

## ARTICLE OPEN



# Comparing utility-reported hours of piped water supply to households' experiences

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Piped water supplies that deliver water only intermittently serve more than one billion people around the world. Measuring the continuity of these intermittent water supplies (IWS) is necessary for tracking utility performance and understanding the impact on consumers. We compared reporting of IWS continuity between utility benchmarking data on hours of water supply and households' reports of water outages in piped systems in Peru. Nationally, the estimated population with IWS as reported by households (23–26%) was slightly higher than that reported by utilities (20–21%) from 2010 to 2014. While the national population with IWS was markedly similar between both measures, household- and utility-reported IWS matched in only 2 of the 23 regions of Peru. We examined the influence of varying thresholds of water supply continuity on the results. Our findings highlight a need to reconcile different approaches to monitoring piped water supply continuity.

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## INTRODUCTION

More than one billion people around the world are served with intermittent water supplies (IWS), in which consumers receive water through a piped network for <24 h per day<sup>1</sup>. IWS can negatively impact water supply infrastructure and result in adverse health effects and higher costs to households due to unsafe water quality, limited water quantities, reliance on alternative sources, and additional expenditures to store, treat, and supplement the intermittently delivered water<sup>2–6</sup>. Continuity of supply is commonly used as a benchmark of utility performance and a goal to be achieved, with 24 h, 7 days a week of supply (continuous supply) considered the gold standard<sup>7–9</sup>.

Despite the widespread prevalence of IWS and the definition of safely managed water under the sustainable development goals (SDGs), indicating that water should be *available when needed*, there is no standard method for measuring or reporting piped water continuity<sup>10,11</sup>. While a piped system is considered an IWS if it regularly provides fewer than 24 h of water supply per day, the hours of supply that utilities provide and consumers receive can vary substantially within the same system and between systems<sup>5,7,10</sup>. Households near a treatment plant or situated off of a trunk main may receive more hours of supply than those at network extremities, as water may need to flow through the trunk main to reach other areas, and pressures can drop throughout the system from high demand, high elevation, or leakages<sup>12–15</sup>. The most systematic collection of data on piped water continuity is collected through the World Bank International Benchmarking Network (IBNET), which asks utilities to report their supply in hours per day. However, many towns and cities have reported in case studies that delivery does not occur daily, a detail that is not captured in IBNET<sup>5,7</sup>. Furthermore, there is no published guidance on how utilities report these hours—such as, as hours supplied from the source or treatment plant, as received by households, the average across an entire city, or the least hours experienced by households. An alternative approach to collecting data on interruptions in supply is asking households directly; several countries' Demographic and Health Surveys (DHS) now include

questions on water outages, although these are not specific to reporting piped water continuity.

The number of people receiving water intermittently is likely to increase as climate change and rapid urbanization further stress resources for providing drinking water<sup>5</sup>. While converting from an IWS to a continuous water supply (CWS) is a common overall goal, this goal is likely unattainable in the near-term for many utilities around the world. Utilities, regulators, and international agencies want to measure and track water service performance to monitor progress and develop strategies for improving continuity in intermittent water supplies. To do so, it is necessary to develop a standard method of measuring and accounting for IWS to allow tracking of progress and to better understand between- and within-country and utility variations of performance.

The objective of this research was to compare utility-reported hours of piped water supply with household-reported measures of reliability, with the goal of triangulating water supply continuity in Peru nationally and regionally. Specifically, we drew on water supply continuity data supplied by Peruvian utilities reporting to the IBNET in all regions in Peru, and a sample of households reporting on continuity of piped drinking water supplies through the DHS program for 2010–2014. We developed and tested methods of aligning these two data sources and determined the thresholds at which utility-reported hours of piped water supply most closely match household-reported outages to better understand variability within different regions of Peru. We also used the same methods to compare national results from three other countries.

## RESULTS

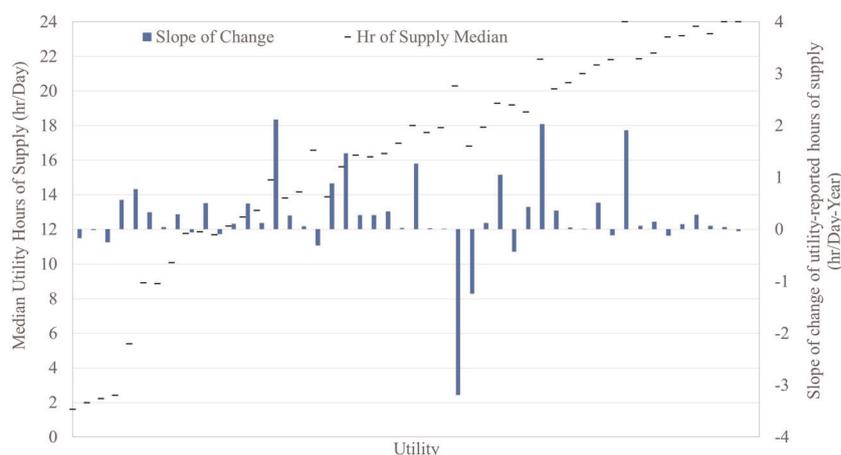
### National comparison

Fifty utilities in Peru reported continuity of supply to IBNET from 2010 to 2014, with reporting utilities covering ~30 million residents. Over that time, water supply coverage (the percent of populations served by these utilities) increased by 6 percentage points (Table 1). The mean hours of supply provided by these

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**Table 1.** Descriptive information of water service in Peru, including summaries of utility- and household-reported intermittency.

