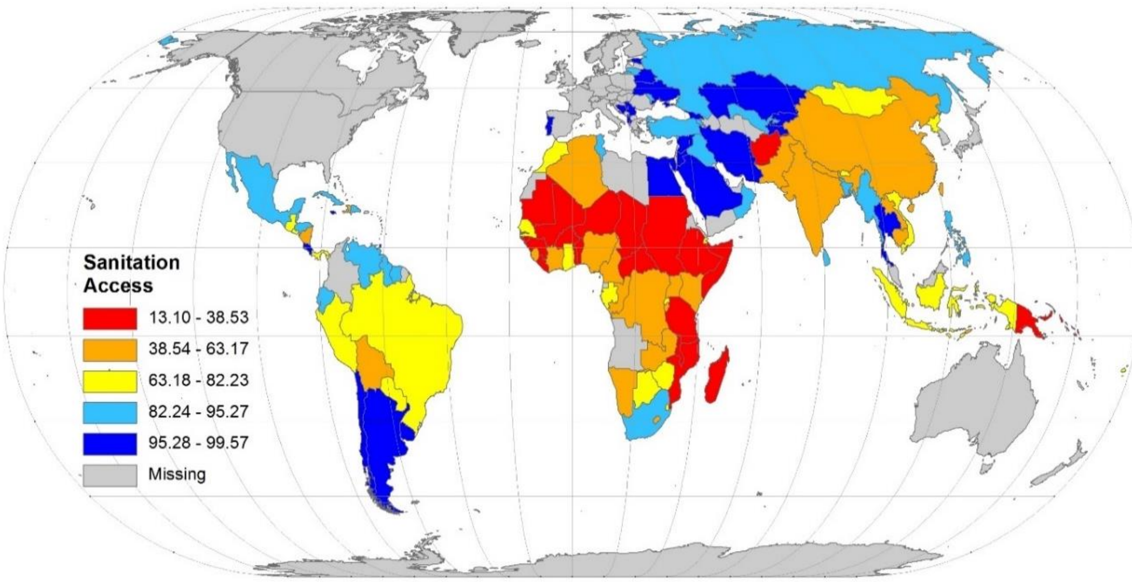

Figure 15. Global sanitation coverage by country (percentage)

Figure 16 shows all the rates of change used in defining the performance frontier for sanitation access. Points defining the performance frontier were Niger (1995), Cambodia (1996), Mozambique (2008), Rwanda (2002), Thailand (1990), Bosnia and Herzegovina (2007), Jordan (2006), Estonia (2006), and Estonia (2007).

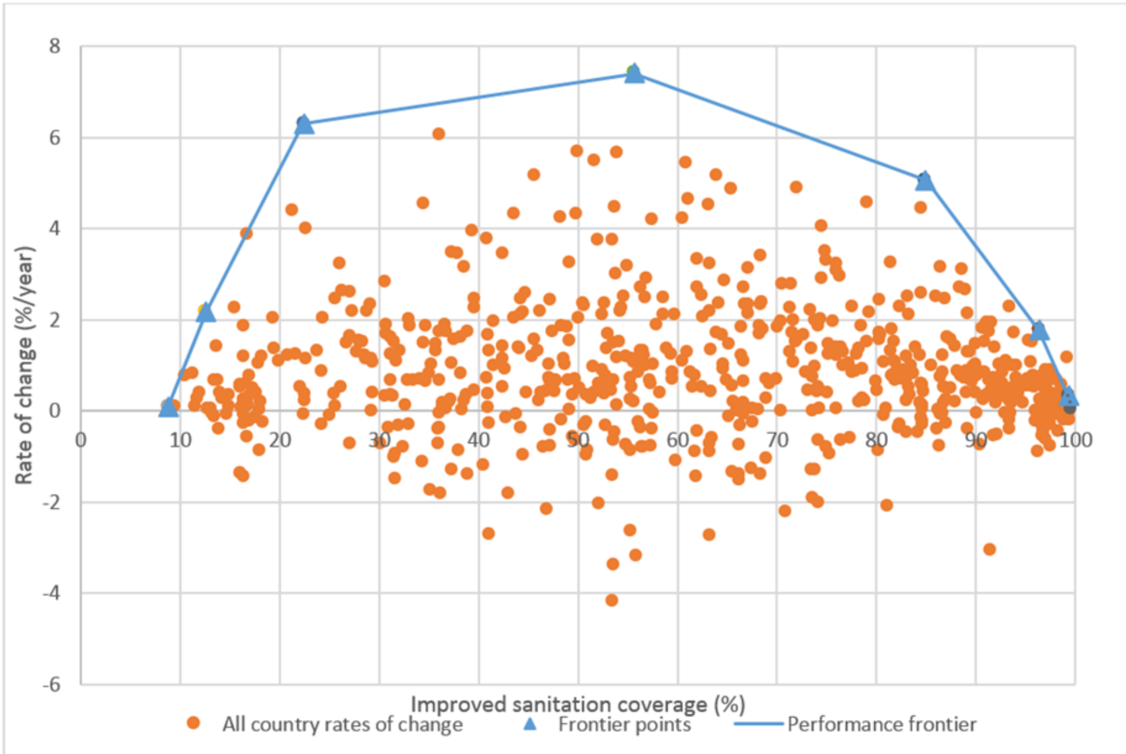

Figure 16. Performance frontier for sanitation access performance based on rates of change from all countries and all times

High and low performing countries

High performing countries for performance in improving sanitation access are Jordan, Malawi, Egypt, Uzbekistan, South Africa, China, Tanzania, Jamaica, Nepal, and Sri Lanka. Low performing countries are Ghana, Sierra Leone, Costa Rica, Timor-Leste, Vanuatu, Democratic Republic of the Congo, Belarus, Thailand, Samoa, and Estonia.

Among the most populated countries in the world, China, Pakistan, and Bangladesh were among high performers while the Philippines, Nigeria, and Russia were among the low performers.

Correlations

Country performance in improving sanitation access is negatively associated with under-five mortality. Performance is also positively associated with the South Asia region, suggesting countries from this region have been performing better as compared to other regions.

There were no other significant associations among country characteristics examined. No governance indicators were associated with sanitation access performance.

Trends in performance

Table 20 shows the trend in country values of performance in improving sanitation access. The trends suggest countries with a positive value are more likely to be improving over time (36%) rather than deteriorating. Conversely, the majority (54%) of countries with a negative value were deteriorating over time rather than improving. This suggests, for sanitation access performance, that improvement and deterioration are long-term phenomena.

Table 20. Trends in country values of sanitation access performance

Sanitation access performance countries (n = 133)				
Sanitation access component value	Trend	n	% of total sanitation access	% of total positive or negative
Positive value	Total positive values	96	72%	-
	↑	35	26%	36%
	→	30	23%	31%
	↓	19	14%	20%
	N/A	12	9%	13%
Negative value	Total negative values	37	28%	-
	↑	1	1%	3%
	→	7	5%	19%
	↓	20	15%	54%
	N/A	9	7%	24%

Country performance in improving sanitation equality

Country rates of change (progression or retrogression, percent per year) in equality of access to sanitation were compared to the performance frontier (best-in-class performance) to generate a country value for performance in improving sanitation equality. We used the gap in rural and urban coverage as our indicator of equality. Values for sanitation equality performance were calculated for 126 countries. Figure 17 summarizes the values.

Figure 18 shows all the rates of change used in defining the performance frontier for sanitation equality which is also shown. Points defining the performance frontier were: Niger (2007), Malawi (2008), India (2000), Paraguay (1999), South Africa (2008), Mexico (2002), Bosnia and Herzegovina (2001), Egypt (2006), Estonia (2011), and Estonia (2009).

