Research Paper

Do household surveys estimate tap water use accurately? Evidence from pressure-sensor based estimates in Coimbatore, India

R. Apoorva, Durba Biswas and Veena Srinivasan

ABSTRACT

Quantifying domestic water use at the household scale is crucial for any policy interventions towards ensuring adequate, equitable and safe water access. In developing country contexts, piped water supply is often one of several sources from which households access water and this is often unmetered. The most common approach to quantifying household water use from multiple sources is through household surveys. But there is no evidence that household surveys accurately estimate water use. This study utilized high-resolution pressure sensor data as a reference to evaluate the effectiveness of conventional household survey methods through a sample of 82 households in Coimbatore city in South India. The pressure sensors produced detailed, continuous and accurate information on all sources of water accessed through the household storage infrastructure, but they were expensive and intrusive. Compared with pressure-sensor derived estimates of tap water use, household surveys alone fared very poorly. However, household surveys and well designed water diaries of supply and pumping coupled with simple one-time field measurements emerged as a valid approach to quantifying household water use from taps under multiple source dependence.

Key words | household water use, household survey, multiple source dependence, sensor monitoring, unmetered connections, water diary

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INTRODUCTION

Ensuring adequate, equitable and safe water supply to domestic consumers is the primary goal for water supply utilities. However, in developing country contexts, it is often difficult to ascertain if this goal is being met; quantifying water supply and use remains a challenge.

Public water supply is unmetered in many developing water utilities (Nauges & Whittington 2010). Where metering exists, it may not cover the entire population (McKenzie & Ray 2009) and often, the meters are unreliable (Bergh & Nordberg 1996; Nauges & Whittington 2010). Moreover, many households continue to depend on multiple sources of water to meet their needs (McIntosh 2003; Nauges & Whittington 2010).

Quantifying water supply and use is particularly challenging under intermittent water supply. It is estimated that a third of water utilities in Africa and Latin America and more than half in Asia supply water intermittently (WHO & UNICEF 2000). Households adapt to intermittent water supply through investments in water storage infrastructure such as underground sumps and overhead tanks (OHTs) as well as containers like drums, buckets and pots (Thompson *et al.* 2001; Devasenadhipathi *et al.* 2016; Kumpel *et al.*

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2017). Consequently, the combination of duration, pressure, the timing of water supply and in-house storage determine household access to water and use.

The Indian situation

With rapid urbanization in India, the piped water infrastructure has been unable to keep pace with the needs of the population. As cities grow, a significant fraction of the urban population lacks access to piped water supply. Even households with piped supply connections may supplement with water from public standpipes (PSPs), private bore wells, public and private water tankers, water vendors and water kiosks (Zérah 2002; Shaban & Sharma 2007; Srinivasan 2008). Most supply is 'intermittent'; water is supplied through the piped mains for a few hours a day and must be stored in-house for use.

In recent years, there has been a major push to upgrade the current intermittent piped water systems to pressurized and fully metered 24/7 systems, where consumers bear the full cost of water. Proponents argue that metering and pricing will decrease water use. In contrast, sceptics argue that supplying water 24/7 will increase water use; so it is an unrealistic goal. Sceptics also argue that increasing tariffs may induce households to meet part of their needs from their own wells resulting in groundwater depletion.

The absence of data on household water use limits evidence-based urban water policy. Notwithstanding recent work (Kumpel *et al.* 2017), *quantitative* evidence on the impacts of a 24/7 water supply on household water consumption is largely non-existent. One major reason is that water supply is often unmetered prior to the introduction of 24/7 systems. Even where ex-ante data on piped water consumption exists, no previous study has quantified all sources of water. So, total water consumption is often unknown.

A key missing piece of evidence is whether higher prices will increase or decrease total water use. Prior studies from the developed world assume a single source and pressurized, continuous piped water supply to households with functional meters. However, in developing countries, there is a need to account for multiple source dependence as well as the differing source characteristics and service levels. The inability to do this has limited empirical estimations of price and income elasticity (Nauges & Whittington 2010).

Quantification of water use provides information that serves as a preliminary, yet crucial step towards improving water access to households, especially in regions where intermittency is high and linked with inequities in household water access. Our study tackles this problem by systematically comparing estimation methods using data collected from three different tools using a sample of 82 households in Coimbatore city in India. This study compares, for the first time, water-use estimation methods using data collected from conventional household surveys and water diaries with a novel pressure-sensor based estimation method.