	2010	2011	2012	2013	2014	Mean	Source
Population total (millions)	29.3	29.7	30.1	30.5	31.0	30.1	UNPD <sup>a</sup>
Urban population (%)	76%	77%	77%	77%	77%	76.8	UNPD <sup>a</sup>
<b>Utility-reported data</b>							
Utilities reporting continuity/utilities reporting to IBNET	49/50	50/50	50/50	49/50	48/50	49/50	IBNET <sup>b</sup>
Population covered (millions)	15.9	16.3	16.7	17.1	17.5	16.5	IBNET <sup>b</sup>
Coverage (%)	85	86	88	90	91	88	IBNET <sup>b</sup>
Mean continuity of supply (h/day)	15.1 (SD: 6.3)	15.3 (SD: 6.2)	15.9 (SD: 6.3)	16.0 (SD: 6.5)	16.2 (SD: 6.2)	15.7	IBNET <sup>b</sup>
Population served by utilities reporting < 24 h/day (millions)	15.9	16.2	16.6	17.0	17.4	16.6	IBNET <sup>b</sup>
Population served by utilities reporting <12 h/day (millions)	3.4	3.4	3.40	3.5	3.6	3.5	IBNET <sup>b</sup>
<b>Household-reported data</b>							
Households surveyed	26,605	26,528	27,218	28,324	30,361	27,807	DHS <sup>c</sup>
Households surveyed with piped water supply	19,900	19,919	20,360	20,531	22,468	20,636	DHS <sup>c</sup>
Urban households reporting outages <sup>d</sup>	3180	2931	3240	2993	3371	3143	DHS <sup>c</sup>
Rural households reporting outages <sup>d</sup>	2078	2014	1869	1768	2104	1938.8	DHS <sup>c</sup>
Total households surveyed with outages <sup>d</sup>	5258	4945	5109	4761	5475	5109	DHS <sup>c</sup>
<b>Calculated indicators</b>							
Percent of the population served by utilities reporting <12 h/day (%)	21.0%	21.2%	20.4%	20.6%	20.3%	20.7%	Calculated from IBNET
Percent of surveyed households using piped water and reporting outages (%)	26.4%	24.8%	25.1%	23.2 %	24.4%	24.8%	Calculated from DHS

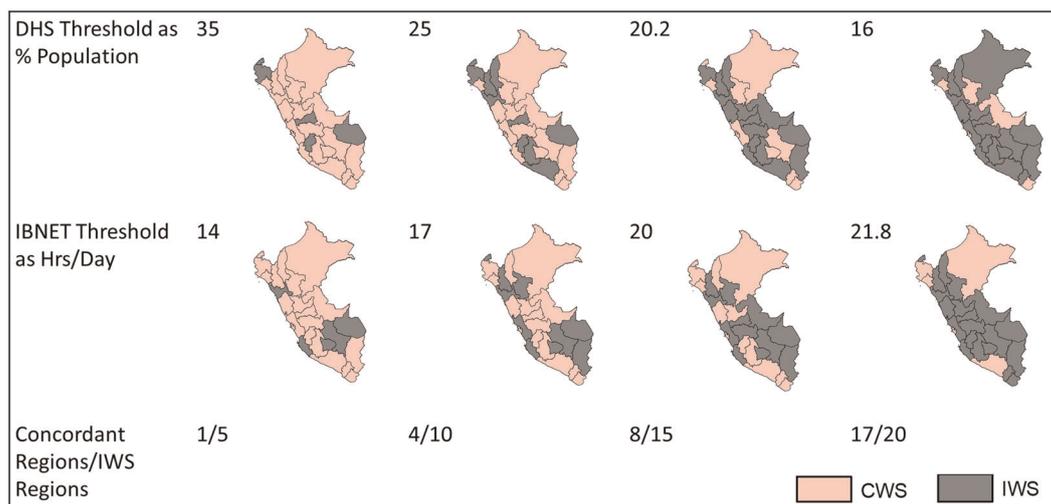
<sup>a</sup>Ref. 17.<sup>b</sup>Ref. 18.<sup>c</sup>Refs 19–23.<sup>d</sup>Yes to question SH43 in DHS (in English: in the last 2 weeks was water discontinued for a day or more? (Yes/No); in Spanish: En las últimas dos semanas ¿Tuvo un corte de agua todo un día o más tiempo?) (Si/No).**Fig. 1** Continuity as reported by utilities to IBNET in Peru. Each reporting utility is on the x-axis, shown in order of median hours of supply from left to right. Horizontal lines represent median hours of supply for each utility (left hand y-axis). Blue bars represent the slope of change of supply hours between 2010 and 2014 (right hand y-axis) (data in Supplementary Table S1). Values for the slope is the average change in h/day per year.

utilities was 15.7 h per day (h/day) (SD: 0.7), with mean supply continuity increasing by almost 1 h/day over these 5 years, although this increase was not consistent across all utilities (Supplementary Table S1). Coverage by piped water connections for urban populations in Peru increased from 89 to 91% and for rural populations from 53 and 61% piped from 2010 to 2014 (Supplementary Fig. S1)<sup>16,17</sup>.