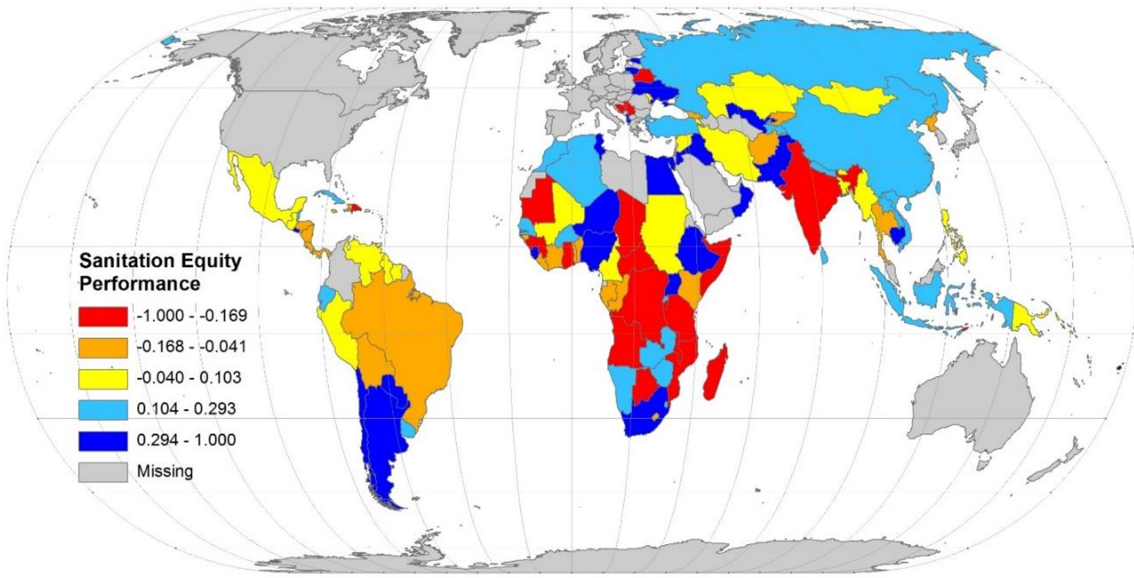

Figure 17. Sanitation equality performance: component values by country

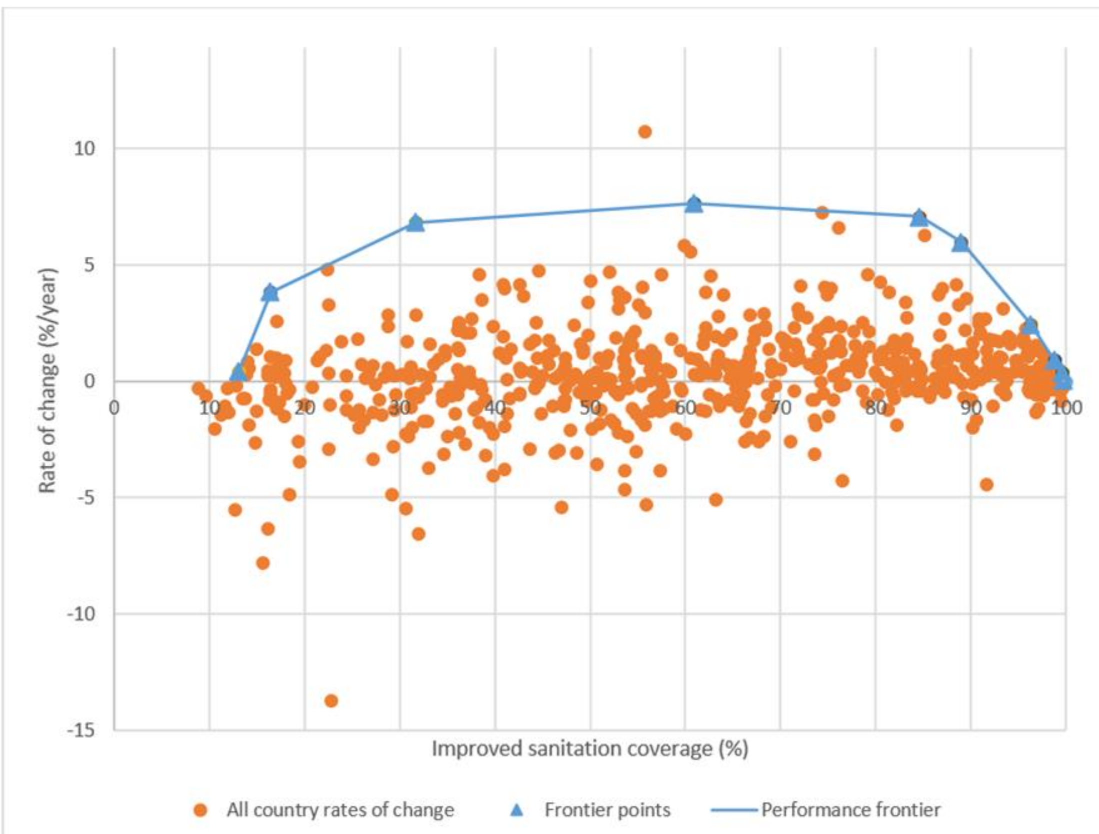

Figure 18. Performance frontier for sanitation equality based on rates of change from all countries and all times

High and low performing countries

High performing countries for improving equality in sanitation are Egypt, Niger, Estonia, Jordan, Ukraine, South Africa, Chile, Pakistan, Fiji, Uzbekistan, and Palau. Low performing countries are Vanuatu, Botswana, Mauritania, Samoa, India, Belarus, Central African Republic, Burundi, Timor-Leste, and Tanzania.

Among the most populated countries in the world, Pakistan, Nigeria, and Indonesia were among high performers while the Philippines, Brazil, and India were among the low performers.

Correlations

Country performance in improving sanitation equality is associated with control of corruption, government effectiveness, regulatory quality, and rule of law. These results suggest sanitation inequality is highest in countries with poor governance.

In terms of country characteristics, performance is positively associated with both GDP and GNI per capita and negatively correlated with income classification. Sanitation equality performance is significantly higher in the Middle East and North Africa region as compared to other regions. It is also significantly associated with countries that have a larger urban population.

Trends in performance

Table 21 shows the trend in country values for sanitation equality performance. The trends suggest countries with a positive value are more likely to be increasing over time (47%) rather than deteriorating. Conversely, 39% of countries with a negative value deteriorated over time rather than improving. This suggests improvement and deterioration are long-term phenomena.

Table 21. Trends in country values of sanitation equality performance

Sanitation equality performance counties (n = 126)				
Sanitation equality component value	Trend	n	% of total sanitation equality	% of total positive or negative
Positive value	Total positive values	70	56%	-
	↑	33	26%	47%
	→	20	16%	29%
	↓	10	8%	14%
	N/A	7	6%	10%
Negative value	Total negative values	56	44%	-
	↑	3	2%	4%
	→	17	13%	24%
	↓	27	21%	39%
	N/A	9	7%	13%

Implications for policy and practice

The indicators of water and sanitation performance which were developed using frontier analysis generate further value from water and sanitation coverage data available from the JMP by assessing country rates of change in access and equality and benchmarking these rates to best-in-class performance.

Our results indicate that, with few exceptions, there are no significant associations between most country characteristics, such as GDP per capita, and performance on water and sanitation access and equality. Thus, even countries with limited resources can make great strides in both advancing water and sanitation and progressively realizing the human right to water and sanitation. It also suggests that the performance indicators are "fair," in that they fairly compare countries across different levels of water and sanitation coverage.

The performance indicators have implications for policy, decision-making, advocacy, accountability, human rights, and WaSH investment targeting. The indicators enable evidence-based decision-making to identify country strengths and weaknesses with respect to performance on water and sanitation access and equality. They provide national policy makers with a new instrument to identify aspects of water and sanitation access and equality in need of targeted improvement.

In terms of advocacy, accountability, and human rights, the performance indicators address some of the norms of the human right to water and sanitation and it is one of the first instruments capable of quantitatively assessing progressive realization. Future analyses can address additional human rights norms as more data become available. The performance indicators fairly compare country performance, which enables countries at different levels of water and sanitation coverage to be compared and ranked. Rankings encourage healthy competition between countries and behavior change to drive improvements.

For the human rights community, the performance indicators enable objective and comparable assessment of progressive realization. The performance indicators should be useful for human rights treaty organizations that conduct country reviews.

In terms of WaSH investment targeting, the performance indicators enable finance ministers, donors and investors to make decisions about WaSH investment targeting. Figure 19 illustrates how the component values could inform decision-making. Lower-performing countries may represent opportunities for more active efforts to improve the enabling environment and reform programs to enhance performance and achieve more rapid progress on water and sanitation access and equality. High-performing countries (countries with high component values) and low levels of water and sanitation coverage represent opportunities for investments in infrastructure programs to move toward universal access to water and sanitation. Countries with high performance and intermediate coverage may focus their efforts on service quality improvements – for example, to piped water at home and toilets with piped sewer system. Countries approaching 100% coverage may focus investments in upgrading services and targeting under-served populations.

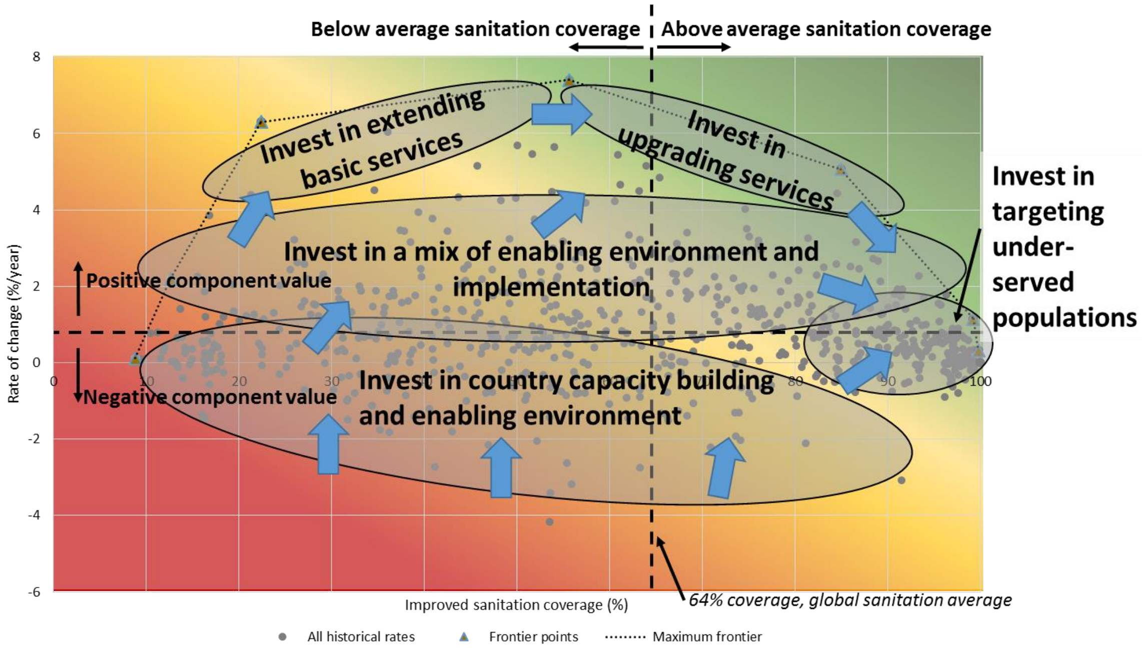

Figure 19. Using the water and sanitation performance indicators as a decision tool: an example with sanitation access performance

CHAPTER 7: JOINT DISCUSSION

In this dissertation, I sought to answer two research questions: (1) what are examples of additional value and information that can be derived from the analysis of water and sanitation service delivery monitoring data and (2) what are examples of opportunities to improve water and sanitation service delivery monitoring – adding no or minimal costs and constraints – such that they add value for policy, programming, or practice?

Deriving additional value from monitoring

Using input-output-outcome monitoring data collected through surveys, I demonstrate several examples of unrealized value and information that can be derived by analyzing monitoring data beyond their immediate intended purpose. Using water infrastructure monitoring data, I conducted two of the largest studies on water service availability parameters (e.g. functionality, continuity) – analyzing more than 80,000 water systems in five countries. These studies revealed substantial and previously unreported differences in water service availability by sub-national region.

Bayesian Networks (BNs) are useful in causal assessments of environmental problems for evidence-based policy analysis and decision-making (Carriger et al., 2016). However, few studies have used BNs to analyze drinking water services in low- and middle-income countries (LMICs) (Phan et al., 2016). Using BNs and regression, I corroborated theory and quantified relationships between management, infrastructure, and financial factors and water service availability parameters. Few studies have reported the relative influence of factors associated with water service availability parameters in sub-Saharan Africa and there are no large studies from Latin America and the Caribbean.

In Chapter 3 on water system functionality in Tanzania and Nigeria, higher functionality was associated with fee collection. In Tanzania, functionality was higher if fees were collected monthly rather than in response to system breakdown. Systems in Nigeria were more likely to be functional if they were used for both human and livestock consumption. In Tanzania, systems managed by private operators were more functional than community-managed systems. The BNs found strong dependencies between functionality and system type and administrative unit (e.g. district). The BNs predicted functionality increased from 68% to 89% in Nigeria and from 53% to 68% in Tanzania when best observed conditions were in place.

In Chapter 4 on water supply continuity in Central America, good condition infrastructure and year-round water availability were associated with higher 24-hour service. The availability of support for system rehabilitation in Honduras and for preventative maintenance in Nicaragua were associated with higher availability of 24-hour services. The BNs predicted that good condition infrastructure and year-round water availability were more influential on 24-hour service than management variables such as the availability of external technical support and funds to rehabilitate the system.