Review of literature

In the developing world, household water-use estimation needs to account for the varied mechanisms through which the households access and use water. In the absence of metering, various tools are currently used to collect data and estimate household water use. Although millions of dollars are spent on infrastructure and research each year, there is very little validation of the different tools or analyses comparing different methods.

The literature distinguishes between households accessing water through a piped connection or tap in the house ('tap households') and households that must collect water manually from a water access point ('non-tap households') (Strand & Walker 2005).

Studies that focus on non-tap households estimate water volumes collected in containers such as pots, buckets and drums (Cairncross & Kinnear 1992; Wutich 2008; Zuin *et al.* 2011; Singh & Turkiya 2013; Oageng & Mmopelwa 2014). For non-tap households, data on water use is collected through direct observations or recollection of the number of pots of water collected or maintenance of diaries of water collection, but limitations on the use of retrospective data collected through surveys has been documented by Wutich (2008).

Under intermittent piped supply, tap households invest in storage structures like sumps and OHTs. Water flows by gravity from the OHTs to the taps in the house. The present study focuses on tap households with such permanent storage structures.

Prior analyses of tap households have relied on metered data (Strand & Walker 2005; Andey & Kelkar 2009; Nauges & van den Berg 2009; Briand *et al.* 2010). Few studies have attempted to quantify water use from taps, where water use is unmetered (Vaidyanathan & Saravanan 2004; Shaban & Sharma 2007; Singh & Turkiya 2013; Kumpel *et al.* 2017). A review of methods is complicated by the fact that many quantitative studies on water demand fail to adequately describe the approaches used (Wutich 2008) making them hard to replicate or categorize. In any case, studies that quantify water consumption from multiple sources remain rare.

Two pre-dominant quantification approaches have been used in literature: quantification of *water consumption* for various end-uses and quantification of *water supplied* from different sources. For each approach, different data collection tools have been used including household surveys, water diaries, direct observations and measurements.

Household surveys

Consumption-based approaches

Most household surveys collect self-reported, retrospective information on water use for different end uses and water use by source (Vaidyanathan & Saravanan 2004; Singh & Turkiya 2013). Most involve one-time data collection, barring a few exceptions such as Wutich (2008).

Supply-based approaches

Household surveys may also collect proxy data on water use such as the duration of piped supply, the time required to fill household storage structures (Kumpel *et al.* 2017), or the duration of pumping from sumps to OHTs (Vaidyanathan & Saravanan 2004; Devasenadhipathi *et al.* 2016). Some studies have complemented proxy data with field measurements of household water storage containers (Shaban & Sharma 2007; Kumpel *et al.* 2017).

Studies based on household surveys report information on the overall dependency on sources (Shaban & Sharma 2007), but quantification of the water accessed from multiple sources at the household level is rare. A recent study focusing on water access from municipal piped supply excluded non-utility sources (Kumpel *et al.* 2017). Self-reported data from household surveys were used to account for water accessed by dominant sources by Zuin *et al.* (2011) and self-reported proxy data on pumping times, pump horsepower rating and pump make were utilized to estimate piped water and groundwater use in households by Srinivasan (2008).

Reliability of retrospective data on water use including proxy data has been reported to be an aspect of concern (Zuin *et al.* 2011; Devasenadhipathi *et al.* 2016) requiring further investigation.

Water diaries

Consumption-based estimates

Studies that deploy household water diaries are limited. In metered households in Australia, water diaries were utilized by O'Toole *et al.* (2009) and Beal *et al.* (2013). In non-tap households, water diaries have been utilized to record water use by each household member for various activities over a seven-day period by Wutich (2008). To our knowledge, water diaries have not been reported to record water supply in unmetered tap households.

Direct observations

Consumption-based estimates

Measurements of tap flow rates and container sizes have been supplemented with tap use duration to estimate end use based consumption through household surveys (Shaban & Sharma 2007; Singh & Turkiya 2013). Direct observations of taps to assess water end use and waste patterns was reported by Kumpel *et al.* (2017).

Comparisons across methods

In the absence of validation and standardization, most studies reinvent the wheel or perpetuate common mistakes. There are only a handful of comparative studies that triangulate across methods. Water use estimates derived from household surveys and direct observations were found to be comparable in non-tap households in Sudan (Cairncross

& Kinnear 1992). In a large-scale, cross-sectional study of domestic water use in East Africa over two time periods, field observations augmented household surveys of tap and non-tap households (Thompson *et al.* 2001).