Over the same years, a mean of 24.8% (SD: 1.2%) of households surveyed through the Demographic and Health Survey (DHS)

reported that water was unavailable for an entire day in the past 2 weeks (Table 1), although this varied between 3.3 and 49.8% in different regions (Supplementary Table S2). The percent of households reporting these outages decreased by a mean of −0.32 percentage points (SD: 0.014) annually (Table 1 and Supplementary Table S2).

Utility-reported supply continuities ranging from 1.6 to 24 h/day, although these varied between years (Fig. 1 and Supplementary Fig. S3 and Supplementary Table S1). Most utilities



**Fig. 2** Regions in Peru classified as intermittent with varying thresholds of the percent of population in the DHS considered as IWS and IBNET-reported hours of supply. Each column represents setting thresholds (for household or utility-reported data) resulting in the number of IWS regions of 5, 10, 15, and 20. Concordant regions/IWS regions represents the number of regions that are the same between both measures.

showed small improvements in continuity of a  $\leq 2\%$  increase in supply hours (Fig. 1). Of the 50 utilities, 13 reported a decline in hours of supply (indicated by a negative slope of change in their supply hours) from 2010 to 2014 (Fig. 1). All but 2 of the 50 utilities provided  $< 24$  h per day of supply, and 13 utilities reported  $< 12$  h per day on average. Using a threshold of 12 h/day, which is also used by the World Health Organization/UNICEF Joint Monitoring Program (JMP) to define IWS, an estimated 3.5 million people in Peru were served by IWS between 2010 and 2014, which is  $\sim 21\%$  of the total population (Table 1). There were no associations between the hours of water supply of a utility and the population served (Fig. S2 and Supplementary Table S3), nor was the improvement or decline in hours dependent on the median hours of supply provided (Fig. 1).

The estimated percent of households with IWS as reported by households using DHS data was slightly higher than the population reported by utilities through IBNET for the same years (Table 1). Therefore, on a national level and using our designations (utilities reporting  $< 12$  h supply and households reporting an outage in the last 2 weeks categorized as intermittent), utilities reported more supply continuity than households do, although these estimates were notably within 5 percentage points.

#### Regional comparison

While national estimates of the populations served by IWS using utility- and household-reported data were close, these did not align between regions (Fig. 2). Notably, many regions had no utility-reported population with IWS when households did report intermittency in the surveys; conversely, many regions had a high-utility-reported percent of the population with IWS and low household-reported outages. Overall, there was a much wider range of utility-reported populations with IWS (from 0 to 100%), while household-reported IWS per region stayed within a narrower range of values (between 2.65 and 49.3%) due to our methods of classifying regions as IWS or not IWS.

We conducted this analysis using both 12 and 16 h/day thresholds for the utility-reported IWS. While 12 h/day is used by the World Health Organization/UNICEF Joint Monitoring Program (JMP), we chose to examine the more stringent threshold of 16 h/day<sup>16,24</sup>. As will be seen in the sensitivity analysis, using a threshold of 16 h/day for utility-reported data resulted in equivalent percentages of the population with IWS as from household-reported outages,

suggesting that 16 h/day may be a more representative “threshold” at which people report outages in their water supply in this case.

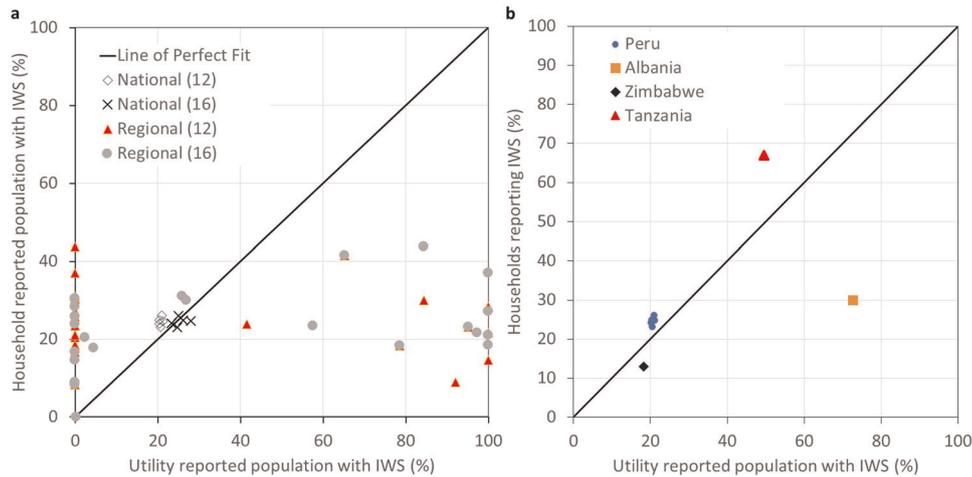
We defined regions as either supplying IWS or not based on a threshold of each region’s percent population with IWS (for household-defined IWS) or number of hours of supply per day (for utility-defined IWS) (Fig. 2). For example, lowering the threshold of percent population with household-reported IWS (e.g., from 35 to 25%) increased the number of regions defined as IWS; correspondingly, increasing the threshold for utility-reported hours of supply (e.g., from 14 to 17 h/day) increased the number of regions defined as IWS. When we varied both thresholds to arrive at the same number of regions categorized as IWS, the regions we categorized as IWS were not concordant: for example, both methods yielded 10 IWS regions when using the 25% and 17 h/day thresholds, but only four of these regions were the same (Fig. 2). The highest concordance in regions was achieved when thresholds were set as at least 16% and 21.8 h/day were used. Only two regions, Huánuco and San Martín, had utility- and household-reported continuity values that closely matched (Fig. 3a and Supplementary Tables S1 and S3).