In Chapter 5, I systematically compiled health care facility survey data to produce the first coverage estimates of environmental conditions in health care facilities (HCFs) in LMICs. These findings suggest coverage is poor in many HCFs in LMICs. Data for 21 indicators of environmental conditions and standard precautions were compiled from 78 LMICs which were representative of 129,557 HCFs. Half of HCFs lack piped water, 33% lack improved sanitation, 39% lack handwashing soap, 39% lack adequate infectious waste disposal, 73% lack sterilization equipment, and 59% lack reliable electricity. Using nationally representative data from six countries, an estimated 2% of facilities provide basic water, sanitation, hygiene, and waste management. Statistically significant differences in coverage exist between HCFs by: urban-rural setting, managing authority, facility type, and sub-national administrative unit.

Survey data on household water and sanitation can be transformed to reveal new insight. In Chapter 6, I used frontier analysis to transform household water and sanitation survey data into indicators of water and sanitation performance. Water and sanitation performance analysis provides policymakers with an accountability instrument to assess country progress on meeting full realization of human rights obligations.

These are examples of actual, unrealized value and new information from the analysis of water and sanitation service delivery monitoring data. The analyses from Chapter 3 and 4 reveal value-added practice and programming improvement opportunities. Water systems in LMICs need increased availability of post-construction support, improved water system management (e.g. ensuring fees are collected, public accountability forums held), and construction of system types that are context appropriate such that system operators are able to obtain support from maintenance technicians with the appropriate skills to fix the system and spare parts are readily available to fix specific system types. Government and external support actors should ensure sufficient post-construction support activities are provided (and not simply implementation of new projects), including 'software' components such as improved governance and capacity building of staff at the local government level. Further, many people in rural areas of these countries live in extreme poverty. If universal access to basic water services is to be achieved, budgets must account for the fact that many communities may not be able to provide sufficient financial resources to support water systems over time on their own. Communities, local and government actors, and external support actors should identify opportunities to improve cost-recovery for operations, maintenance, and capital replacement such as modifying fee structures. These actors should look for opportunities to improve financial viability by identifying alternative sources of funding such as public financing.

There are several value-added policy, programming, and practice findings from the analysis of HCF data in Chapter 5. For example, monitoring data can be used to inform facility-level improvements. Once low coverage areas are identified, facility managers, infection prevention and control practitioners, and program managers might collaborate to identify simple technology and low-cost solutions to improve the situation progressively. However, higher levels of service are necessary to protect patients and health care workers. Governments and external support agencies should upgrade services to ensure that all HCFs have sufficient, continuously-available, safe piped water in the facility. Sanitation facilities that safely manage patient fecal wastes are imperative to prevent infection in the HCF and nearby communities.

These studies are important for understanding the extent to which factors influence water and sanitation services. The findings reveal important operational insights that were otherwise buried in spreadsheets and geospatial maps. The findings provide important information to water and sanitation service delivery actors to help them identify water service improvement opportunities and informs evidence-based decision-making for better management, policy, programming, and practice.

Opportunities to improve monitoring

There are many examples of simple data collection improvement opportunities for input-output-outcome monitoring collected through surveys that do not add substantial cost or burden.

Many of these simple improvements would make these data more valuable. As demonstrated in the literature review (Chapter 2), opportunities to improve monitoring include developing appropriate data collection instruments (including SMART survey questions), clear definition and reporting of the sample frame, obtaining ethics approval, and conducting quality assurance and quality control (QA/QC) throughout the data collection process.

Refinements to survey instruments are an opportunity where small changes with minimal cost would greatly improve data quality and increase the opportunity for new insight. For example, some of the questions in the water supply infrastructure surveys were not specific or relevant. Because of this, an estimated 15-40% of the data from each dataset were excluded for analysis. The excluded data represent a substantial opportunity to improve water and sanitation service delivery monitoring and an opportunity to gain more insight. Replacing ambiguous, non-specific questions with questions based on theory or evidence would improve model fit and provide more interesting value through service delivery studies.

Water infrastructure surveys (such as those analyzed in my dissertation) are increasingly conducted and the Waterpoint Data Exchange, an online database that compiles many of these datasets, has data from 38 LMICs (as of this writing) and that number is growing rapidly (WPDx, 2015). To improve monitoring and generate more value from these data, it is fundamental that actors who support and develop these surveys ensure that questions are policy relevant, based on evidence (e.g. known disease burden, known determinant of service), and fundamentally sound (e.g. meet the ‘SMART’ or equivalent criteria). These instruments must be revisited and revised over time; and their findings clearly and publicly reported so that others can learn from them (including an assessment of the performance of survey questions).

After collecting monitoring data, there are several opportunities to improve the analysis and reporting of service delivery studies using monitoring data. Examples include selecting appropriate analysis methods, clearly reporting bias, limitations, and possible improvement opportunities for future monitoring, and developing policy, programming, and practice insights and solutions.

These suggested improvements may substantially improve data quality. For example, problems such as poorly defined questions and insufficient QA/QC likely result in additional ‘noise’ in the dataset which may result in lower r-squared values and magnitudes of association that do not reflect the real-world situation. In Chapter 4 on water supply continuity in Central America, data collectors in Honduras conducted more QA/QC as compared to Panama and Nicaragua. The r-squared value for the Honduras model was nearly twice as high as the models for Panama and Nicaragua. In the BN models, the receiver operating characteristic (ROC, which is an indicator of model accuracy) was also higher in Honduras as compared to the other countries. The higher ROC for Honduras meant a model fit that was considered ‘moderately accurate’ as compared to ‘less accurate’ in Nicaragua and Panama (Greiner et al., 2000).

The checklist manifesto: standardizing good practice for survey-based monitoring

Monitoring is complex but comprises many relatively simple steps. Actors who plan monitoring must design initiatives that can be used to collect water and sanitation service delivery data that are valid. However, valid data requires a commitment to good-practice. As the literature review in my dissertation demonstrates, inconsistent sampling methods, survey questions, and reporting are examples of common problems associated with monitoring initiatives. Further, guidance on good-practice water and sanitation service delivery monitoring is fragmented or non-existent (Sanitation and Water for All Global Monitoring Harmonsation Task Team, 2015). Poor data collection and inadequate reporting waste scarce financial and human resources.

In systems and services with many steps, checklists are commonly used to reduce error and ensure data are valid. For example, surgeons use checklists to prevent medical errors and infection. Pilots use checklists to prevent aircraft failure and crashes. Engineers use checklists to ensure construction projects meet building codes. Evidence from other fields suggest that regardless of a person's level of expertise, a well-designed checklist can improve outcomes (Gawande & Lloyd, 2010).

Good practice guidance, organized as checklists, need to be developed for water and sanitation service delivery monitoring. Properly applied, they will improve data quality and improve harmonization of water system monitoring. Reporting criteria for types of water and sanitation monitoring data collection and the development of policy relevant, reliable, and evidence-based survey questions for monitoring initiatives will contribute to data improvements and standardization. These improvements will contribute to understanding of the status and conditions of water and sanitation services.

Parting thoughts

Together, these studies demonstrate substantial, unrealized value that can be derived from survey-based input-output-outcome monitoring data. Improvements to monitoring and analysis of these data are major opportunities to make better use of limited resources, inform evidence-based decision-making for better management, policy, programming, and practice, and improve water and sanitation service delivery.

APPENDIX 1 FOR CHAPTER 3

Table 22. Average age of water system types in Tanzania

System type	Age
Nira	11.8
Afridev	9.7
Cemo	9.8
Gravity	17.1
India Mark II	11.9
India Mark III	11.0
KSB	16.6
Mono	16.9
Play pump	11.3
Rope pump	8.9
SWN 81	13.6
SWN 80	16.7
Submersible	14.2

Table 23. Sensitivity analysis for main functionality BN model – Nigeria

Node	Mutual Information	Percent	Variance of Beliefs
functionality	0.90216	100	0.2168666
Water system type	0.03184	3.53	0.0093359
Number of animals	0.01069	1.19	0.0030542
LGA	0.00436	0.484	0.0012822
Pay for water	0.00268	0.297	0.0008817
Poverty	0.00249	0.275	0.000745
Distance to urban center	0.00076	0.0847	0.0002323
Depth to water	0.00039	0.0437	0.0001193
Population density	0.00026	0.0288	0.000078
Urban rural setting	0.00007	0.0082	0.0000221

Table 24. Sensitivity of functionality to a finding at another variable for Tanzania

Node	**Mutual Information**	**Percent**	**Variance of Beliefs**
Functionality	0.99684	100	0.2489058
Water system type	0.00422	0.423	0.0014527
Age	0.00288	0.289	0.0009962
Public meeting	0.00045	0.0455	0.0001566
Poverty	0.00042	0.0419	0.0001439
Pay for water	0.00041	0.041	0.0001411
Management type	0.00039	0.0392	0.0001349
district	0.00022	0.022	0.0000757
Distance to urban center	0.00012	0.0116	0.0000398
Groundwater productivity	0.00009	0.0087	0.0000299
Climate zone	0.00001	0.00127	0.0000043
Depth to water	0.00001	0.000815	0.0000028
Population density	0.00001	0.000742	0.0000025
Urban rural setting	0.00001	0.000671	0.0000023

Table 25. Bayesian network model evaluation results for Nigeria and Tanzania

Model evaluation	**Nigeria**	**Tanzania**
Logarithmic Loss	0.5338	0.5659
Quadratic Loss	0.3578	0.3846
Spherical payoff	0.7974	0.7814
Area under the receiver operating characteristic (ROC)	0.7099	0.7386

APPENDIX 2 FOR CHAPTER 4

Table 26. Selected descriptive statistics for all water systems analyzed in Honduras

Variable	Variable levels	n	Hours of service	Percent of systems providing 24-hour service
Region	Atlantida	170	21.1	81%
	Choluteca	146	8.8	18%
	Colon	164	19.9	73%
	Comayagua	49	19.1	69%
	Copan	173	20.3	78%
	Cortes	51	14.7	49%
	El Paraiso	274	17.6	62%
	Francisco Morazan	364	16.3	57%
	Intibuca	166	13.9	43%
	La Paz	118	20.9	78%
	Lempira	359	21.5	82%
	Ocotepeque	57	21.2	75%
	Olancho	382	20.9	80%
	Santa Barbara	197	19.5	69%
	Valle	65	6.4	12%
	Yoro	211	18.5	67%
Population served (quintile)	Lowest	588	18.7	70%
	Second lowest	579	19.0	70%
	Middle	596	18.5	68%
	Second highest	590	18.1	64%
	Highest	593	17.3	59%
Supply type	Electric pump piped	291	6.8	13%
	Gravity piped	2655	19.6	72%
Sufficient water summer	No	909	12.6	33%
	Yes	2037	20.9	81%