In a study of non-tap households in Bolivia, Wutich (2008) compared household water use estimates based on water diaries and household surveys and found that the water diary provided the most accurate estimate. A study involving metered tap households in Australia compared household water use based on data collected through computer-assisted telephone interviews and a seven-day water diary. The level of agreement between the two approaches was found to vary for different end-uses (O'Toole *et al.* 2009).

To our knowledge, no prior study has attempted to validate different methods of estimating tap water use and present best practices. The objective of this study is to compare methods of quantifying household water use, to identify a best practice. This article thus addresses a major gap in the literature.

METHODS AND DATA

Site description

This paper is based on a study of household water use in Coimbatore city located in Tamil Nadu state in India (see Appendix A in Supplementary Material). With a population of over 1 million (Census of India 2011), the city has an intermittent dual water supply system operated and maintained by the Coimbatore City Municipal Corporation (CCMC). Piped water supply includes water imports from the Siruvani and Bhavani rivers and groundwater drawn from local bore wells (Srinivasan *et al.* 2014). PSPs, which are street taps, are of two types, providing either imported river water or local groundwater. Water tankers are operated by CCMC and private agencies, supplying primarily imported river water and local groundwater, respectively.

River water has been the preferred source of potable water use and groundwater is generally viewed as a less desirable source (Bergh & Nordberg 1996). In this paper, no distinctions are made between surface and groundwater sources, and only total household water use is considered.

Metering of piped water supply is limited to older parts of the city. The newly added peripheral parts of the city are characterized by infrequent water supply and lack of metering. Households access water from multiple sources that include tap connections (often shared across multiple households), PSPs, water tankers and self supply through private bore wells (Devasenadhipathi *et al.* 2016). A household survey (N = 579) was conducted by the same team in 2014 on a representative sample of households, residing in single houses or houses within a common compound, that excluded low-income slum settlements and apartment complexes in 10 representative wards across CCMC. This survey established that only 30% of the households access water from a single source. The majority of the households accessed water from two sources (65%), predominantly tap connection supplemented with either PSP or private bore well. The rest accessed water from three sources. Approximately 89% of households had a tap connection. Of these, only 26% had no permanent water storage structures.

This study compares four methods of estimating household tap water use on a sample of 82 households with tap connections and permanent storage infrastructure in Coimbatore. The protocols used for sampling, data collection and water use estimation are described in this section.

Sampling protocol

A non-random convenience sampling protocol was used to select households. This was carried out through local contacts of the survey team, and local college students, who volunteered for the study. The fieldwork component of the study was carried out during the period October 2015–August 2016.

The survey does not claim to be representative or random. The objective of sampling was to get sufficient variation in the sources of water use and household infrastructure. In the context of this study, non-random sampling is acceptable because no inferences are extrapolated from the sample to the population. The team ensured that the sample covered different categories of tap households with permanent storage infrastructure based on the three-level stratification used by Devasenadhipathi *et al.* (2016): with and without volumetric water meters installed by the utility; with high and low piped water supply

frequency; and high-income and low-income households, selected based on an asset index from the pre-selection questionnaire.

The survey team approached three colleges in Coimbatore and presented the proposed study objectives. Interested students were provided with a pre-selection questionnaire designed to identify households that were both suitable for the study and willing to participate. Households were selected based on the following criteria: a) presence of an in-house piped connection, not shared by more than two households; b) absence of water use for commercial purposes; and c) presence of permanent water storage structures.

Data collection protocol

Since the objective of the study was comparison of methods, three independent types of data collection tools were used – household survey, water diary, and sensor-based monitoring. Data collection was carried out by a team of trained enumerators ensuring adherence to ethical guidelines and clear *a priori* communication of the study objectives and methods to the participant households.

Household survey

A detailed household survey was conducted on the sample. It contained questions on demographic and socio-economic characteristics of the households, household infrastructure, sources of water to which the households had access, sources used for various end uses, and the households' perception of water supply and quality. The survey also collected proxy data to quantitatively estimate tap water use such as frequency of supply, pumping, etc.