#### Global analysis

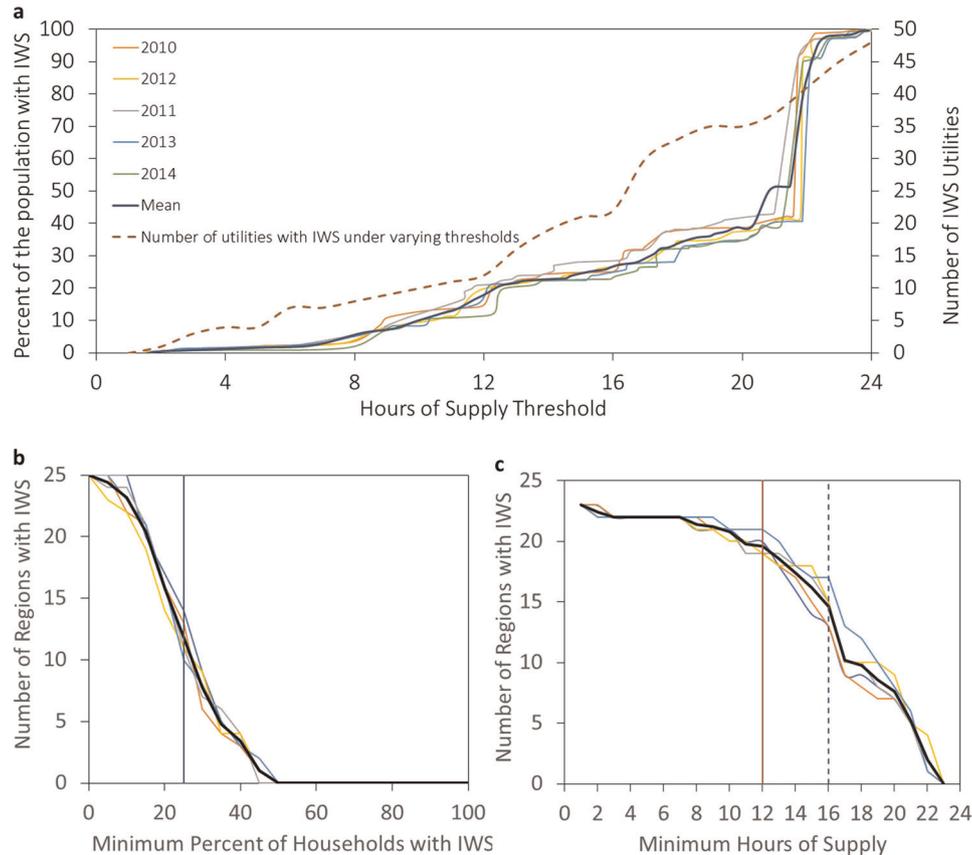
We compared utility- and household-reported continuity for three other countries (Fig. 3b). In Albania, the mean utility-reported IWS population was 73% across 2008–2012, while only 30% of households reported outages. In Tanzania, 50% of the population received utility-reported IWS in 2015 (using the 12 h/day threshold), while 67% of the population received household-reported IWS the same year. Data from Zimbabwe for 2014 and 2015 suggest that the utility and household estimates were similar, with 18% and 13% of the population with IWS reported by utilities and households, respectively.

#### Sensitivity analysis

We examined the influence of threshold selection on our results. In the national analysis, we categorized utilities with  $< 12$  h/day as IWS, which is consistent with the threshold used by the JMP for “available when needed”<sup>16,24</sup>. If instead a threshold of 16 h/day was used, the percent of the population defined as IWS would be consistent with the household-reported percent, with both at 26% (Fig. 4a). Thirteen of the 50 utilities in Peru supplied fewer than 12 h/day and almost half (24 utilities) supplied fewer than 16 h/day.



**Fig. 3 Population with IWS defined using utility- and household-reported definitions.** **a** National and regional data from Peru. For the regional data, each point represents a 5-year average per region, and for the national data, each point represents a different year of data. Different symbols represent different thresholds used (12 or 16 h/day); **b** Other countries, including mean values for Peru (2010–2014), Albania (2012), Zimbabwe (2014, 2015), and Tanzania (2015, 2016) using a 12 h/day threshold.



**Fig. 4 Population and regions with IWS under varying thresholds.** **a** The threshold hours of supply for 2010–2014 for the utilities in Peru and corresponding percent of the population classified as served with IWS. **b** The number of regions in Peru classified as IWS depending on the population threshold used for household-reported outages (threshold of 25% shown as vertical line for reference). The maximum proportion of households reporting an outage in a region was 49.8%. **c** The number of regions in Peru classified as IWS based on the threshold utility-reported hours of supply (thresholds of 12 and 16 h/day shown as vertical lines).