Table 27. Selected descriptive statistics for all water systems analyzed in Nicaragua

Variable	Variable levels	n	Hours of service	Percent of systems providing 24-hour service
Region	Boaco	90	15.0	49%
	Carazo	41	14.8	12%
	Chinandega	121	12.7	40%
	Contales	88	17.5	64%
	Esteli	191	17.5	66%
	Granada	30	13.1	33%
	Jinotega	267	17.6	62%
	Leon	185	17.1	63%
	Madriz	120	10.4	29%
	Managua	68	9.7	21%
	Masaya	42	10.1	7%
	Matagalpa	402	18.2	66%
	Nueva Segovia	167	14.7	48%
	RACCN	47	21.1	79%
	RACCS	158	16.8	60%
	Rio San Juan	48	16.6	56%
	Rivas	50	14.0	34%
Population served (quintile)	Lowest	430	16.6	62%
	Second lowest	423	16.7	59%
	Middle	434	17.1	62%
	Second highest	414	15.5	52%
	Highest	414	14.1	36%
Supply type	Electric pump piped	692	13.1	37%
	Gravity piped	1423	17.5	63%
Sufficient water summer	No	628	13.3	42%
	Yes	1487	17.2	59%

Table 28. Selected descriptive statistics for all water systems analyzed in Panama

Variable	Variable levels	n	Hours of service	Percent of systems providing 24-hour service
Region	Bocas del Toro	26	21.3	81%
	Chiriquí	51	17.2	55%
	Coclé	52	17.9	52%
	Colón	31	21.4	84%
	Comarca Emberá	5	12.2	40%
	Comarca Kuna Yala	28	18.1	71%
	Comarca Kuna de Madungandí	5	19.2	60%
	Comarca Ngobe Bugle	76	19.0	67%
	Darién	4	18.0	75%
	Herrera	52	17.1	58%
	Los Santos	79	18.8	65%
	Panamá	19	21.2	84%
	Panamá Oeste	9	16.4	56%
	Veraguas	62	17.5	58%
Population served (quintile)	Lowest	102	17.1	59%
	Second lowest	98	20.2	73%
	Middle	98	18.4	65%
	Second highest	102	18.2	62%
	Highest	99	18.5	61%
Supply type	Electric pump piped	195	16.5	50%
	Gravity piped	304	19.7	73%
Sufficient water summer	No	218	16.3	54%
	Yes	281	20.1	72%

Table 29. Water system rates and sufficient collection to cover operations, maintenance, and capital costs

Country		Honduras		Nicaragua		Panama	
Variable	Level	n	Percent (%)	n	Percent (%)	n	Percent (%)
Household tariff (USD per month)	No tariff	125	4.2	484	22.9	237	47.5
	0 to 1	1,433	48.6	863	40.8	121	24.3
	1 to 2	966	32.8	263	12.4	27	5.4
	2 to 3	215	7.3	141	6.7	22	4.4
	3+	207	7.0	364	17.2	92	18.4
Capital costs (monthly household rates)	Sufficient collection	34	1.2	161	7.6	184	36.9
	Insufficient collection	2,912	98.9	1,954	92.4	315	63.1
Operations costs (monthly household rates)	Sufficient collection	218	7.4	366	17.3	240	48.1
	Insufficient collection	2,728	92.6	1,749	82.7	259	51.9
Maintenance costs (monthly household rates)	Sufficient collection	265	9.0	384	18.2	348	69.7
	Insufficient collection	2,681	91.0	1,731	81.8	151	30.3
Operations and Maintenance costs (monthly household rates)	Sufficient collection	51	1.7	179	8.5	168	33.7
	Insufficient collection	2,895	98.3	1,936	91.5	331	66.3
Capital, operations, and maintenance costs (monthly household rates)	Sufficient collection	2	0.1	143	6.8	33	6.6
	Insufficient collection	2,944	99.9	1,972	93.2	466	93.4

Table 30. Univariable and multivariable logistic regression model for 24-hour water services in Honduras

Explanatory variable		Unadjusted model			Adjusted model			
		OR	CI	p-value	OR	CI	p-value	Wald test p-value
Source type	Groundwater vs. surface water	0.5	(0.4, 0.5)	<0.001	0.7	(0.5, 0.8)	<0.001	**<0.001**
Supply type	Gravity piped vs. electric pump piped	17	(12, 24.2)	<0.001	24.4	(15.5, 38.3)	<0.001	**<0.001**
Age	5-10 vs. 0-5 years	1.6	(1.1, 2.2)	0.027	1.2	(0.7, 2)	0.617	0.8547
	10-15 vs. 0-5 years	1.3	(1, 1.8)	0.152	1	(0.6, 1.6)	0.819	
	15-20 vs. 0-5 years	1.3	(0.9, 1.7)	0.267	0.9	(0.6, 1.4)	0.49	
	20-25 vs. 0-5 years	1.2	(0.9, 1.7)	0.337	1	(0.6, 1.5)	0.785	
	25-30 vs. 0-5 years	1.1	(0.8, 1.6)	0.662	1	(0.6, 1.6)	0.75	
	30+ vs. 0-5 years	0.9	(0.7, 1.2)	0.303	0.9	(0.6, 1.4)	0.458	
Sufficient water in the summer	Sufficient water in the summer vs. not	8.6	(7.2, 10.2)	<0.001	9.7	(7.7, 12.1)	<0.001	**<0.001**
Sufficient water in the winter	Sufficient water in the winter vs. not	11.8	(7.9, 17.8)	<0.001	5	(3, 8.4)	<0.001	**<0.001**
Funds available per household (quintile)	Second lowest funds vs. lowest	1	(0.8, 1.3)	0.933	1.1	(0.8, 1.6)	0.801	0.498
	Middle funds vs. lowest	1.3	(1.1, 1.7)	0.038	1.3	(0.9, 1.9)	0.254	
	Second highest funds vs. lowest	1.7	(1.3, 2.1)	<0.001	1.3	(0.9, 1.9)	0.233	
	Highest funds per user vs. lowest	1.8	(1.4, 2.3)	<0.001	1.4	(1, 2)	0.145	
Deforestation	Little deforestation vs. a lot	1.9	(1.5, 2.4)	<0.001	1.3	(1, 1.9)	0.162	0.3698
	No deforestation vs. a lot	2.2	(1.8, 2.8)	<0.001	1.3	(0.9, 1.9)	0.247	
State of the intake	Requires maintenance vs. good condition	0.9	(0.7, 1)	0.033	1	(0.8, 1.3)	0.684	0.3858
	Requires rehabilitation vs. good condition	0.4	(0.4, 0.5)	<0.001	0.8	(0.5, 1.2)	0.17	
State of the conduction	Requires maintenance vs. good condition	0.8	(0.7, 1)	0.005	0.8	(0.6, 1)	0.022	**0.0486**
	Requires rehabilitation vs. good condition	0.5	(0.4, 0.6)	<0.001	0.7	(0.5, 1.1)	0.075	
State of the storage	Requires maintenance vs. good condition	0.9	(0.7, 1)	0.018	1.2	(0.9, 1.6)	0.277	0.32
	Requires rehabilitation vs. good condition	0.5	(0.4, 0.6)	<0.001	0.9	(0.6, 1.4)	0.592	
State of the distribution	Requires maintenance vs. good condition	0.9	(0.7, 1)	0.023	1.2	(0.9, 1.6)	0.285	**0.0098**
	Requires rehabilitation vs. good condition	0.4	(0.3, 0.5)	<0.001	0.6	(0.4, 1)	0.031	
Population served (quintile)	Second lowest vs. lowest	1.1	(0.8, 1.4)	0.885	0.8	(0.6, 1.1)	0.109	**<0.001**
	Middle vs. lowest	1	(0.8, 1.3)	0.637	0.7	(0.5, 1)	0.024	
	second highest vs. lowest	0.8	(0.7, 1)	0.039	0.4	(0.3, 0.6)	<0.001	
	highest vs. lowest	0.7	(0.5, 0.8)	<0.001	0.3	(0.2, 0.4)	<0.001	
Ethnicity	Indigenous vs. mestizo	1.2	(1, 1.4)	0.244	0.9	(0.6, 1.3)	0.39	0.39
Region	Choluteca vs. Atlantida	0.1	(0.1, 0.1)	<0.001	0.2	(0.1, 0.3)	<0.001	**<0.001**
	Colon vs. Atlantida	0.7	(0.4, 1.1)	0.109	1.2	(0.6, 2.2)	0.736	
	Comayagua vs. Atlantida	0.6	(0.3, 1.2)	0.098	1.2	(0.5, 3.2)	0.711	
	Copan vs. Atlantida	0.9	(0.6, 1.5)	0.56	1.1	(0.6, 2.1)	0.912	
	Cortes vs. Atlantida	0.3	(0.2, 0.5)	<0.001	0.4	(0.2, 0.9)	0.014	
	El Paraiso vs. Atlantida	0.4	(0.3, 0.7)	<0.001	0.5	(0.3, 0.8)	0.005	
	Francisco Morazan vs. Atlantida	0.4	(0.3, 0.5)	<0.001	0.4	(0.3, 0.7)	0.001	
	Intibuca vs. Atlantida	0.2	(0.2, 0.4)	<0.001	0.4	(0.2, 0.8)	0.004	
	La Paz vs. Atlantida	0.9	(0.5, 1.6)	0.588	1	(0.4, 2.1)	0.83	
	Lempira vs. Atlantida	1.1	(0.7, 1.8)	0.718	1.4	(0.8, 2.5)	0.391	
	Ocotepeque vs. Atlantida	0.8	(0.4, 1.6)	0.407	0.5	(0.2, 1.2)	0.115	
	Olancho vs. Atlantida	1	(0.7, 1.6)	0.84	1.3	(0.8, 2.3)	0.418	
	Santa Barbara vs. Atlantida	0.6	(0.4, 0.9)	0.012	0.9	(0.5, 1.7)	0.683	
	Valle vs. Atlantida	0.1	(0.1, 0.1)	<0.001	0.2	(0.1, 0.4)	<0.001	
	Yoro vs. Atlantida	0.5	(0.4, 0.8)	0.003	1.2	(0.7, 2.1)	0.687	
Service provider status	In process of legalization vs. not legalized	1.3	(1, 1.7)	0.071	1.1	(0.8, 1.6)	0.75	0.4236
	Legally established vs. not legalized	1	(0.8, 1.2)	0.59	0.9	(0.7, 1.2)	0.247	
Bank account	Bank account vs. none	1.3	(1.2, 1.6)	0.001	1.3	(1, 1.7)	0.077	0.077
Accounting	Financial accounting vs. none	1.2	(1, 1.4)	0.082	0.9	(0.7, 1.2)	0.215	0.215
Minutes	Meeting minutes vs. none	1.2	(1, 1.5)	0.125	1.4	(1, 2.1)	0.069	0.069
Held a meeting in the past 6 months	Held a meeting in the past 6 months vs. none	0.9	(0.8, 1.2)	0.343	0.8	(0.6, 1.1)	0.139	0.139
At least one woman involved	At least one woman involved vs. none	0.9	(0.7, 1)	0.024	1	(0.8, 1.3)	0.959	0.959
Regulations	Regulations in place vs. none	1.1	(0.9, 1.3)	0.69	0.8	(0.6, 1.1)	0.149	0.149
Attends to the watershed	Some attention vs. none	2	(1.5, 2.6)	<0.001	1.2	(0.8, 1.7)	0.65	0.8849
	Most attention vs. none	2.6	(2, 3.4)	<0.001	1.1	(0.7, 1.7)	0.804	
Preventative maintenance	Committee conducts preventative maintenance vs. none	1.1	(0.9, 1.2)	0.863	1	(0.8, 1.4)	0.936	0.936
Technical support	System receives technical support vs. none	1.2	(1, 1.4)	0.063	1.1	(0.8, 1.3)	0.933	0.933
Corrective maintenance	Committee conducts corrective maintenance vs. none	2	(1.5, 2.8)	<0.001	2.1	(1.4, 3.4)	0.002	**0.002**
Funds available	Funds available vs. none	1.5	(1.2, 1.9)	0.001	0.7	(0.5, 1.1)	0.066	0.066
Replacement	Replacement funds available vs. none	1.2	(1.1, 1.5)	0.024	1	(0.8, 1.2)	0.5	0.5

