Measuring household consumption and waste in unmetered, intermittent piped water systems

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Abstract Measurements of household water consumption are extremely difficult in intermittent water supply (IWS) regimes in low- and middle-income countries, where water is delivered for short durations, taps are shared, metering is limited, and household storage infrastructure varies widely. Nonetheless, consumption estimates are necessary for utilities to improve water delivery. We estimated household water use in Hubli-Dharwad, India, with a mixed-methods approach combining (limited) metered data, storage container inventories, and structured observations. We developed a typology of household water access according to infrastructure conditions based on the presence of an overhead storage tank and a shared tap. For households with overhead tanks, container measurements and metered data produced statistically similar consumption volumes; for households without overhead tanks, stored volumes underestimated consumption because of significant water use directly from the tap during delivery periods. Households that shared taps consumed much less water than those that did not. We used our water use calculations to estimate waste at the household level and in the distribution system. Very few households used 135 L/person/d, the Government of India design standard for urban systems. Most wasted little water even when unmetered, however, unaccounted-for water in the neighborhood distribution systems was around 50%. Thus, conservation efforts should target loss reduction in the network rather than at households.

1. Introduction

At least 300 million urban residents in low- and middle-income countries receive piped water through intermittent rather than continuous flow systems [*Kumpel and Nelson*, 2016]. This situation is rarely by design; as cities expanded and populations grew, the water networks, originally designed to deliver water continuously, were unable to cope with increasing demand and gradually started to supply water in rotation to different parts of the city [*Totsuka et al.*, 2004; *Galaitsi et al.*, 2016]. Irregular deliveries of water under intermittent water supply (IWS) can result in difficulties as well as inequities of access among consumers. Intermittent flow also imposes stresses on the piped infrastructure [*Christodoulou and Agathokleous*, 2012]; upgrading to continuous water supply (CWS) is regularly proposed as the way to reduce coping costs as well as water waste [*McIntosh*, 2003].

Urban water managers require measurements of how much water residents consume to understand patterns of water access and water losses, and thence to identify effective measures to improve supply conditions. However, conventional water accounting methods do not apply in unmetered and intermittent systems. Water accounting methods for piped water supplies have been established for the fully pressurized and metered systems typical of high-income nations. These methods assume that the utility provides enough water to meet household demand ("demand-driven" supply systems) and that water meters are ubiquitous [*Alegre et al.*, 2000; *IWA*, 2003; *Mutikanga et al.*, 2013]. In an IWS regime, the system can shift from demand to supply driven, where the quantity of water delivered to a household is a function of the utility's allocation (i.e., frequency and duration of supply) and water pressure. Additionally, IWS systems typically have many households without meters: in India, where IWS is the norm, only 43% of connections among the 28 utilities reporting to the International Benchmarking Network (IBNET) in 2009 were metered [*van den Berg and Danilenko*, 2011].

Microscale factors further constrain the volume of water available to households and complicate its measurement. Households with their own tap and a hose can access water for the entire delivery period, but as

the number of households sharing a connection increases, access to the water declines. The need to carry pots of water from tap to home limits access, depending on the queue to fill pots and the labor available to fetch water. Some households attach pumps directly to distribution system pipes, increasing flow through their tap while decreasing pressure for nearby users. Households with IWS must store their water for use between delivery periods. Low socioeconomic status (SES) households usually lack roofs strong enough to support an overhead storage tank and may also be too space constrained to store large containers inside; high SES households can install overhead or underground tanks to sustain water-consuming appliances and irrigated gardens. All of these household-level water infrastructures intersect with water consumption patterns, such as using alternative sources when piped water is not available and shifting water-intensive tasks such as laundry to delivery periods [*Rosenberg et al.*, 2007].

IWS regimes can be improved by increasing the frequency and reliability of water delivery, or can be eliminated entirely by converting to continuous supply; both paths require that utilities reduce water losses [*Ismail and Puad*, 2007; *Vairavamoorthy et al.*, 2007]. Water loss is ubiquitous in urban supply networks and, in many developing countries, is estimated to exceed 50% of water input to a distribution system [*Kingdom et al.*, 2006; *van den Berg and Danilenko*, 2011]. While water loss can occur in utility networks or in households, few data are available on the relative importance of losses at each scale in IWS systems. Definitions of water loss also vary by sociopolitical and institutional context, and conceptions of what constitutes waste and sufficiency are important for developing water accounting metrics that are acceptable to different stakeholders.