More than 90% of the population experienced outages for at least 2 h/day (Fig. 4a). The largest change in populations classified as IWS occurred at 21.8 h/day, with the population increasing from 52 to 71%, since this is the continuity supplied in Lima, which

provides water to more than 9.2 million people. The number of regions in Peru defined as IWS is inversely proportional to the minimum percent of the population responding “yes” to SH43 (for household-reported data, Fig. 4b) or minimum hours of supply

**Table 2.** Number of households [percent of surveyed households with piped water] using piped water as their primary source responding to questions on water continuity in the DHS from Peru in 2013 and 2014.

		SH43: Water continuous for the past 2 weeks <sup>a</sup>		Total	Percent concordance
		Yes	No		
SH42: Is water available to drink for the whole day?	2013	Yes	10,742 [52%]	1979 [10%]	12,721 [62%] 65%
		No	5028 [25%]	2782 [13%]	
		Total	15,770 [77%]	4761 [23%]	
	2014	Yes	11,328 [50%]	2351 [10%]	13,679 [61%] 64%
		No	5665 [26%]	3124 [14%]	
		Total	16,993 [76%]	5475 [24%]	

<sup>a</sup>Inverse of the original question, which was whether water was discontinued for a day or more in the last 2 weeks. Bolded values represent the total household surveyed with piped water in that year. Note that the questions presented are from the English survey data files and were not translated by the authors, and there may be differences in the translations of the questions asked.

threshold (for utility-reported data, Fig. 4c). When changing the threshold from 12 h/day to 16 h/day the average number of regions classified as intermittent dropped from 20 to 13 (Fig. 4c).

#### Household reporting of outages

We examined the difference between two recently introduced questions asked of households for reporting on supply continuity in Peru in the DHS, question SH42 (“Is water available for one whole day?”) and question SH43 (“In the last 2 weeks, was water discontinued for a day or more?”) (Table 2). We found that more people answered “Yes” to water being continuous for the past 2 weeks (or “No” to SH43) than “Yes” to SH42 in 2013 (77% versus 62% of households) (Table 2). The percentages of concordant answers were 65 and 64% in 2013 and 2014, respectively. In 2014, 26% of the surveyed household reported that the drinking water source was not available for a whole day but was continuous in the past 2 weeks, and 10% of the households responded that water was available for the whole day but that it was not continuous in the past 2 weeks (i.e., was discontinued for a day or more) (Table 2).

## DISCUSSION

We found that the percent of the population with IWS in Peru as reported by households (23–26%, depending on the year) was a few percentage points greater than that reported by utilities (20–21%). However, comparing results by region suggests that this may be a coincidence: many regions had no utility-reported population with IWS even when households with piped water supply reported outages. These results depend on the thresholds we selected to compare the two data sources. For the utility-reported IWS, 16 h/day (e.g., 8 h/day of outages) may be when most households tend to notice or report intermittency, although, notably, households experiencing any interruption in supply (i.e., <24 h/day) are still “discontinuous” and are likely subject to some of the same negative impacts of coping with IWS. The appropriate threshold for the percent of a population within a region reporting an outage to produce consistent household- and utility-reported continuity is uncertain, as concordant regions were few, suggesting it may be not only the threshold selection causing disparate results. Results comparing the national populations with IWS from three other countries (Albania, Tanzania, and Zimbabwe) do not suggest a clear connection between utility- and household-reported data.

Within a town or city, households can experience different hours of supply due to network hydraulics, elevation, water demand, and valve operations; those on a trunk main may receive continuous water supply, while those located far from the water

treatment plant may receive supply once a week<sup>15,25</sup>. Therefore, household-reported outages may better capture this variability than utility-supplied information on their provided hours of supply. Relatedly, there is little guidance provided to utilities on how to calculate their hours of supply; it is possible some are reporting the hours that they run their pumps inputting to the distribution system, while others may report on their targeted valve operation periods. While it is likely each utility’s method is consistent from year to year, they may not be comparable between utilities. Long-term and seasonal variations in hours of supply may also be responsible for the discrepancies. For example, some of the observed variability may be seasonal trends (e.g., continuity may be greater in a rainy season). Household-reported outages varied more year to year than utility-reported data, which is expected. Variations between households are expected due to sampling and timing of visits, while the utility likely reports using a consistent method year to year. Also, since the data for utilities were influenced by utilities serving larger populations (e.g., Lima), the national results for IWS may be relatively stable if these did not change over the studied time period.

In the 2 years that included two household survey questions on drinking water availability, there was inconsistency in the answers to these questions within the same households. Lack of consistency in defining and reporting reliability has been highlighted as a common issue in studies and data collection frameworks<sup>10</sup>. Of the surveyed households using piped water, 35% and 36% in 2013 and 2014, respectively, responded with opposite answers when asked both about a water outage for a day or more in the past 2 weeks and whether water to drink was available for the whole day (yes to one and no to the other, or vice versa). These two questions inquire about two different experiences: one is about severe intermittency within a specified time period (SH43) while the other (SH42) is about access to water more generally. These each address two different sides of water access: is supply available, and do they have water when they need it? Question SH43 may not be indicative of the true nature of water availability in a household throughout a day since it focuses on severe intermittency, and results based on lower thresholds (e.g., <12 h/day) may be more comparable. Also, given the 2-week recall period, responses may hide seasonality of supply (e.g., if a utility supplies water intermittently to a household in dry seasons and continuously in wet seasons). However, SH42 is likely a worse indicator of IWS, as households may (and likely do) have storage and alternative sources and therefore would report that water is always available during the day<sup>26–28</sup>. We posit that question SH43 may be better than SH42 for understanding continuity of supply, which is why it was used in the analysis presented. However, alternative questions could be designed to allow categorization of supply as continuous, moderately intermittent, and/or severely

intermittent, or to capture how often the outages (or water deliveries) occur (e.g., once in a week or every day). Notably, one question was phrased as availability while the other was phrased as the lack thereof, which may have influenced peoples' responses. In countries where intermittency is more severe, it may be easier for households to recall how many times piped water is available rather than how many times it is out; conversely, in systems where supply is mostly continuous, it may be easier for households to recall outages.