Table 31.Univariable and multivariable logistic regression model for 24-hour water service in Nicaragua

Explanatory variable		**Unadjusted model**			**Adjusted model**			
		OR	**CI**	**p-value**	**OR**	**CI**	**p-value**	**Wald test p-value**
Supply type	Gravity piped vs. electric pump piped	2.9	(2.4, 3.5)	<0.001	3.4	(2.6, 4.4)	<0.001	**<0.001**
Sufficient water in the winter	Sufficient water in the winter vs. not	3.1	(1.9, 5)	<0.001	1.8	(1, 3.2)	0.068	0.068
Sufficient water in the summer	Sufficient water in the summer vs. not	2.1	(1.7, 2.5)	<0.001	2.6	(2.1, 3.3)	<0.001	**<0.001**
Age	5-10 vs. 0-5 years	0.8	(0.6, 1.1)	0.055	1.1	(0.8, 1.5)	0.988	0.1126
	10-15 vs. 0-5 years	0.7	(0.6, 1)	0.008	0.9	(0.6, 1.2)	0.208	
	15-20 vs. 0-5 years	0.7	(0.5, 0.9)	0.002	0.9	(0.6, 1.2)	0.336	
	20-25 vs. 0-5 years	0.7	(0.5, 1)	0.014	0.8	(0.6, 1.2)	0.229	
	25-30 vs. 0-5 years	0.6	(0.4, 0.9)	0.006	0.8	(0.5, 1.3)	0.276	
	30+ vs. 0-5 years	0.3	(0.2, 0.5)	<0.001	0.5	(0.4, 0.9)	0.006	
Deforestation	Little deforestation vs. a lot	1.2	(0.9, 1.5)	0.397	1	(0.7, 1.3)	0.672	0.3252
	No deforestation vs. a lot	1.8	(1.4, 2.2)	<0.001	1.2	(0.9, 1.7)	0.479	
State of the catchment	Requires maintenance vs. good condition	0.8	(0.7, 0.9)	<0.001	0.9	(0.7, 1.2)	0.212	0.1069
	Requires rehabilitation vs. good condition	0.5	(0.4, 0.6)	<0.001	0.7	(0.4, 1)	0.036	
State of the conduction	Requires maintenance vs. good condition	0.7	(0.6, 0.9)	<0.001	0.9	(0.7, 1.2)	0.393	0.4249
	Requires rehabilitation vs. good condition	0.5	(0.4, 0.6)	<0.001	0.8	(0.5, 1.2)	0.196	
State of the storage	Requires maintenance vs. good condition	0.7	(0.6, 0.8)	<0.001	1	(0.8, 1.3)	0.66	0.8666
	Requires rehabilitation vs. good condition	0.5	(0.4, 0.6)	<0.001	1	(0.6, 1.4)	0.644	
State of the distribution	Requires maintenance vs. good condition	0.7	(0.6, 0.8)	<0.001	0.8	(0.6, 1.1)	0.055	**0.0342**
	Requires rehabilitation vs. good condition	0.4	(0.3, 0.5)	<0.001	0.6	(0.4, 0.9)	0.013	
Population served (quintile)	Second lowest vs. lowest	0.9	(0.7, 1.2)	0.27	0.8	(0.6, 1.1)	0.052	**<0.001**
	Middle vs. lowest	1	(0.8, 1.3)	0.862	0.9	(0.6, 1.2)	0.261	
	second highest vs. lowest	0.7	(0.5, 0.9)	0.002	0.6	(0.5, 0.9)	0.002	
	highest vs. lowest	0.4	(0.3, 0.5)	<0.001	0.4	(0.3, 0.6)	<0.001	
Ethnicity	Indigenous vs. mestizo	1.4	(1.1, 1.9)	0.017	1	(0.7, 1.4)	0.843	0.843
Region	Carazo vs. Boaco	0.2	(0.1, 0.5)	<0.001	0.2	(0.1, 0.4)	<0.001	
	Chinandega vs. Boaco	0.7	(0.4, 1.2)	0.182	1	(0.6, 1.9)	0.874	**<0.001**
	Contales vs. Boaco	1.9	(1.1, 3.4)	0.048	1.9	(1, 3.6)	0.08	
	Esteli vs. Boaco	2.1	(1.3, 3.4)	0.007	2.3	(1.3, 4)	0.009	
	Granada vs. Boaco	0.6	(0.3, 1.3)	0.141	0.9	(0.4, 2.3)	0.713	
	Jinotega vs. Boaco	1.8	(1.1, 2.8)	0.028	1.3	(0.7, 2.2)	0.488	
	Leon vs. Boaco	1.8	(1.1, 3)	0.024	1.4	(0.8, 2.6)	0.284	
	Madriz vs. Boaco	0.5	(0.3, 0.8)	0.004	0.3	(0.2, 0.6)	<0.001	
	Managua vs. Boaco	0.3	(0.2, 0.6)	<0.001	0.4	(0.2, 1)	0.027	
	Masaya vs. Boaco	0.1	(0.1, 0.3)	<0.001	0.1	(0.1, 0.4)	<0.001	
	Matagalpa vs. Boaco	2.1	(1.3, 3.3)	0.002	1.6	(0.9, 2.8)	0.12	
	Nueva Segovia vs. Boaco	1	(0.6, 1.7)	0.88	0.8	(0.5, 1.5)	0.448	
	RACCN vs. Boaco	3.9	(1.8, 8.8)	0.001	1.8	(0.8, 4.5)	0.215	
	RACCS vs. Boaco	1.6	(1, 2.7)	0.087	1.9	(1.1, 3.4)	0.049	
	Rio San Juan vs. Boaco	1.4	(0.7, 2.8)	0.41	2.7	(1.2, 6.2)	0.024	
	Rivas vs. Boaco	0.6	(0.3, 1.2)	0.09	0.7	(0.3, 1.5)	0.297	
Service provider status	In process of legalization vs. not legalized	1.1	(0.9, 1.3)	0.886	0.9	(0.7, 1.2)	0.193	0.1013
	Legally established vs. not legalized	1	(0.9, 1.2)	0.796	1.2	(0.9, 1.5)	0.337	
Bank account	Bank account vs. none	0.8	(0.7, 1)	0.008	1.2	(0.9, 1.5)	0.434	0.434
Accounting	Financial accounting vs. none	0.8	(0.7, 0.9)	0.002	0.7	(0.5, 0.8)	<0.001	**<0.001**
Minutes	Meeting minutes vs. none	1.1	(0.9, 1.3)	0.561	1.2	(0.9, 1.6)	0.281	0.281
Held a meeting in the past 6 months	Held a meeting in the past 6 months vs. none	1.2	(1, 1.4)	0.315	1.2	(0.9, 1.6)	0.407	0.407
At least one woman involved	At least one woman involved vs. none	1	(0.8, 1.2)	0.429	0.8	(0.6, 1.1)	0.065	0.065
Regulations	Regulations in place vs. none	1.1	(0.9, 1.3)	0.658	1.2	(0.9, 1.5)	0.344	0.344
Attends to the watershed	Some attention vs. none	1.1	(0.8, 1.3)	0.955	1	(0.7, 1.4)	0.79	0.9165
	Most attention vs. none	1.3	(1.1, 1.7)	0.027	1.1	(0.8, 1.4)	0.956	
Preventative maintenance	Committee conducts preventative maintenance vs. none	1	(0.9, 1.2)	0.614	1.3	(1.1, 1.7)	0.047	**0.047**
Technical support	System receives technical support vs. none	0.9	(0.7, 1)	0.033	1.1	(0.9, 1.4)	0.495	0.495
Corrective maintenance	Committee conducts corrective maintenance vs. none	1.1	(0.9, 1.3)	0.748	1.1	(0.8, 1.5)	0.684	0.684
Funds available	Funds available vs. none	1.2	(1, 1.4)	0.279	1.1	(0.9, 1.4)	0.71	0.71
Replacement	Replacement funds available vs. none	0.9	(0.7, 1.1)	0.067	1.1	(0.8, 1.4)	0.769	0.769

Table 32. Univariable and multivariable linear regression model results for water service continuity in Panama