In this study, we develop new methods to estimate household water use and loss in intermittent and unmetered piped water supply regimes. The study was carried out in a part of Hubli-Dharwad, India, a city with severe intermittency and minimal metering, similar to the conditions found in more than 450 similar-sized towns in India [*Bapat and Agarwal*, 2003; *Registrar General of India*, 2011]. We estimated the quantity of water that households collected and used by combining three distinct methods: metered data (though these were few), storage container inventories, and structured observations of water collection and use. We used estimates of per capita water use to estimate and compare water loss in households and in the distribution system. Previous methods of measuring household water consumption without meters, such as diaries or survey recall, focus on measuring end-uses of water for specific purposes rather than the overall volume of water available to households. These methods can suffer from systematic inaccuracies by income bracket. In addition, diary-based records are often inconsistent among family members, and extensive survey-based data are expensive to gather [*Wutich*, 2009; *Willis et al.*, 2011; *Beal et al.*, 2013; *Fan et al.*, 2014; *Morrison and Friedler*, 2015]. There is, therefore, an acute need for practical methods of estimating water consumption and loss in data-scarce environments. The methods we develop are based mainly on observable characteristics of household water access and infrastructure, augmented by a small number of short surveys, and represent a practical rather than ideal toolkit for estimating water consumption and loss in intermittent and data-scarce systems.

2. Research Design and Methods

In this section, we locate our study site and describe: (i) our household water access typology by scarcity experienced in use and storage, (ii) our multimethod approach to estimating and interpreting household water consumption, and (iii) our use of these estimates, augmented by tap observations and utility data, to assess water losses at the household and the system levels.

2.1. Study Site

Hubli-Dharwad, India, is a twin city in the state of Karnataka with a population of just under 1 million. Treated water from the Malaprabha River and the rain-fed Neersagar Lake is delivered to consumers through a piped distribution system. Water is delivered in sequence to sections of the city at different times, and residents without overhead storage tanks fill up their containers so that they have enough water between one delivery period and the next. Residents occasionally supplement their piped supplies with alternative sources, including private and public boreholes, smaller piped networks, tanker trucks, handpumps, public cisterns, lakes, and bottled water [*Kumpel and Nelson*, 2013].

The data for this paper were collected while conducting a larger study on the effects of a partial transition from IWS to CWS on water quality, household economics, and child health [*Kumpel and Nelson*, 2013; *Burt*

and Ray, 2014; *Ercumen et al.*, 2015]. Continuous water supply was piloted in eight of the 67 wards (local administrative boundaries) in Hubli-Dharwad. These eight wards were selected by a government agency (the Karnataka Urban Infrastructure Development and Finance Corporation) and were intended to represent the diverse socioeconomic conditions in the city. Our survey was conducted in eight wards that received water intermittently. We selected these to match the SES and water and sanitation conditions of the continuous supply wards. Within these eight wards, 1951 households were enrolled in the survey (additional details of the matching approach, comparisons of selected study wards to all wards in the city, and a map of the selected wards, are provided in *Ercumen et al.*, 2015]. Enumerators collected data from household respondents between November 2010 and February 2012. Our metered data, storage container inventories, and water delivery information came from a subset of these 1951 households (between November 2010 and February 2011). Tap observations and structured observations of water collection took place during the beginning of the monsoon season, in June and July 2011. During the entire study period, consumers reported receiving municipal water every 1–16 days.

2.2. Water Access Typology

We interviewed 40 households (representing a range of SES within eight study wards), as well as water managers in Hubli-Dharwad, to develop a typology of water access [*Woelfle-Erskine*, 2012]. We classified households based on their delivery regime and storage infrastructure (e.g., water pressure and length of delivery period) and social factors (e.g., number of users sharing a tap) that influenced the volume of water they consumed. The final classification was based on: (1) access to a water tap (whether the tap was public or owned by the household, their landlord, or a neighbor, and how many households shared it); and (2) presence or absence of an overhead tank (typically 1000 L or larger). We categorized the four types of water access as follows (Table 1):

1. Type 1 (Restricted): Consumers without an overhead tank who accessed water from: (a) a public connection, (b) a neighbor's connection shared with more than two other households, or (c) their own connection shared with more than three other households.
2. Type 2 (Limited): Consumers without an overhead tank who accessed water from: (a) a neighbors' connection shared with one or two other households, or (b) their own connection that was shared with at most three other households.
3. Type 3 (Partial): Consumers with an overhead tank who accessed water from their own connection shared with at least one other household.
4. Type 4 (Plentiful): Consumers with an overhead tank who accessed water from their own connection that was not shared with any other households.