#### Study limitations

There are several limitations to the data sources used for this analysis and methods. The data reported by IBNET represent only the population served by reporting utilities, although there may be people in a region with a piped water connection not operated by an IBNET-reporting utility. Similarly, households reporting to DHS may be reporting on piped supply from a community-based organization that does not report to IBNET. However, we estimate that the percent of households reporting hours of supply about a non-IBNET provided piped water supply to be minimal, since the IBNET coverage aligns with published coverage data from household surveys (according to the World Health Organization/UNICEF Joint Monitoring Program (JMP), the urban coverage of piped drinking water in Peru increased from 80 in 2010 to 82% in 2014 (Supplementary Fig. S1), which compares to utility-reported coverage through IBNET of 85 in 2010 and 91% in 2014<sup>16,23</sup>). It is possible that those served by smaller agencies that do not report to IBNET may experience more intermittent supply and report the outages, although there were no associations with utility size and supply continuity for IBNET-reporting utilities (Supplementary Fig. S2). Utilities may also overestimate their coverage and population served, although coverage reported by IBNET is similar to that reported for piped water nationally. Additionally, there may have been other changes to utilities from year to year, such as combining or regionalizing some service or changing service areas. Much of our analysis relied on categorizing entire utilities and entire regions as IWS or not IWS, which hides a much more complex reality. If data with a finer geographic resolution were available, it could be possible to better match households living in a particular utility's jurisdiction; however, such data were unavailable. The data from households was collected through nationally representative surveys, however, variability in which households are surveyed year to year, and the time of the year in which data are collected, would be expected to influence results. Also, all results for household-reported continuity are based on a percent of households, while IBNET is based on a percent of the population.

#### Recommendations

This study presented the challenges associated with measuring and accounting for IWS with data available from utilities and/or households. Better metrics for reporting on continuity should be developed, tested, and standardized to identify gaps in and opportunities for improving utility performance. There are currently no standards for how hours of supply are measured or reported or how to report the variability of supply that occurs over a week or season. Better information may help regulatory agencies and water utilities managers provide more equitable supply within a city or town<sup>29–31</sup>. Specific recommendations for improving data collection follow:

- *Utility measurement of continuity.* While utilities report their average supply duration, it is not clear what this average represents. For example, it could represent the hours a pump is operated at a water treatment plant or the average duration experienced by households at the end of the network. Utilities could better capture continuity of supply through reporting by utility workers responsible for turning supplies on and off

(i.e., valve operators), although the reliability of data collection through field utility employees has been challenging to maintain in practice<sup>32</sup>. Utilities could regularly survey or collect customer complaints regarding supply continuity by randomly selecting households for in-person or phone-based surveys. While sensors could be used to detect outages, these have to be installed at static locations and may be best located at pump houses and treatment plants; utilities that struggle to supply continuous supply may also have challenges maintaining such a sensor network.

- *Water delivery/outage patterns.* An important first step to improving such metrics would be to include the number of days between supply in IBNET reporting: currently, a utility supplying 5 h of supply every day is equivalent to a utility supplying 17.5 h of water twice in a week and to a utility supplying water for 24 h per day for 5 months and then 1 h per week for 7 months. This could be achieved by reporting both average hours per day and days per week or the ranges throughout the year (i.e., “wet” season and “dry” season). Continuity can vary substantially within a city; notably, the IBNET database does have an indicator for the number of people in a utility served by IWS (which would be equal to or less than the population coverage), however, few utilities report this indicator.
- *Predictability of supply.* Including an indicator of whether the supply is scheduled (and the schedule is followed) or whether outages are unpredictable would be advantageous for benchmarking customers' experiences. The impacts of the delivery patterns described above on customers is likely to be substantially different: Galaiti et al.<sup>33</sup> suggested that predictable intermittency, irregular intermittency, and unreliable intermittency—defined by how much households could rely on delivery or outages at certain times—affected their experience with, and the negative impacts of IWS. Households that know exactly when to expect water, and can therefore plan household activities and be home when the water is arriving, will have a different level of water access than those who do not know when water will be delivered and spend scarce resources on alternative water sources or miss work to wait for the arrival of water<sup>6</sup>. Notifications of when water in an IWS would be delivered were associated with modest reductions in stress in low-income households<sup>32</sup>.