Water diary

The households were requested to maintain a water diary for a two-week period that coincided with the sensor-based monitoring period. The diary consisted of a *Supply Record*, a *Pump Record* and a *Container Record*. The record formats were handed over to the respondents at the beginning of the monitoring period and the team explained how the diary entries were to be noted. During a follow-up visit made to each household within a week to conduct the household survey, the team verified the progress on maintenance of the records. Participating households were provided with a small monetary incentive of Rs. 500 (~8 USD) for maintaining the diary.

The *Supply Record* required households to record the dates of piped water supply. The households which accessed water from the nearest PSP by connecting a hosepipe directly to their sump also noted this practice. The *Pump Record* required households to note the capacity and make of all the pumps (sumps to OHTs and bore wells to OHTs). For each pump, the dates and pump operation timings were recorded. The *Container Record* required households to note the number of small containers (pots and drums) of water collected from their piped water connection, neighbour's piped connection and from the PSP.

Sensor-based monitoring

The sensor-based monitoring consisted of two components: standard volumetric meters and submersible pressure sensors, and was carried out over two weeks.

Standard volumetric meters: Domestic water meters (single/multi-jet) that are commonly used in India, cost approximately Rs. 600 (<10 USD). A typical metered household has a standard volumetric meter installation prior to the entry of the piped connection to the sump.

In 43 metered households, we noted the meter readings at the beginning and end of the monitoring period. In addition, we installed meters in 35 households, where the plumbing arrangements permitted this. In the sample, 8 households remained unmetered due to inaccessibility of the piped mains. Thus, the sample included households metered by the utility, metered by the survey team and households that remained unmetered.

Submersible pressure sensors

In this study, we used submersible pressure sensors with a programmable integrated data logger that automatically recorded water levels with the date and time of measurement (see Appendix B, Supplementary Material). The sensors were deployed by the survey team in all the sumps and OHTs of each sample household and they were

programmed to record water levels at 5-minute and 1-minute intervals, respectively. A reference pressure sensor within a radius of 10 km recorded atmospheric pressure at 5-minute intervals. At the end of the monitoring period, the pressure data was downloaded and converted into water level data using Onset HOBOware® Pro (Ver. 3.7.8) software.

Methods of estimating household water use

We used both consumption and supply-based approaches to estimate household water use. The different quantification approaches, data collection tools and the associated methods of estimating water use are described in Table 1 below.

Stated End-Use method

The total water consumption by the household was estimated based on the volume of water or proxy data reported to be used for various end uses by the respondents (see Table 1) and converted to average daily per capita water use. This has been elaborated in Appendix D in the Supplementary Material.

Sump fill method

The average daily piped water supply to a household was estimated using proxy data (see Table 1). The estimation was restricted to households which use an exclusive sump to store piped water and which were aware of their sump capacities (30%).

Pump duration method

Data from the *Pump Record* was utilized to estimate the total volume of water pumped to the OHT(s) (see Table 1). All sampled households (except one) manually operated the pumps, which enabled the respondents to be aware of pumping durations and timings.

While the *Pump Record* provides data on pumping duration, the average flow rate during pumping requires measurement. In this study, the average flow rate during pumping for each household was estimated using the pressure-sensor water-level time series. Alternatively, the flow rate from the sump(s)/ bore well to OHT(s) can be estimated by recording the change in sump water level during the pumping period or an ultrasonic flow sensor.

Water balance method

The high-resolution water level data was supplemented with storage structure dimension measurements and plumbing connection diagrams to analyse household-level water consumption, supply (see Table 1) and losses using Microsoft Excel VBA.

For each household, the total tap water consumption accessed from different sources as intercepted by these structures was independently estimated using pressure sensor data. The water balance of the sump(s) and OHT(s) were estimated for each 5-minute and 1-minute periods to estimate supply and consumption, respectively.

Since the study monitored both the sump(s) and OHT(s), it was possible to estimate supply (what entered the household storage structures) and consumption (what left the OHT(s) into household taps) separately.

Consumption estimate: Water use from the OHT(s) and sump(s) was estimated to determine the total tap water consumption. Water accessed and stored in small containers and *in-situ* water use (non-tap water) as recorded in the water diary was added to this estimate to determine total water consumption (tap + non-tap sources). The average daily per capita water consumption for each household was estimated by accounting for shared connections and the household size.

Supply estimate: Water inflows intercepted by the sump from all possible sources – piped supply, PSP through hose pipe and private bore well was estimated. Direct groundwater inflows from the bore well to the OHT(s) were estimated.