Explanatory variable		**Unadjusted model**			**Adjusted model**			
		OR	**CI**	**p-value**	**OR**	**CI**	**p-value**	**Wald test p-value**
Supply type	Gravity piped vs. electric pump piped	2.7	(1.9, 3.9)	<0.001	5.2	(3, 9.2)	<0.001	**<0.001**
Sufficient water in the summer	Sufficient water in the summer vs. not	2.3	(1.6, 3.3)	<0.001	2.7	(1.6, 4.6)	<0.001	**<0.001**
Sufficient water in the winter	Sufficient water in the winter vs. not	3	(1.8, 5.3)	<0.001	1.6	(0.8, 3.3)	0.228	0.228
Age	1-10 vs. 0 years	1	(0.6, 1.8)	0.918	1.2	(0.6, 2.5)	0.776	0.6569
	10-20 vs. 0 years	0.8	(0.5, 1.4)	0.304	0.9	(0.5, 1.8)	0.68	
	20-30 vs. 0 years	0.9	(0.6, 1.5)	0.605	0.8	(0.4, 1.5)	0.397	
Deforestation	Little deforestation vs. a lot	1.3	(0.7, 2.5)	0.564	1	(0.4, 2.4)	0.953	0.982
	No deforestation vs. a lot	2.3	(1.2, 4.4)	0.013	1	(0.4, 2.4)	0.852	
Intake status	Requires maintenance vs. good condition	0.6	(0.4, 0.9)	0.005	0.5	(0.3, 1)	0.025	**0.0061**
	Requires rehabilitation vs. good condition	0.4	(0.2, 0.6)	<0.001	0.3	(0.2, 0.7)	0.002	
Conduction status	Requires maintenance vs. good condition	0.7	(0.5, 1)	0.021	0.6	(0.3, 1.2)	0.101	0.2513
	Requires rehabilitation vs. good condition	0.4	(0.2, 0.7)	<0.001	0.6	(0.2, 1.7)	0.285	
State of the storage	Requires maintenance vs. good condition	0.2	(0.1, 0.4)	<0.001	0.3	(0.1, 0.8)	0.018	**0.0019**
	Requires rehabilitation vs. good condition	0.9	(0.6, 1.3)	0.443	1.8	(0.9, 3.4)	0.116	
State of the distribution	Requires maintenance vs. good condition	0.6	(0.4, 0.9)	0.003	0.7	(0.4, 1.4)	0.295	0.5691
	Requires rehabilitation vs. good condition	0.3	(0.2, 0.6)	<0.001	0.8	(0.3, 2)	0.526	
Population served (quintile)	Second lowest vs. lowest	2	(1.1, 3.6)	0.03	1.8	(0.9, 3.7)	0.136	0.6176
	Middle vs. lowest	1.4	(0.8, 2.4)	0.346	1.2	(0.6, 2.4)	0.744	
	second highest vs. lowest	1.2	(0.7, 2)	0.668	1.2	(0.6, 2.4)	0.721	
	highest vs. lowest	1.1	(0.7, 1.9)	0.797	1.1	(0.5, 2.3)	0.912	
Ethnicity	Indigenous vs. mestizo	1.5	(1, 2.2)	0.054	1.8	(1.1, 2.9)	0.034	**0.034**
Service provider status	In process of legalization vs. not legalized	1	(0.5, 2)	0.852	0.7	(0.3, 1.9)	0.439	0.1639
	Legally established vs. not legalized	1.4	(0.8, 2.3)	0.301	1.4	(0.7, 3.1)	0.436	
Bank account	Bank account vs. none	1	(0.7, 1.4)	0.734	1	(0.6, 1.6)	0.748	0.748
Accounting	Financial accounting vs. none	1	(0.7, 1.5)	0.878	1	(0.6, 1.7)	0.901	0.901
Minutes	Meeting minutes vs. none	1.3	(0.9, 1.8)	0.304	1.1	(0.6, 1.8)	0.956	0.956
Held a meeting in the past 6 months	Held a meeting in the past 6 months vs. none	1.2	(0.8, 1.8)	0.461	0.9	(0.6, 1.5)	0.601	0.601
At least one woman on water committee	At least one woman involved vs. none	0.6	(0.4, 1)	0.028	0.6	(0.4, 1.1)	0.091	0.091
Regulations	Regulations in place vs. none	1.4	(1, 2.1)	0.081	1.6	(0.9, 2.8)	0.126	0.126
Attends to the watershed	Some attention vs. none	1.6	(0.9, 3.1)	0.184	1.1	(0.5, 2.5)	0.913	0.8987
	Most attention vs. none	2.1	(1.2, 3.9)	0.02	1	(0.4, 2.2)	0.842	
Committee conducts preventative maintenance and funds available	No preventative maintenance and funds available vs. none	3.4	(1.8, 6.6)	<0.001	1.3	(0.5, 3.3)	0.619	--*
	Preventative maintenance and no funds available vs. none	1.8	(0.8, 4.1)	0.172	0.8	(0.3, 2.4)	0.653	
	Preventative maintenance and funds available vs. none	2.3	(1.4, 4)	0.003	0.7	(0.3, 1.7)	0.364	
Technical support	System receives technical support vs. none	0.9	(0.6, 1.2)	0.299	0.8	(0.5, 1.3)	0.265	0.265
Corrective maintenance	Committee conducts corrective maintenance vs. none	1.4	(0.9, 2.1)	0.144	1	(0.6, 1.9)	0.922	0.922
Replacement funds	Replacement funds available vs. none	1.8	(1.2, 2.7)	0.005	2	(1.2, 3.5)	0.016	**0.016**

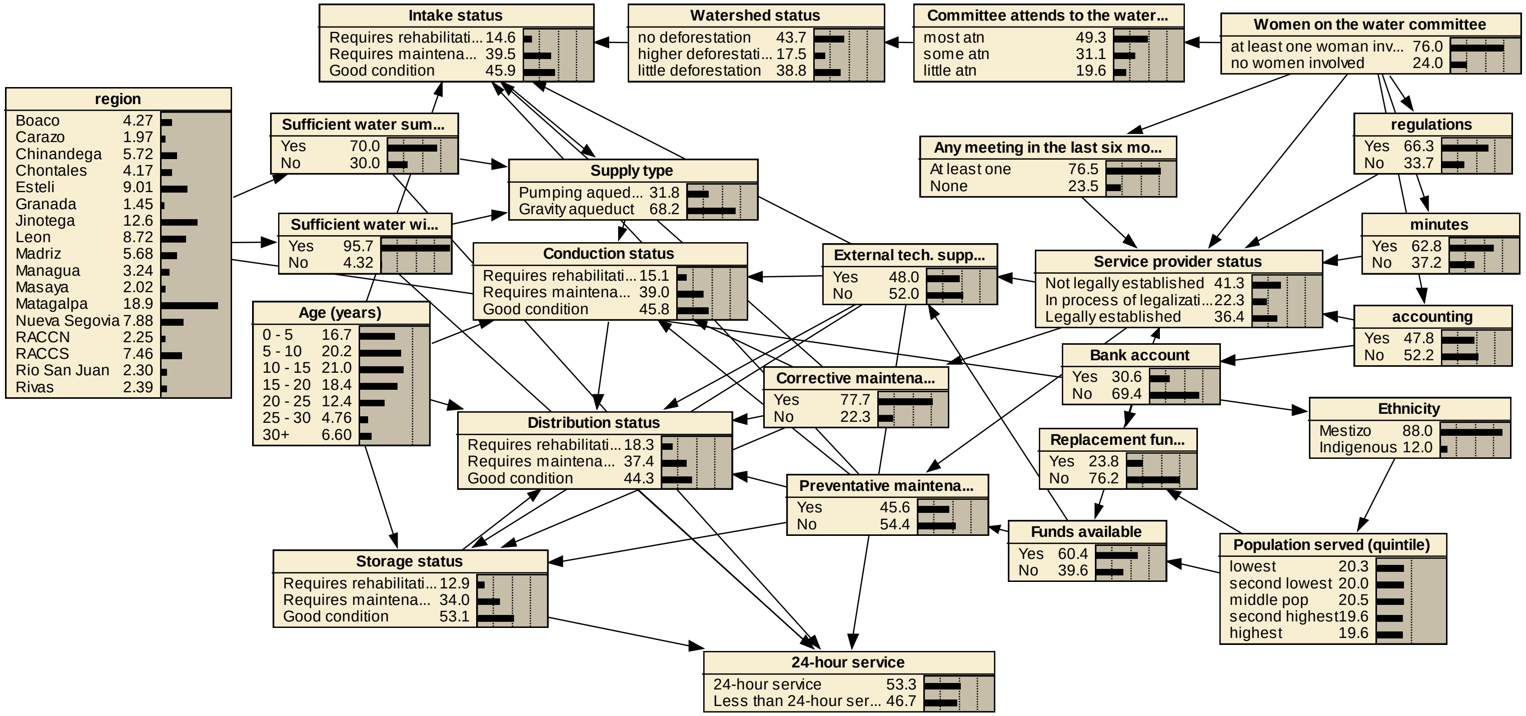

Figure 20. Base-case Bayesian network model for Nicaragua.

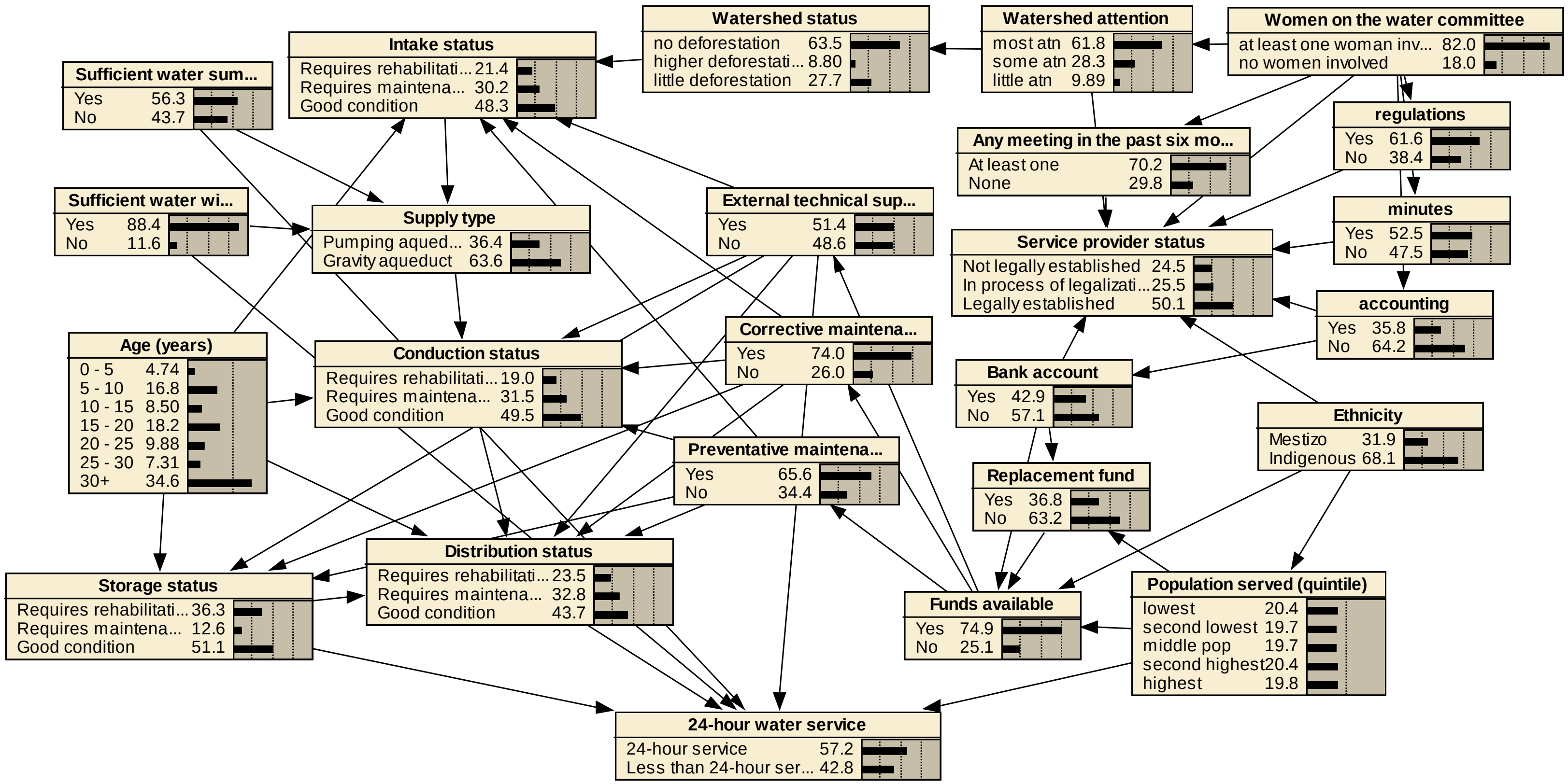

Figure 21. Base-case Bayesian network model for Panama

Table 33. Sensitivity of 'Continuity' to a finding at another node (Honduras)