Types 1 and 2 households generally had no indoor plumbing; Types 3 and 4 households had indoor plumbing connecting their tanks to their tap(s). We classified 1898 of the 1951 households enrolled in the survey according to this typology; the remaining 53 households could not be classified due to unanswered survey questions.
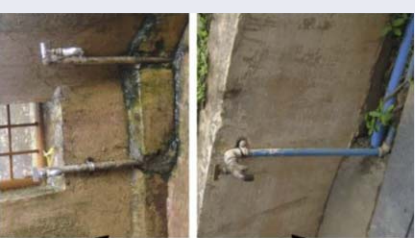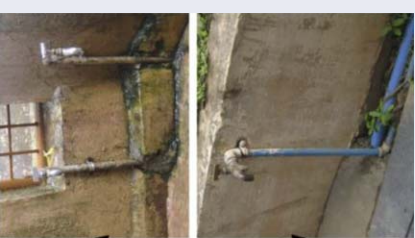
2.3. Measurement of Water Use by Households

We used two methods to measure household water use: (1) metered data when available, and (2) inventories of storage containers augmented by an estimate of direct use from the tap (Table 1). The direct use estimates relied on survey data on time to fill containers (which, in this supply constrained region, are usually filled carefully without much spillage), time to use the tap directly, and the number of days between water deliveries. We report water use data as liters per capita per day (LPCD) or kiloliters per connection per month (kL/con/m); converting kL/con/m to LPCD relied on survey data of the number of people in the household, the number of households sharing a tap, and the number of days between delivery periods. We constrained all measurements to municipal water supply and excluded supplementary water sources.

2.3.1. Metered Volumes

Metered consumption records were available for only 212 of the 1898 households in the survey that we could classify according to the water access typology; most residences were simply charged a flat fee of INR 90 per month (USD 1.64) [*Burt and Ray*, 2014]. We obtained monthly consumption records from the water utility during November 2010 to February 2011 or, for households that were metered but could not be matched to utility records, enumerators recorded the volume from the most recent bill. Metered consumption data were reported in units of kL/con/m.

Table 1. Water Access Types and Measurement Methods[a]

Household Water Access Type	Definition	% in HH Survey (n = 1951)[b]	Measurements and Data Sources		
			Metered $LPCD_{meter}$	Storage + Direct Use $LPCD_{s+u}$	
			V_m, N, p From Survey (n = 212)	$LPCD_{storage}$: V_s, p, d From Survey (n = 327)	$U*LPCD_{storage}$: N, p, T_s, T_t From survey (n = 1026 for U)
	Type 1. Restricted 1. No overhead tank; and 2. Public tap; or 3. Neighbor's tap shared with >2 HH; or 4. Own tap shared with >3 HH	15.5%	Yes (n = 3)	Yes (n = 67)	Yes (n = 171)
	Type 2. Limited 1. No overhead tank; and 2. Neighbor's tap shared with ≤ 2 HH; or 3. Own tap shared with ≤3 HH	49.3%	Yes (n = 95)	Yes (n = 172)	Yes (n = 855)
	Type 3. Partial 1. Overhead tank; and 2. Own tap shared with ≥1 HH	12.5%	Yes (n = 18)	Yes (n = 41)	Structured observation conducted, but U not calculated as little direct use observed
	Type 4. Plentiful 1. Overhead tank; and 2. Own tap, not shared	20.0%	Yes (n = 96)	Yes (n = 47)	Not observed nor calculated

[a]HH: household; N: number of HH sharing tap; p: number of people per HH; d: days between delivery periods; Ts: time to fill storage; Td: duration of delivery period; Tt: total time households used water from a tap.
[b]We could not identify the type for 2.7% of households.

We converted to units of LPCD as follows:

$$LPCD_{meter} = \frac{V_m}{D * N * P}$$ (1)

where

V_m = metered volume in kL/con/m (from utility records or bill seen during household survey);

D = 30.42 (average number of days in a month);

N = number of households sharing the tap (from household survey);

P = number of people in the household (from household survey).

2.3.2. Storage Capacity and Direct Water Use

Storage containers were counted and their capacities estimated for a systematically sampled subset of our study households (n = 327 of the 1898 households classified by water access type). Enumerators measured height, perimeter, and shape of water storage containers to calculate each container's volume. Households reported the volumes of overhead and underground tanks. If multiple households shared these tanks, we divided the total volume evenly among them. Where overhead and underground tank volumes were unknown, we substituted the overall mean volume for the same type of tank (e.g., plastic and concrete). Households also reported whether the water in underground and overhead tanks was municipal water, borehole water, or mixed; only municipal water volumes were used in our estimates. Calculations of storage capacity assumed that all containers were empty before the delivery period and were filled completely each period; the validity of this assumption is discussed in the results section. We converted the volume of storage containers to LPCD as follows:

$$LPCD_{storage} = \frac{V_s}{P * d}$$ (2)

where:

V_s = volume (liters) of storage containers per household (container survey); and d = average number of days between delivery periods (from household survey)

Type 1 and 2 households also performed a myriad of water-intensive tasks during the delivery period. We defined the total volume of water a household drew from a tap as the volume of water added to storage plus the volume of water used directly from the tap for these tasks:

$$V_t = V_s + V_u$$ (3)

where

V_t = total volume consumed by a household from a delivery period;

V_u = volume used directly during delivery periods, after filling all storage containers.