## METHODS

### Study site

Peru had a population of ~32 million with a per capita GDP of US\$211 Billion in 2017<sup>34</sup>. Drinking water in Peru is provided by 53 Municipal Service Providers (*las Entidades Prestadoras de Servicios de Saneamiento*, EPS) that provide surface or groundwater to cities and towns in Peru, serving >62% of the country's population<sup>35</sup>. Approximately 11,800 community-based organizations, known as Sanitation Services Administrative Committees (*Juntas Administradoras de Servicios de Saneamiento*, JASS), provide water to the remaining 29% of Peru's rural population and 9% of Peru's population that live in 490 small municipalities<sup>35</sup>. The National Sanitation Services Supervisory (SUNASS), a regulatory agency funded through a surcharge on water bills, regulates and oversees the EPS<sup>35–37</sup>. EPS are spread throughout the country; the median elevation for the utilities is 783.6 m and the country as a whole has an average elevation of 1555 m (Supplementary Fig. S1). We selected Peru for this analysis due to its high coverage by piped water (85–91% of the Peruvian population had access to piped water in 2017)<sup>35,37</sup>, and continuous reporting by utilities: 48 of the 50 utilities in Peru reporting continuity to IBNET for every year from 2010 to 2014 (Supplementary Table S1).

### Data sources

Utility-reported water supply continuity were obtained from the IBNET, which compiles global data on water and sanitation utilities performance (ib-net.org)<sup>18</sup>. IBNET data from utilities in Peru from 2010 to 2014 were

**Table 3.** Household survey questions relating to source and continuity of drinking water from the DHS in Peru (the DHS Program-Peru: continuous DHS<sup>19–23</sup>).

Question ID	Translated question	Answer options
HV 201	Source of drinking water <sup>b</sup>	Piped water; piped into dwelling; piped outside dwelling but within building; public tap; tube well water; Well inside dwelling; public well; surface water; spring; unprotected spring; river/dam/lake/stream etc.; rain water; tanker truck; bottled water; other; missing; not applicable
SH42 <sup>a</sup>	Water to drink is available the whole day? <sup>c</sup>	Yes; no; missing; not applicable
SH43	In the last 2 weeks was water discontinued for a day or more? <sup>d</sup>	Yes; no; missing; not applicable

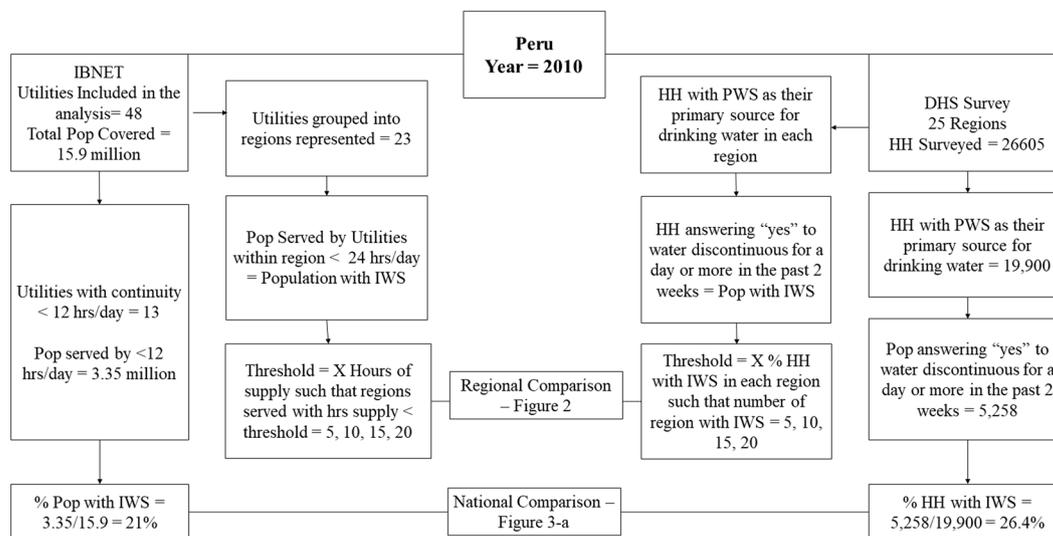
<sup>a</sup>This question was not asked until 2013.

<sup>b</sup>“Cuál es la fuente principal de abastecimiento de agua que utilizan en su hogar para tomar o beber? (dentro de la vivienda, fuera de la vivienda, pero dentro del edificio, pilón/grifo público, pozo en la casa/patio/lote, pozo público, manantial (puquio), agua de lluvia, camión tanque/aguatero, agua embotellada)”

<sup>c</sup>“La fuente de abastecimiento de agua en el hogar está disponible todo el día? (Si/No)”

<sup>d</sup>“En las últimas dos semanas, Tuvo un corte de agua todo un día o más tiempo? (Si/No)”

Note that the questions presented are from the English survey data files and were not translated by the authors, and there may be differences in the translations of the questions asked.



**Fig. 5** Methods used to compare utility- (IBNET) and household- (DHS) reported water supply continuity for the whole country (National, I, on the outer part of the graph) and by region (Regional, II, inner part of figure). X = threshold of the minimum % population with IWS to deem a region intermittent. The numbers shown are from 2010 and used as an illustrative example; the analysis was performed for each year. Pop population, HH households, PWS piped water supply, IWS intermittent water supply.

obtained from the online database. The accuracy of these data depends on reporting by utilities and/or regulators<sup>38</sup>.