Comparison of methods

In this study, the Water Balance method serves as a reference for comparison with the described consumption and supply-based methods. In all cases, we ensured an 'apples-to-apples' comparison.

Table 1 | Methods of estimating household water use and related datasets

Quantification approach	Data collection tool	Method of estimation	Proxy data	Additional data	Water use estimation formulae
Consumption-based	Household survey	Stated End-Use method	Household water use patterns related to potable consumption, hygiene and amenity uses.	Water-use coefficients (from literature/ assumptions)	$Total\ water\ consumption = \Sigma\ water\ consumption\ for\ each\ end\ use$ (Detailed note in Supplement). Applicability- Source independent thereby accounting for all sources of water accessed.
Supply-based	Household survey	Sump-Fill method	Frequency & duration of water supply, fraction of sump filled during each supply period and stated sump volumetric capacity. (Retrospective average of previous month).		$Total\ monthly\ piped\ water\ supply = \sum_{i=1}^{m} Sump\ volume * \text{Fill fraction} * Supply\ frequency$ This accounts for m sumps in a household. Applicability- Piped water supply volume stored in the sump(s). Excludes water accessed from sources such as PSPs, tankers and private bore wells.
Supply-based	Water diary	Pump Duration method	Actual dates and durations of pumping for two weeks. Includes pumping from sump(s) to OHTs and bore well to OHT(s)/ sump.	Volumetric flow rate estimated from pressure sensor data OR Measurements of volumetric flow rate.	$Total\ volume\ pumped = \sum_{i=1}^{p} Pumping\ duration * Estimated\ flow\ rate$ This accounts for p pumps in a household. Applicability- Water use from piped supply stored in sump(s), private bore wells, PSP water diverted to sump(s).
Consumption & Supply-based	Sensor monit-oring	Water Balance method	Pressure sensor data in sumps and OHTs for two weeks.	a) Measurement of sump and OHT dimensions to determine volumetric capacity. b) Actual dates of piped supply, PSP diversion to the sump, bore well pumping (for same time period) from water diary.	Consumption/supply was estimated from the Water Balance of sumps and OHTs. $Consumption_{OHT} = \Delta S - Inflow_{OHT}$ $Supply_{sump} = \Delta S - Outflow_{sump}$ where ΔS refers to change in storage. Applicability- a) Supply from all sources intercepted by household sump(s) and OHTs. b) Consumption from the OHTs and sump(s).

RESULTS

The primary contribution of this paper is an accurate estimation of household tap water use in unmetered, intermittent piped supply systems, addressing an important missing gap in the literature. The study provides a way to compare and evaluate different estimation methods based on commonly used data collection tools, namely household surveys and water diaries.

The water use estimates from the Water Balance method coupled with the mapping of household level plumbing arrangements provided a rich micro-level picture of *tap*

water use through the household level water infrastructure pathways. Household surveys/ water diaries were used to collect data on non-tap water use.

Household water infrastructure characteristics

Of the sampled households, 54% had a volumetric water meter installed by the utility, of which 20% were not functional. Water meters were installed in an additional 35 households, mainly (78%) households not metered by the utility. By design, all households had sumps and OHTs. The median sump and OHT storages were 3,800 litres and 1,000 litres, respectively.

Of the sampled households, 20% had a private bore well. Typically, groundwater is pumped from the well into an OHT, although a part of the water being pumped might be diverted directly via a tap for outdoor use. Approximately 4% of the sampled households had such direct access taps. Of the sampled households, 11% had an exclusive OHT to store groundwater while 7% had one or more common OHTs that store a mixture of piped water and groundwater.

Of the sampled households, 35% shared a piped water connection with one other household. In these cases, the two households access water from separate or common OHTs.

Household water access characteristics

While a large fraction of the household water accessed from the piped water connection and private bore wells is mediated through the complex household water infrastructure of sumps and OHTs, households also access water from other pathways which are important to understand and map to obtain a complete picture of household water use (Figure 1).

Additionally, 12% (10 households) accessed water from the nearest PSP by connecting a hose pipe to their sump. Direct water use from the piped supply connection (prior to entry into the sump) or PSP for end uses such as gardening was difficult to quantify. In the cases where households provided proxy information to estimate direct water use, this was inherently subject to errors. Only 7% of households reported this and the volumes were small.

Tanker water access was reported by only one of the sampled households during a supply constrained time period that did not coincide with the study period.