We estimated V_u indirectly as follows:

$$V_t = V_s + U \cdot V_s$$ (4)

where

U = fraction of storage volume that was directly used during delivery periods (U = 0 indicates no water use after filling storage containers; $U > 0$ indicates some water use directly from the tap after storage containers had been filled).

To calculate U, we substitute volume with the flow rate multiplied by durations of time into equation (4) to obtain:

$$T_t \cdot Q = T_s \cdot Q + U \cdot T_s \cdot Q$$ (5)

where

T_t = duration of time a household consumed water from the tap (see equation (7) below);

Q = flow rate from the tap (cancels out in final equation);

T_s = duration of time a household used to fill containers (from household survey).

Solving equation (5) for U, we get the difference between the total duration of time households used a tap and the duration spent storing water, divided by the duration households spent storing water:

$$U = \frac{T_t - T_s}{T_s} \tag{6}$$

To estimate T_t, we use the household survey question, "...after you filled your storage containers, what did you do with the remaining water at the tap?" with responses coded as: (a) used it the entire time water was available; (b) next person used it; (c) left it on; or (d) turned it off (supporting information Table S2). For each household in the survey, T_t was assigned as:

$$T_t = \begin{cases} T_s, & \text{if } T_d \leq T_s \\[2mm] \dfrac{T_d}{N}, & \text{if response } a,\ b,\ or\ c \\[4mm] \dfrac{T_d/2}{N}, & \text{if response } d \end{cases} \tag{7}$$

where

T_d = duration of delivery period reported by a household (from household survey).

Therefore, the total volume of water consumed by a household including both storage and direct use is given by:

$$LPCD_{s+u} = LPCD_{storage} + U \cdot LPCD_{storage} \tag{8}$$

Or, in units of per connection per month, as:

$$V_{s+u} = LPCD_{s+u} \cdot D \cdot N \cdot P \tag{9}$$

2.4. Measurement of Water Losses at Households

We investigated water losses at the household level using two different methods: (i) tap observations were used to estimate household-level water waste; and (ii) structured observations were used to gain a comprehensive understanding of water practices during delivery periods (Table 2).

2.4.1. Tap Observations

To investigate household water waste during delivery periods, we conducted two rounds of tap observations (n = 1708 taps) in July 2011 in an area of Ward 14 that inclu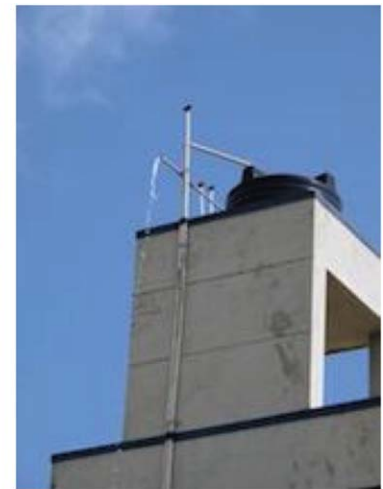ded all four types of water infrastructure. We walked through the entire service area and recorded, for each household tap, which of four water-related activities was occurring: (a) using; (b) wasting; (c) wasting-while-using; or (d) no apparent use (Figure 1). The "using" category included filling containers, washing clothes, floors or entrances, and irrigating plants. The "wasting" category included taps flowing with no person present or tanks overflowing. The "wasting-while-using" category described washing while a tap flowed freely. In the "no apparent use" households, the tap was not visibly on. We also classified each house by whether a roof tank was present or absent.

Table 2. Methods to Investigate Water Losses at Households and in the Distribution System

Method	Number of Observations
Household-Level Losses	
1. Tap observations during supply periods. Each surveyed tap was classified in one of the four categories (Figure 1): (a) using; (b) wasting; (c) wasting-while-using; (d) no apparent use	1708 taps (Ward 14)
2. Structured observations of households during supply periods	10 households
Distribution System Losses	
1. Estimated water consumption per connection per month compared with estimated utility supply per month based on: a) Median metered volume per connection per household type multiplied by the fraction of households of each type in the ward; b) Median storage added to direct use per connection per household type multiplied by the fraction of households of each type in the ward; c) Standard estimate used by the utility for unmetered connections.	8 wards

a) *Using.* Consumers fill storage containers from a hose.

b) *Wasting.* Water overflowing from an overhead teank.

c) *Wasting-while-using.* Water filling into a basin while laundry is washed.

d) *No apparent use.* No visible signs of water near or outside house.