The DHS Program collects, analyzes, and disseminates representative longitudinal data on population and health in over 90 countries<sup>39</sup>. These surveys documented coverage and continuity of drinking water in household (Table 3). Household survey results for Peru were obtained for 2010–2014<sup>19–23</sup>. For all analyses, we used the subset of households surveyed who reported using piped water as their primary drinking water source (including piped water, piped into dwelling, piped outside dwelling, and public tap) (Question HV 201, Table 3).

### Matching regions

Data from IBNET were reported by utility (which, in Peru's case, corresponds to a city), while DHS records reported data from individual households by region. To harmonize these, we first identified the longitude, latitude, and elevation of the utilities using Google Maps based on the IBNET utility or city name<sup>40</sup>. When we could not locate a utility office on Google Maps, the coordinates of the center of the served city were used instead. We used these coordinates to group the utilities into their respective regions by matching each utility's location to the list of regions from the country profile in World Bank publications

(Supplementary Table S4)<sup>34</sup>. In 25 of the 27 regions in Peru, there were between 1 and 5 utilities reporting supply continuity to IBNET (no utilities reported from Callao and Piura). To arrive at an average utility-reported continuity (h/day) for a region with more than one utility, we calculated the mean hours of supply reported for utilities within that region.

### Comparing utility and household hours of supply

Our analysis was divided into two parts: (1) Method I compared the two data sources at the national level; (2) Method II compared the two data sources at the regional level (Fig. 5). The analysis converted the utility- and household-reported data into comparable values by assigning binary values to utilities or households—each either supplied water intermittently or did not—and calculating percentages of the population using each type of piped water service. This was performed for each year from 2010 to 2014 for each region.

**Method I: national comparison.** We expressed household-reported continuity as the percent of households experiencing IWS, estimated as the sum of the households reporting using piped water as their primary drinking water source and answering “yes” to questions SH43 (that water was discontinued for at least a day in the last 2 weeks) (Table 3 and Supplementary Table S2),

divided by the total number of households using piped water. We expressed utility-reported continuity in Peru as the percent of people served by a utility providing IWS. To estimate this, we categorized utilities as providing IWS if their mean hours of supply between 2010 and 2014 was <12 h/day. We selected 12 h/day as the threshold, as we postulated that households will report an outage of a day if it is out for at least 12 h and to be consistent with current definitions of *available when needed* used by the JMP<sup>24</sup>. We summed the population served by the utilities categorized as IWS (<12 h/day) and divided by the total population covered by reporting utilities. This threshold was varied as part of the sensitivity analysis.

To compare the trends seen in Peru to global data, we collected available data for other countries reporting to IBNET and performed the same comparison as described above. Household surveys for Tanzania and Zimbabwe were available through the DHS Program, while those for Albania were obtained from Living Standards Measurement Study<sup>41</sup>.

**Method II: regional comparison.** To compare intermittency within regions, we compared the regions where utilities reported IWS according to thresholds of hours of supply and the percentage of households with piped water reporting water outages.

We calculated the percent of surveyed households using piped water supply who reported having discontinuous supply during the past 2 weeks ("yes" to questions SH43) for each region (Supplementary Table S2). We then categorized regions as supplying IWS based on whether this percent was greater than a threshold (e.g., if the threshold was set as 25%, then a region was classified as an IWS region if >25% of households reported an outage in the last 2 weeks; this threshold was varied). This yielded two values to compare with utility-reported data: (1) the percent of the population within each region with household-reported intermittent supply; and (2) whether a region was intermittent or not as defined by households.

We obtained utility-reported continuity for each region by grouping utilities into regions (described previously) and classifying each as IWS depending on their hours of supply (varying thresholds were used; e.g., <16 h/day). We calculated the total population with IWS by summing the number of people in each region served by utilities classified as IWS divided by the total population served by utilities in that region. We also calculated the mean hours of supply per day for the utilities in each region to categorize regions as IWS if the mean hours of supply for utilities in that region was less than a threshold (e.g., if the threshold was 16 h/day, then a region was classified as IWS if the mean of utility supply hours in that region was <16 h/day; thresholds were varied). This yielded two values to compare with household-reported data: (1) the percent of population within each region with utility-reported intermittent supply; and (2) whether a region was intermittent or not as defined by utilities. In the regions where all reporting utilities supplied an average greater than the threshold, no populations were classified as receiving IWS; in regions where all the reporting utilities supplied less than the threshold, 100% of the population was classified as receiving IWS.

### Sensitivity analysis

We performed a sensitivity analysis to determine the effect of varying thresholds throughout the analysis for Peru. We plotted the cumulative density function of the mean hours of supply of each utility against the average populations served over the 5 years, the number of regions with IWS according to household reports, and a range of minimum percent of households reporting outages (0–100%) per region against the number of regions with IWS.

### Data analysis

R statistical analysis packages were used to extract and analyze household surveys and cluster utility data by regions<sup>42</sup>. Microsoft Excel statistical functions and Data Analysis tool were used to perform linear regressions. Blank fields were excluded from analysis.

### DATA AVAILABILITY

Data used in this analysis were from public sources and are available for download through the citations provided throughout the paper.

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## AUTHOR CONTRIBUTIONS

F.R., E.K., and R.B. conceived of the study, F.R. and E.K. designed research plan and performed analysis; F.R., E.K., and R.B. drafted the manuscript. All authors contributed to the final manuscript.

## COMPETING INTERESTS

The authors declare no competing interests.

## ADDITIONAL INFORMATION

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