Household water use

The high-resolution pressure sensor data enables detailed mapping of stocks and flows within the water infrastructure at the household scale (Figure 2). This permits differentiation between water consumption and supply by accounting for changes in storage and losses from storage.

The mean water consumption for the households for which consumption from all sources was quantified (N = 77) is 139 LPCD (litres per capita per day). The median

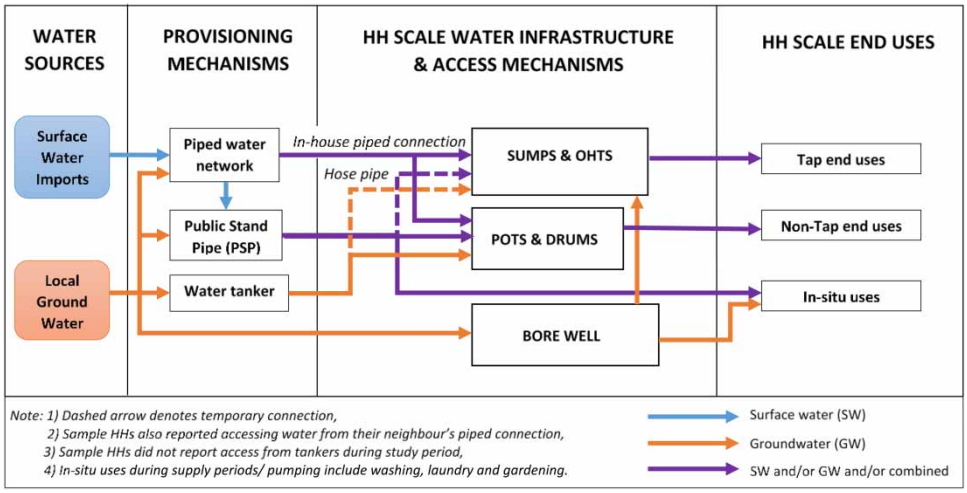

Figure 1 | Typical water access pathways by households in Coimbatore city.

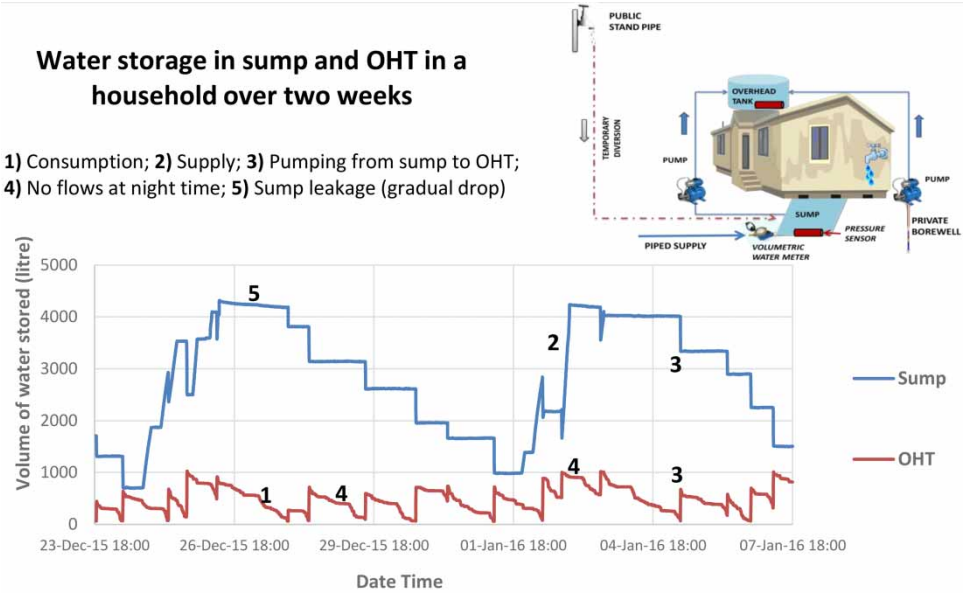

Figure 2 | Time series graph of water storage in a sump and OHT in a household.

water consumption is 111 LPCD, which is lower than the 135 LPCD norm set by the municipality. The distribution of household water consumption is shown in Appendix C in the Supplementary Material.

Comparison of methods of estimating household water use

The scatter plot (Figure 3(a)) comparing water consumption (from all sources) based on the Stated End-Use and Water Balance methods clearly shows that the two methods do not agree well.