Figure 1. Classifications of taps used in the tap survey.

2.4.2. Structured Observations

Structured observation is a standard technique in qualitative water and sanitation research in which an observer spends significant time in participants' homes, and, in a prespecified manner, observes when, how often, and for how long they perform a particular activity [*WHO and UNICEF*, 2012]. We conducted ten structured observations in June and July 2011 in ten randomly selected Types 1, 2, and 3 households (Tables 1 and 2). We did not include Type 4 households because our observations showed that their water use during delivery periods was minimal, except for filling up the tanks. The structured observations indicate the range of water use behaviors and inform interpretation of the container survey and tap observation data. Shortly before water delivery, we measured container volumes and the volume of stored water remaining in containers. We also measured the conductivity of water in storage containers (Extech ExStik II pH/conductivity meter) to determine whether the water in a container had come from a municipal, borehole, or mixed source (the conductivities of treated municipal water and groundwater in Hubli-Dharwad were <600 and >800 μS/cm, respectively) [*Kumpel and Nelson*, 2013].

We observed one tap in each selected household for the entire water delivery period, noting how much previously stored water was thrown away or used, the volume of water stored for future use, and any other ways the household used water while it was on. We recorded the duration of each activity (e.g., washing clothes, bathing, filling containers, letting water flow down, the drain unused). During observations, we asked water users to

explain what they were doing and they offered rationales for the ways they were using or storing water. When multiple households shared one tap, we followed only the one selected household.

2.5. Measurements of Water Loss in the Distribution System

We used the calculations of household water consumption (section 2.3 above) to illustrate water losses at the network level (i.e., in the distribution system) by comparing these quantities to utility estimates of supply to each connection. We estimated unaccounted-for water (UFW), which is the percentage of water input to the system that is not accounted for in measured use, using a water balance approach:

$$UFW = \frac{V_{supply} - V_c}{V_{supply}} \cdot 100 \tag{10}$$

where

UFW = unaccounted-for water;

V_{supply} = volume of water supplied by the utility per connection based on utility bulk meter data (28.6 kL/con/m for Hubli, which is the total bulk supply to residential consumers per month (1649.7 ML/m) divided by the total number of residential connections (57,696) in 2008 [*Karnataka Water Board, H.D.W.S.S.*, 2008]);

V_c = total volume used by a household per connection which was modeled as:

1. V_m, described earlier;
2. V_{s+u}, described earlier; and
3. $V_{utility}$, a flat estimate of 15 kL/con/m, which is used by the Karnataka Urban Water Supply and Drainage Board (KUWS&DB) in Hubli-Dharwad to estimate a standard unmetered connection.

To model residential consumption per ward, we calculated a weighted average of V_c for each ward by multiplying V_c for each household type by the fraction of households of that type in each ward (Table 2). We could only perform this calculation for Hubli, as supply and total connection data were only available from Hubli.

2.6. Statistical Analysis

To reduce the influence of outliers, we used the median as the measure of central tendency and used non-parametric statistical tests. Graphing and data analysis were carried out using R [*R Core Team*, 2015], including the base, psych, car, maptools, rgdal, mapplots, and RColorBrewer packages. Values were considered significant at the $p < 0.05$ level.

3. Results and Discussion

3.1. System Description

In all eight wards during November 2010 to February 2011, the median delivery duration was 4 h and median time between supplies was 6 days. Delivery durations and pressures varied within neighborhoods: households connected to a main line often received water for longer periods, while areas at higher elevations or at the ends of pipelines received water at lower pressures and for shorter durations. The flow rates at household taps connected to the municipal supply varied throughout delivery periods due to changes in the pressure (measured flow rates ranged from 0 to 5.5 L/min).

The composition of households along our typology, which reflects the ability of households to collect and store water, varied across wards (Figure 2). In Wards 14, 25, and 38, more than half of the households had overhead tanks (Types 3 and 4) while in the remaining wards, fewer households (12%–32%) had them (supporting information Table S1). This resulted in substantial within-ward differences: for example, some areas of Ward 38 had storage capacities of >100 LPCD, while neighboring areas within the same ward had <40 LPCD (Figure 2). Other wards with more homogeneous household infrastructure and the majority of residents falling into Types 1 and 2 categories, such as in Wards 57 and 58, had similarly low storage capacities between areas. The percent of households with functioning meters varied within wards: a fifth or fewer of Types 1, 2, and 3 households had meters while 43% of Type 4 households did (supporting information Table S1).