Node	Mutual information	Percent	Variance of Beliefs
continuity	0.95436	100	0.2343493
Sufficient water summer	0.05488	5.75	0.0181087
Sufficient water winter	0.00592	0.62	0.0019939
Storage status	0.00437	0.458	0.0014566
Distribution status	0.00349	0.365	0.0011548
region	0.00293	0.307	0.0009601
Conduction status	0.00243	0.254	0.0008056
Corrective maintenance	0.00192	0.201	0.0006411
Intake status	0.00129	0.135	0.0004241
Source type	0.00043	0.0454	0.0001407
System age(years)	0.00028	0.0295	0.0000914
Preventative maintenance	0.00025	0.0263	0.0000818
Supply type	0.00005	0.00544	0.0000169
Replacement funds	0.00004	0.00449	0.0000139
Watershed status	0.00003	0.00288	0.0000089
Service provider status	0.00001	0.00138	0.0000043
Funds available	0.00001	0.00107	0.0000033
Watershed attention	0.00001	0.000701	0.0000022
Ethnicity	0.00001	0.0006	0.0000019
Bank account	0	0.000508	0.0000016
Funds available per household	0	0.000221	0.0000007
Population served (quintile)	0	0.000179	0.0000006
accounting	0	3.11E+00	0.0000001
External technical support	0	1.44E-05	0
regulations	0	0	0
minutes	0	0	0
Committee held mtg. past six mos.	0	0	0
Women on the committee	0	0	0

Table 34. Sensitivity of 'Continuity' to a finding at another node (Nicaragua)

Node	Mutual information	Percent	Variance of Beliefs
continuity	0.99683	100	0.2489014
Sufficient water summer	0.00938	0.941	0.0032398
Distribution status	0.00783	0.785	0.0026957
External technical support	0.00367	0.369	0.001267
Storage status	0.00365	0.366	0.0012595
Conduction status	0.00092	0.0928	0.0003191
Age	0.00059	0.0595	0.0002044
Sufficient water winter	0.00054	0.0546	0.0001883
region	0.0005	0.0501	0.0001722
Supply type	0.00041	0.0411	0.0001412
Corrective maintenance	0.00014	0.0145	0.0000498
Preventative maintenance	0.00008	0.00821	0.0000282
Service provider status	0.00005	0.00508	0.0000175
Funds available	0.00004	0.00414	0.0000142
Intake status	0.00002	0.00177	0.0000061
Bank account	0.00001	0.00133	0.0000046
ethnicity	0.00001	0.000559	0.0000019
accounting	0	0.000342	0.0000012
regulations	0	0.00013	0.0000005
Women on the committee	0	0.000108	0.0000004
Population served (quintile)	0	0.000102	0.0000004
Minutes	0	9.70E-05	0.0000004
Replacement fund	0	3.98E-05	0.0000002
Any meeting in the past six months	0	2.82E-05	0.0000001
Watershed status	0	0	0
Watershed attention	0	0	0

Table 35. Sensitivity of 'Continuity' to a finding at another node (Panama)

Node	Mutual information	Percent	Variance of Beliefs
continuity	0.98479	100	0.2447475
Distribution status	0.0091	0.924	0.0030756
Sufficient water summer	0.00409	0.415	0.0013893
Storage status	0.00403	0.409	0.0013798
Sufficient water winter	0.00213	0.216	0.0007281
Population served (quintile)	0.00121	0.123	0.0004113
Conduction status	0.00117	0.118	0.0003957
Technical support	0.00071	0.0718	0.00024
Age category	0.00024	0.0245	0.0000818
Supply type	0.00017	0.0173	0.0000578
Preventative maintenance	0.00016	0.016	0.0000535
Corrective maintenance	0.00013	0.0129	0.000043
Funds available	0.00003	0.0026	0.0000087
Intake status	0.00001	0.00106	0.0000035
Ethnicity	0.00001	0.000728	0.0000024
Bank account	0	0.000185	0.0000006
minutes	0	0	0
Women on the committee	0	0	0
regulations	0	0	0
Any meeting in the past six months	0	0	0
Service provider status	0	0	0
Watershed attention	0	0	0
Watershed status	0	0	0
Accounting	0	0	0
Replacement fund	0	0	0

Table 36. Bayesian network model evaluation results for Honduras, Nicaragua, and Panama

Model evaluation	**Honduras**	**Nicaragua**	**Panama**
Logarithmic Loss	0.5495	0.6778	0.6313
Quadratic Loss	0.3640	0.4842	0.4368
Spherical payoff	0.7960	0.7184	0.7514
Area under the receiver operating characteristic (ROC)	0.7044	0.5982	0.6302

Table 37. Predicted 24-hour water service availability in Honduras in different scenarios using Bayesian networks

Scenario	Predicted 24-hour continuity (percentage of systems)	Percentage point difference from base case	State and nodes modified
Best case management, no water scarcity	81	+18	Conduction status (good condition), storage status (good condition), distribution status (good condition), sufficient water summer (yes)
Base case, no water scarcity	72	+9	Sufficient water summer (yes)
Best case management	68	+5	Conduction status (good condition), storage status (good condition), distribution status (good condition), corrective maintenance (yes)
Base case	63	+0	None
Worst case management, no water scarcity	63	+0	Storage status (requires rehabilitation), conduction status (requires rehabilitation), distribution status (requires rehabilitation), preventative maintenance (no), external technical support (no), Sufficient water summer (yes)
Worst case management	55	-8	Storage status (requires rehabilitation), conduction status (requires rehabilitation), distribution status (requires rehabilitation), preventative maintenance (no), external technical support (no)
Base case, water scarcity	43	-20	Sufficient water summer (no)
Worst case management, water scarcity	39	-24	Storage status (requires rehabilitation), conduction status (requires rehabilitation), distribution status (requires rehabilitation), preventative maintenance (no), external technical support (no), Sufficient water summer (no)
Best case management, water scarcity	38	-25	Conduction status (good condition), storage status (good condition), distribution status (good condition), sufficient water summer (no)

Table 38. Predicted 24-hour water service availability in Nicaragua in different scenarios using Bayesian networks

Scenario	Predicted 24-hour continuity (percentage of systems)	Percentage point difference from base case	State and nodes modified
Best case management, no water scarcity	66	+13	Catchment status (Good condition), distribution status (good condition), Sufficient water summer (yes)
Best case management	62	+9	Catchment status (Good condition), distribution status (good condition)
Base case, no water scarcity	57	+4	Sufficient water summer (yes)
Base case	53	0	None
Best case management, water scarcity in summer	52	-1	Catchment status (Good condition), distribution status (good condition), Sufficient water summer (no)
Base case, water scarcity in summer	45	-8	Sufficient water summer (no)
Worst case management, no water scarcity	40	-13	conduction status (requires rehabilitation), distribution status (requires rehabilitation), storage status (requires rehabilitation), corrective maintenance (no), Sufficient water summer (yes)
Worst case management	36	-17	conduction status (requires rehabilitation), distribution status (requires rehabilitation), storage status (requires rehabilitation), corrective maintenance (no),
Worst case management, water scarcity in summer	26	-27	conduction status (requires rehabilitation), distribution status (requires rehabilitation), storage status (requires rehabilitation), corrective maintenance (no), Sufficient water summer (no)

Table 39. Predicted water service continuity in Panama under different scenarios using Bayesian networks

Scenario	Predicted 24-hour continuity (percentage of systems)	Percentage point difference from base case	State and nodes modified
Best case management, no water scarcity	71	+14	Catchment status (Good condition), conduction status (good condition), storage status (good condition), Sufficient water summer (yes)
Best case management	67	+10	Catchment status (Good condition), conduction status (good condition), storage status (good condition)
Base case, no water scarcity	61	+4	Sufficient water summer (yes)
Best case management, water scarcity in summer	61	+4	Catchment status (Good condition), conduction status (good condition), storage status (good condition), Sufficient water summer (no)
Worst case management, no water scarcity	59	+2	conduction status (requires rehabilitation), storage status (requires rehabilitation), distribution status (requires rehabilitation), external technical support (no), water summer (yes)
Base case	57	+0	none
Worst case management	54	-3	conduction status (requires rehabilitation), storage status (requires rehabilitation), distribution status (requires rehabilitation), external technical support (no)
Base case, water scarcity in summer	53	-4	Sufficient water summer (no)
Worst case management, water scarcity in summer	47	-10	conduction status (requires rehabilitation), storage status (requires rehabilitation), distribution status (requires rehabilitation), external technical support (no), water summer (no)