Figure 3(b) shows the scatter plot comparing average daily piped water supply estimated by the Sump Fill method with equivalent piped supply estimates from the Water Balance Method and indicates that agreement between the estimates from the two methods is poor. In contrast, the scatter plot (Figure 3(c)), comparing the average per capita daily water pumped as estimated by the Pump Duration method with the average daily per capita tap water consumption from the Water Balance Method, shows good agreement. This comparison excludes non-tap water use, i.e., water collected and stored in pots, and direct water use from the sump(s) and bore well. It is clear that the diary-based estimates of pumping triangulate well with pressure-sensor based estimates of consumption.

DISCUSSION

Applicability of methods

From Table 1, it is clear that, except for the Stated End-Use method which estimates total water use in a source-independent manner, the water-use estimation methods apply to specific components of household tap water use from one or more sources.

The Sump Fill method is applicable to households that access water into their sumps from a single source – in this case, piped water connection. Both the Pump Duration and Water Balance methods account for tap water use under multiple source dependence. Tap water use estimates need to be supplemented with estimates of non-tap water use based on data collection tools such as household surveys/ water diaries.

Reliability of methods

The Stated End-Use and the Sump Fill methods *utilize household survey* for data collection. It is reported that recall methods are subject to limitations such as retrospection bias, forgetting, and inability to retrieve memories (Wutich 2008).

The Stated End-Use method estimates apply water use coefficients to reported water use behaviour based on proxy data (minutes of bathing, meals cooked, etc.). The

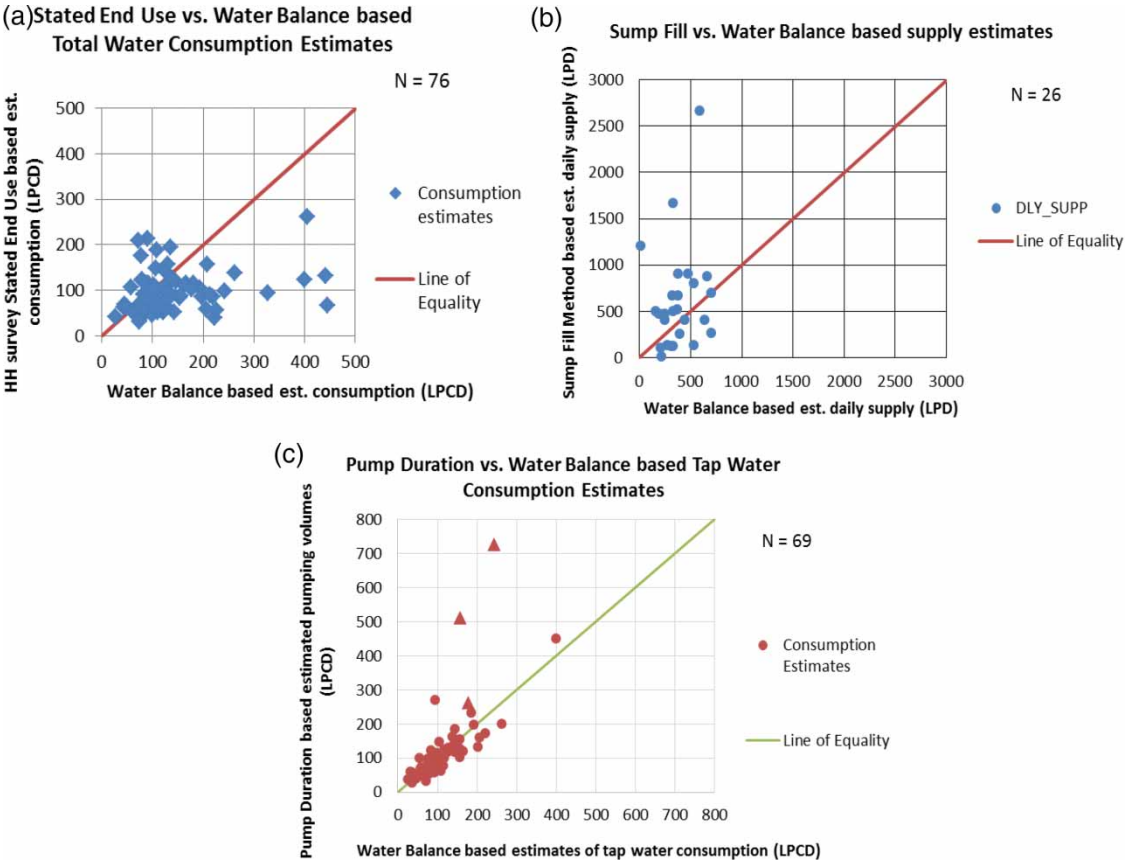

Figure 3 | Scatter plots comparing estimates: a) Stated End-Use vs. Water Balance; b) Sump Fill vs. Water Balance; c) Pump Duration vs. Water Balance.

result did not change when a sensitivity analysis was conducted using an alternative set of coefficients (Appendix D, Supplementary Material).