The geometric mean duration of delivery to a connection in Type 1 households was 4.8 h, the longest duration within the typology, while Types 3 and 4 households had 4.6 and 4.4 h of water delivery, respectively.
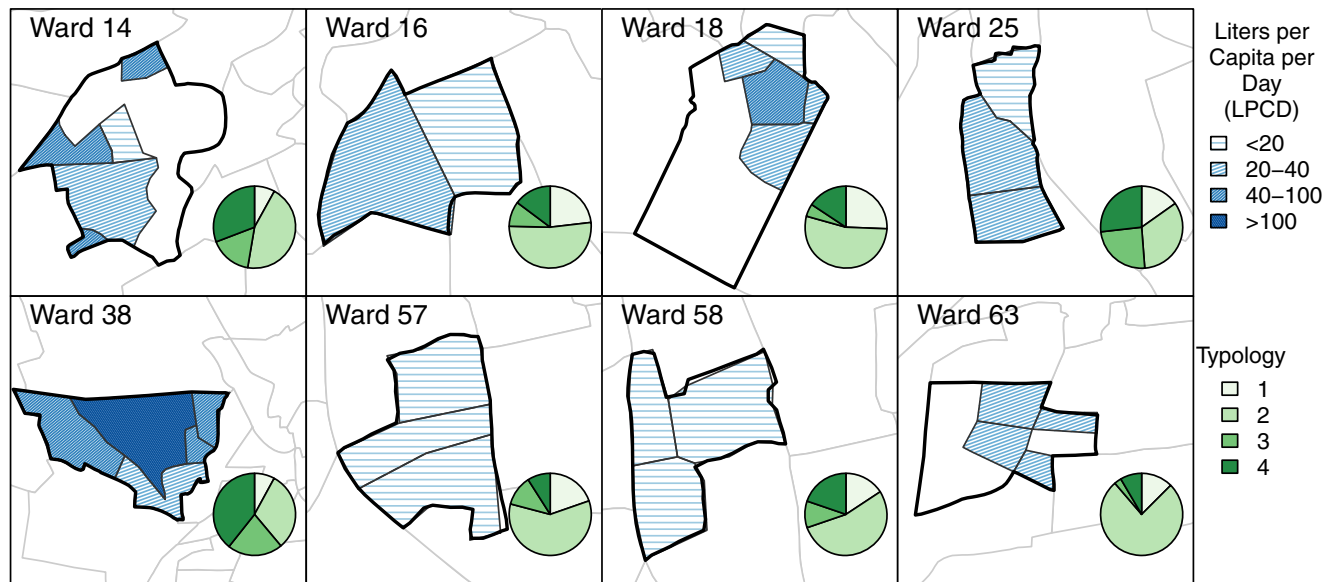
Figure 2. Average household storage capacity in liters per capita per day (LPCD) in areas within sample ward. Pie charts in the bottom right show the household type makeup of each ward. Wards 14, 16, and 18 were located in Dharwad, and Wards 25, 38, 57, 58, and 63 were located in Hubli.

The geometric mean duration among Type 2 households was significantly lower than the other types (4.0 h; Wilcox rank-sum, p < 0.05). However, after dividing the hours of delivery by the number of households sharing the tap, the average duration changed substantially: Type 1 households had a geometric mean of 42 min of access to running water at the tap while Type 2 had 2.7 h, Type 3 had 1.6 h, and Type 4 had 4.4 h.

Pressure also played an important role in water availability, although it is not included in our analysis because it was not possible to collect sufficient pressure data from individual taps. Measured pressure in the distribution system varied among wards and within delivery periods from < 0 to 35 psi [*Kumpel and Nelson*, 2014]. Some households reported attaching pumps directly to taps to draw more water, which decreased flow to
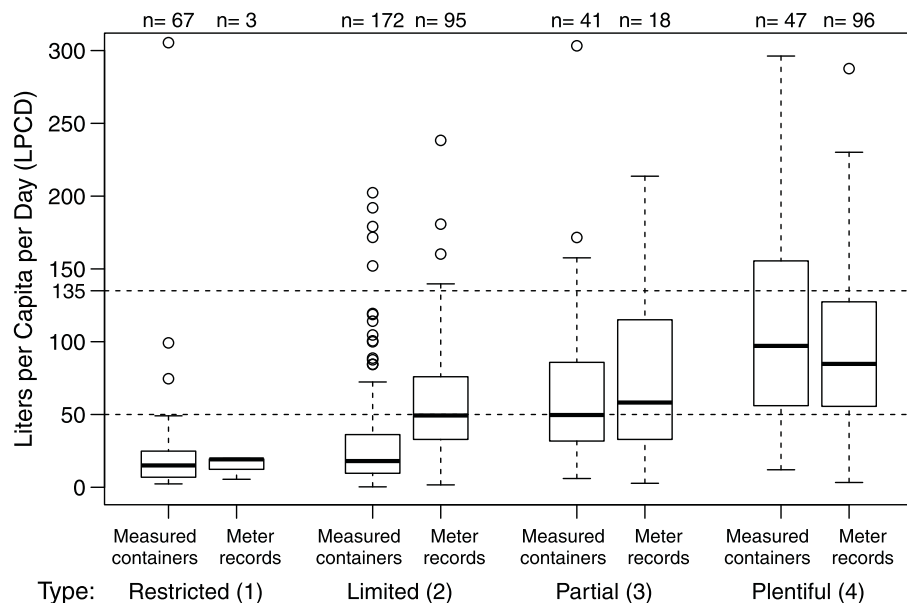
Figure 3. Box and whisker plots show the median (thick line), lower and upper quartiles (bottom and top of the boxes), the minimum and maximum values (the tails), and outliers (dots) of liters per capita per day (LPCD), grouped by household type, using storage container measurements, and meter records. Horizontal lines at 50 LPCD [*Gleick*, 1996; *UNDP*, 2006] and 135 LPCD [*CPHEEO*, 1999; *HPEC*, 2011] indicate human rights and Government of India guidelines for per capita use, respectively.