APPENDIX 3 FOR CHAPTER 6

Table 40. Water and sanitation country performance values

Country	Water access	Water access trend	Water equity	Water equity trend	Sanitation access	Sanitation access trend	Sanitation equity	Sanitation equity trend
Afghanistan	0.56	↓	0.04	↑	0.03	↓	-0.05	↑
Albania	-0.08	→	-0.06	→	0.28	↓	0.46	→
Algeria	-0.12	↑	0.10	↑	0.15	→	0.27	↑
American Samoa	0.06	↓						
Angola							-0.17	↓
Antigua and Barbuda	0.01	N/A			0.19	N/A		
Argentina	0.13	↑	0.27	↑	0.57	↑	0.38	↑
Armenia	0.10	↓	0.07	↓	0.09	↑	0.09	→
Aruba	0.12	N/A			-0.05	N/A		
Azerbaijan	0.14	N/A	0.16	N/A				
Bahamas	0.08	N/A			0.12	N/A		
Bangladesh	-0.02	→	0.05	↑	0.50	↑	0.07	→
Belarus	-0.29	↓	1.00	↑	-0.40	↓	-0.42	↓
Belize	0.07	→	0.05	↓	0.33	→	0.15	↑
Benin	-0.06	↓	-0.07	↓	0.24	→	-0.08	→
Bhutan	0.38	↑	0.20	↑	0.22	N/A	0.01	N/A
Bolivia	0.31	→	0.35	→	0.39	↑	-0.16	→
Bosnia and Herzegovina	0.22	↑	0.08	↑	-0.15	↓	-0.17	↓
Botswana	0.12	→	0.11	→	-0.04	↓	-0.35	↓
Brazil	0.11	↓	0.14	→	0.28	→	-0.10	→
Bulgaria	0.01	→	0.01	→		N/A		
Burkina Faso	-0.01	↓	-0.11	↓	-0.05	→	0.24	↑
Burundi	0.47	↑	0.03	↓	-0.11	→	-0.51	↓
Cambodia	0.01	↓	-0.05	→	0.35	→	0.36	↑
Cameroon	0.01	→	0.06	→	0.05	→	0.05	→
Cape Verde	0.02	→	-0.28	↓	0.26	↓	0.07	↓
Central African Republic	-0.03	↓	0.00	→	0.17	↑	-0.44	↓
Chad	0.02	↓	-0.05	→	-0.02	↓	-1.00	→
Chile	0.16	→	0.16	↑	0.35	↑	0.67	↑
China	0.33	↑	0.21	↑	0.66	↑	0.25	↑
Colombia	-0.69	↓	-0.02	↑				
Comoros	-0.07	↓	0.06	↓	0.28	↑	0.03	→
Congo	0.15	↑	0.14	↑	0.07	↓	-0.07	→
Cook Islands				→	0.25	↑		
Costa Rica	-0.17	→			-0.27	↓	-0.06	→
Cote d'Ivoire	0.12	→	-0.04	→	0.14	→	-0.11	↓
Cuba	0.10	N/A	0.09	N/A	0.07	↓	0.21	→
DR Congo	0.22	↑	0.12	→	-0.39	↓	-0.19	↓

Djibouti	0.18	N/A	-0.30	N/A	-0.01	N/A	-0.19	N/A
Dominican Republic	-0.17	↓	0.19	→	-0.17	→	-0.24	→
Ecuador	0.04	↓	0.03	↓	0.11	→	0.15	↓
Egypt	0.00	↓	-0.05	→	0.94	↑	1.00	↑
El Salvador	1.00	↑	0.50	↑	0.60	↑	0.51	↑
Estonia	0.12	↑	0.00	→	-1.00	↓	1.00	↑
Ethiopia	0.29	→	0.12	↑	0.34	↓	0.46	↑
Fiji	-0.01	N/A	0.11	N/A	0.45	↑	0.60	↑
French Polynesia					-0.10	N/A		
Gabon	0.18	N/A	0.21	N/A	0.08	N/A	-0.11	N/A
Gambia	0.15	↓	-0.23	↓	-0.07	↓	-0.26	↓
Georgia	0.04	↓	0.02	↓	-0.12	→	-0.14	→
Ghana	-0.30	→	-0.09	↓	-0.23	→	-0.22	→
Guam	-0.03	↑			0.09	→		
Guatemala	-0.13	↓	-0.08	↓	0.20	↓	0.00	↓
Guinea	0.19	→	0.00	↓	0.22	↑	-0.20	↑
Guinea-Bissau	0.17	↓	0.06	↑	0.19	↑	-0.12	→
Guyana	-0.10	↓	0.05	↓	0.21	→	0.09	→
Haiti	0.02	→	0.06	↓	0.50	↑	-0.08	↓
Honduras	0.11	→	-0.12	→	-0.10	→	-0.06	→
India	0.00	↓	0.13	→	0.29	↑	-0.41	↓
Indonesia	-0.03	→	0.06	→	0.29	↑	0.25	→
Iran	0.03	→	-0.02	→	-0.01	↓	-0.01	↓
Iraq	0.50	↑	0.46	↓	0.45	↑	0.42	→
Jamaica	0.14	→	0.07	→	0.62	↓	-0.06	→
Jordan	-0.35	↓	-0.14	↓	1.00	↑	0.89	↑
Kazakhstan	0.30	↑	0.18	↑	0.10	↓	0.07	→
Kenya	0.14	→	-0.03	↓	0.18	→	-0.07	→
Kiribati	0.13	N/A	0.01	N/A	0.13	↑	0.06	→
North Korea	-0.20	↑	-0.04	→	0.34	N/A	-0.07	N/A
Kyrgyzstan	0.30	→	-0.15	↓	-0.02	↓	-0.07	↓
Lao PDR	0.49	↑	-0.01	↓	0.34	→	0.13	↑
Lesotho	0.16	↑	-0.02	↑	0.26	↑	-0.10	→
Liberia	0.58	↑	0.78	↑	-0.13	↓	-0.16	↓
Lithuania	0.05	→	-0.03	→	0.35	↑	0.41	↑
Madagascar	0.00	→	0.01	↓	-0.12	↓	-0.25	↓
Malawi	0.15	↓	0.09	↓	0.97	→	-0.26	↓
Maldives	0.48	↑	0.24	↑	0.58	↑	0.53	↑
Mali	0.68	↑	0.10	↑	0.00	↓	-0.02	→
Marshall Islands	0.22	↑	0.07	→	0.11	→	0.09	→
Mauritania	-0.15	↓	0.18	↓	0.26	↑	-0.36	→
Mauritius	0.20	N/A	0.06	N/A	0.18	N/A	0.16	N/A
Mexico	0.38	↑	-0.03	→	0.21	→	0.10	↓
Micronesia	0.25	N/A	-0.03	N/A	0.28	N/A	0.03	N/A
Mongolia	0.16	↓	0.45	↑	0.25	→	0.10	↓

Montengro	0.10	N/A	-0.06	N/A				
Morocco	0.09	↑	0.05	↑	0.21	→	0.25	↑
Mozambique	0.23	↑	-0.23	↑	0.38	↑	-0.21	↑
Myanmar	0.33	↑	0.14	↑	0.07	↓	0.06	↓
Namibia	-0.15	↓	-0.13	↓	0.10	→	0.28	↓
Nepal	0.61	→	0.32	→	0.62	↓	0.23	→
Nicaragua	0.09	→	-0.02	↓	0.09	→	-0.14	↓
Niger	0.34	→	0.56	↑	0.01	↓	1.00	↑
Nigeria	0.57	↑	0.27	→	-0.04	↓	0.42	→
Niue	-0.04	N/A				N/A		
Northern Mariana Islands	0.15	→			0.21	→		
Palestine	-0.31	↓	-0.10	↓	-0.14	↓	-0.05	↓
Oman	0.19	N/A	0.03	N/A	0.25	N/A	0.49	N/A
Pakistan	0.40	↑	0.27	↓	0.52	↑	0.64	↑
Palau	0.15	→	0.11	↓	0.61	↑	0.54	↑
Panama	0.09	→	0.05	↓	0.05	→	-0.05	↓
Papua New Guinea	0.07	N/A	0.06	N/A	-0.01	N/A	0.07	N/A
Paraguay	0.20	→	0.09	↑	0.45	→	0.32	↑
Peru	0.29	→	0.31	→	0.25	→	0.10	↑
Philippines	0.00	→	0.01	↓	0.08	↓	0.01	→
Portugal	0.11	N/A	0.02	N/A		N/A		
Republic of Korea	0.17	↓	0.24	↑		↑		
Republic of Moldova	0.13	↑	0.06	↑	0.14	→	0.06	↑
Russian Federation	0.12	↑	0.13	↑	-0.17	↑	0.18	→
Rwanda	0.19	↓	0.01	↓	0.45	↓	0.15	↑
Saint Lucia	0.22	↑	0.01	→	0.01	↓	0.02	↓
Samoa	-0.14	↓	-0.10	↓	-0.69	N/A	-0.39	↓
Sao Tome and Principe	0.45	N/A	0.11	N/A	0.23	N/A	-0.07	N/A
Saudi Arabia	0.12	N/A			0.28	→		
Senegal	0.14	↑	0.33	→	0.33	↓	0.24	→
Serbia	-0.06	↓	-0.03	↑	0.05	→	-0.30	↓
Sierra Leone	0.06	→	0.89	↑	-0.26	N/A	0.51	↑
Solomon Islands	-0.37	N/A	-0.07	N/A	0.34	N/A	-0.02	N/A
Somalia	0.51	N/A	-1.00	N/A	0.00	↑	-0.38	N/A
South Africa	0.13	↑	0.10	↑	0.67	↑	0.68	↑
Sri Lanka	0.50	↑	0.30	↑	0.61	↑	0.28	↑
Sudan	-0.12	N/A	0.03	N/A	-0.06	N/A	0.03	N/A
Suriname	0.17	N/A	0.17	N/A	-0.01	N/A	-0.01	N/A
Swaziland	0.24	↓	0.17	↓	0.22	↓	0.17	↓
Syrian Arab Republic	-0.05	↓	0.11	→	-0.02	↓	-0.03	↓
Tajikistan	0.63	↑	0.47	↑	0.12	↑	0.14	↑
Thailand	0.47	↑	0.19	→	-0.41	↓	-0.16	↓
Timor-Leste	-0.03	↓	-0.27	↓	-0.30	↓	-0.74	↓
Togo	0.16	↑	-0.10	↓	0.02	→	-0.04	→

Tonga					-0.07	N/A	-0.09	N/A
Trinidad and Tobago	0.12	↑	0.01	→	-0.19	↓	0.04	↓
Tunisia	0.13	↓	0.12	→	0.25	↑	0.41	↑
Turkey	0.24	→	0.12	↓	0.17	↑	0.14	↑
Tuvalu	0.15	N/A	0.02	→	0.12	N/A	-0.02	N/A
Uganda	0.16	↓	0.02	→	0.14	→	0.39	→
Ukraine	0.30	↑	0.24	↑	0.50	↑	0.73	↑
Tanzania	0.34	↓	0.48	→	0.63	↑	-1.00	↓
Uruguay	0.28	↓	0.38	↑	0.27	→	0.29	→
Uzbekistan	0.23	↑	0.02	↑	0.70	↑	0.54	↑
Vanuatu	0.26	→	0.17	→	-0.36	↓	-0.34	↓
Venezuela	0.07	N/A	0.03	N/A	0.13	N/A	0.08	N/A
Viet Nam	0.45	→	0.13	↓	0.24	→	0.17	↑
Zambia	0.10	→	0.20	↑	-0.03	→	0.13	→
Zimbabwe	0.47	→	0.51	→	-0.12	↓	0.11	↓

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