With reference to the Sump Fill method, a comparison of sump volumes as reported in the household survey and as estimated from measurements by the survey team showed that in half of the households considered (N = 26), the reported sump volumes differed from measured volumes by more than 20%. The Sump Fill method estimates rely not only on the respondent's awareness of the household sump capacity but also on her/ his awareness and ability to be aware of and recall piped supply timings and sump filling.

The Pump Duration method, which utilizes a water diary for collecting proxy data on pumping dates and durations, relies on the respondent's active participation and interest in diary maintenance. Limitations with diary records described in the literature include forgetting to fill entries, one-time entry of all diary events rather than as they occurred, and heaping (Wutich 2008).

In our study, about 10% of sampled households failed to maintain the *Pump Record*. In three households which maintained the record (symbol 'Δ' in Figure 3(c)), there were major mismatches between the dates and duration of pumping recorded and that verified using the pressure sensor data, indicating potential false diary entries.

The Water Balance method involves the continuous record of water levels in the storage structures. The water level data is only limited by the pressure sensor accuracy (maximum error was approximately 2 cm in water level measurement) and resolution. The errors associated with this method arise from: a) errors in the sump(s)/ OHT(s) dimension measurements by the survey team; and b) errors in estimating water consumption and supply with respect to the equations in Table 1.

To reduce the errors in measurement, the survey team was trained to accurately measure storage structure dimensions using a measuring tape and an ultrasonic distance meter. To reduce the errors associated with water use estimation, we used small data recording intervals, 1-minute

for OHT(s) to determine consumption and 5-minutes for sump(s) to determine supply. This helped improve the accuracy of ΔS in the estimation equations. Using engineering calculations, we estimate the average error margin associated with water use estimates to be approximately $\pm 5\%$.

Among the methods used in this study, we found that the water use estimates from the high-resolution pressure-sensor time series to be the most accurate and comprehensive. Therefore, these estimates have been used as a reference for comparing household survey and diary-based approaches to quantifying household water use. Standard volumetric meters were also found to be reasonably consistent and reliable for measurement of piped water supply (Appendix E, Supplementary Material), but would require some plumbing retrofits which are not always feasible.

CONCLUSIONS

The case of Coimbatore illustrated the characteristics of water infrastructure, the multiplicity of water sources and the complexity of water access mechanisms at the household level in a developing country context.

There is a gap in the literature in the quantification of household tap water use in regions where: a) piped water supply is intermittent and unmetered; b) households have invested in temporary and permanent household water storage infrastructure; and c) households depend on multiple sources of water. Recognizing this gap, this study utilized high-resolution pressure sensors as a novel way to accurately quantify at the household level.

While the Water Balance method provided a high-resolution accurate micro-level quantification of water use at the household level, the high costs of the pressure sensors and duration of this approach make it an expensive tool for general application in developing country contexts. The study was both expensive and time-consuming to analyse because every house was plumbed differently. It also involved a highly skilled and interdisciplinary research team familiar with both household surveys and management of sensors.

However, the accuracy and reliability associated with the Water Balance method using pressure sensors made it a suitable choice as a reference method to compare and evaluate household water use estimations using commonly used data collection tools reported in literature, namely household surveys and water diaries.

This study finds that methods of estimation that rely on household surveys alone as a data collection tool do not reliably estimate household water use. The estimation method based on maintenance of water diaries as the data collection tool was found to generate a more reliable estimate of household water use.

This study also suggests that well designed and administered water diaries may be an appropriate method to quantify tap water use under multiple source dependence in households with permanent storage infrastructure. Water diaries may be used in conjunction with household surveys wherein the latter can be designed to collect qualitative data on socioeconomic and water use variables while the former can be designed to capture quantitative proxy data on pumping duration and timings.

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