Table 3. Estimated Per Capita Water Consumption by Household Type Using the Different Measurement Methods[a]

Definition	Metered	Storage and Use			
	Metered Consumption, $LPCD_{metered}$ (V_m)	Storage Capacity, $LPCD_{storage}$	Direct Use, U	Volume Used While Tap On, $U*LPCD_{storage}$	Total Consumption[b], $LPCD_{s+u}$ (V_{s+u})
Type 1. Restricted	19.2 (12.0 kL/con/m)	15.0	40%	6.0	21.0 LPCD (15.7 kL/con/m)
Type 2. Limited	49.3 (12.0 kL/con/m)	18.0	110%	19.8	37.8 LPCD (9.8 kL/con/m)
Type 3. Partial	58.2 (18.5 kL/con/m)	49.6	Not calculated	Not calculated	49.6 LPCD (25.1 kL/con/m)
Type 4. Plentiful	84.7 (15.5 kL/con/m)	97.1	Not calculated	Not calculated	97.1 LPCD (17.9 kL/con/m)

[a]U for Types 1 and 2 households is the ratio of the volume of water used during delivery to the volume of water stored. All values are median.
[b]Estimated as storage capacity added to volume used while tap on for Types 1 and 2 and as storage capacity for 3 and 4.

nearby taps. Fewer Type 1 or Type 2 households (11 and 24%, respectively) than Types 3 and 4 households (62 and 77%, respectively) had pumps. Half of those households with pumps (58%, n = 731) reported attaching them directly to the tap; pumps were also used for filling overhead tanks from underground sumps.

3.2. Household Water Consumption
Average daily per capita metered and storage volumes were higher for households with less-restricted water access (i.e., sharing connections with fewer households, larger storage capacities) (Figure 3). Metered volumes and storage volumes did not produce statistically different consumption volumes for Types 3 and 4 households, although the sample size for Type 3 households with meters was low.

For Type 2 households, however, estimates of stored volumes were significantly lower than metered volumes (Wilcox rank-sum, $p < 0.05$; Figure 3). Despite their differences in storage capacities, Types 2 and 3 households had similar median metered consumption (Figure 3). These discrepancies between metered consumption and storage capacity support our observations that people, particularly in Types 1 and 2 households, carried out water-intensive tasks after filling containers. Therefore, stored water volumes can substantially underestimate total use for households without overhead tanks.

All household types had a median storage capacity (measured container volume) less than the Government of India design standard of 135 LPCD for cities with piped water and partial sewage [*HPEC*, 2011] (Figure 3 and Table 3).

Estimates of direct use for Types 1 and 2 households indicated that Type 1 households used 40% and Type 2 used 110% of their storage volumes while the water was being supplied (Table 3). Type 1 households were typically constrained by the needs of many other users at the same tap; this limitation restricted their overall municipal water use, based on storage and direct use estimates, to 21.0 LPCD. Since only three Type 1 households were metered, this storage-plus-use estimate may more accurately reflect total consumption. The median consumption for Type 2 households was 37.8 LPCD, which approaches their median metered volume of 49.3 LPCD (Figure 3 and Table 3). Although Type 2 and Type 3 households consumed similar volumes of water based on meter records, the volumetric use while on suggests that the timing of that use is different: intermittency imposes coping costs on Type 2 households, who wait until delivery periods to wash accumulated clothes and dishes. Both metered and storage capacity estimates were statistically similar for Type 3 and Type 4 households (Figure 3 and Table 3), therefore it is likely that, if any water is used during delivery, the volume is similar to that remaining in the tank at the beginning of a delivery period.

3.3. Water Loss at Households
"Wasted" water is usually defined as water lost to leaks or not put to beneficial use. Low-income households without overhead tanks and without indoor plumbing often have only one indoor or outdoor tap. For these households, the primary source of "wasted water" is nonbeneficial consumption. But what are beneficial uses, and who determines beneficial and nonbeneficial uses for a given water system? Defining and regulating which uses of water are necessary is always socially contingent, and often contested. Customary practice can differ greatly from household to household, and amongst water users with different water-intensive appliances.
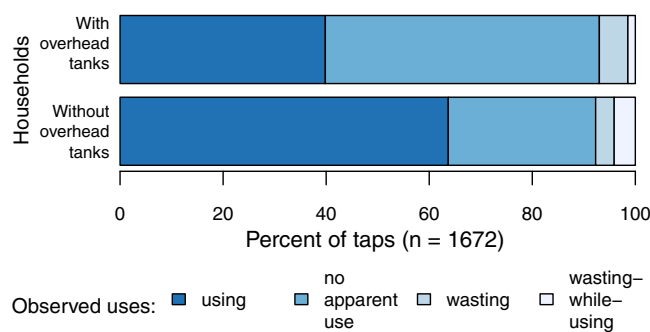
Figure 4. Percent of taps in the tap observation with an observed water use behavior at households in a low SES and high SES neighborhood (Ward 14).

During the tap observation and structured observations, we found that shutoff valves were present at almost all households. The valves were usually turned off once containers were filled. Underground and overhead tanks (100–10,000 L capacity) were typically fitted with float valves that shut off inflow when the tank was full. For households with a shared connection, water collection times were so limited that the water was used the whole time it was on. Where water service periods were shorter than 4 h, taps were in continuous use for filling or washing containers, with each family using the hose for 40 min to 2 h, and a line of users waiting to fill containers.

Data from the household survey supports this general pattern. After they finished filling their containers and using the water, 28% of households reported passing their tap on to another household, 17% reported using all of the available water from their tap, 56% reported turning the tap off, and only four households reported leaving the tap on after filling (total n = 1951). If our reports are correct, few households flagrantly wasted water by letting taps run unattended. We cannot, however, dismiss the possibility of Hawthorne Effect: people may "waste" less under observation than they would have otherwise done.

From the tap observation in Ward 14, we found that, by any definition, overall waste was very low (Figure 4). For households with overhead tanks, we observed wasting at 6% and wasting-while-using at 1% of households (n = 646). For households without overhead tanks, we observed wasting at 4% and wasting-while-using at another 4% of households (n = 1026). Households with hoses (with or without pumps) used more water directly from the tap to clean entrances, vehicles, and drains, while those without hoses cleaned entrances and drains with greywater from washing clothes and occasionally cleaned vehicles with greywater or tap sources. Households with hoses were observed to use much more water for these tasks than the one or two *kodas* (16 L plastic containers) typically used when cleaning by hand.

Proponents of a transition from intermittent to CWS in urban water systems advance two mechanisms for household water waste under IWS: (1) people store more water than they need and then throw away what remains in storage containers when water comes again [*McIntosh*, 2003], and (2) people leave the tap open the entire time water is on, whether or not they are using water from that tap. In Hubli, utility employees frequently echoed this second proposition, saying that households wasted water by running hoses into drains when clothes were being washed. The minority of residents that wasted-while-using, however, considered this "waste" a beneficial use as it flushed debris from the drains.

The amount of water remaining in storage containers at the start of a new water delivery period is the maximum amount that might be thrown away before the containers are refilled. Our structured observations showed that these volumes ranged from 16 to 132 L in containers used to store drinking water and 0–886 L in containers used to store washing water. For Types 1 and 2 households, while some water often remained in containers when the new delivery arrived, this stored water was used for less essential tasks such as flushing out gutters. Overall, only 23% of households in the survey reported at least sometimes "throwing" the remaining water away and 18% of households reported always or sometimes not having extra water; otherwise, households reported using the water for chores or such as cleaning or gardening.

3.4. Water Loss in the Distribution System

To compare the scale of water loss at households to that of the utility, we estimated the magnitude of unaccounted-for water between the supply input to the distribution system and consumption by residential connections. We used three approaches for estimating water consumption per connection in each ward (Table 2). For the first two approaches, median household consumption by connection was estimated using the per capita consumption reported in Table 3, taking into account the number of people sharing a connection, and the fraction of households of each type in a ward. Based on metered volumes, the mean was

Table 4. Monthly Median Consumption Per Connection (kL/con/m) and Unaccounted-For Water (UFW) in Wards 25, 38, 57, 58, and 63 (All in Hubli) Using Three Models: (a) V_m—Median of the Metered Volume Per Connection Multiplied by the Proportion of Households of Each Type Per Ward; (b) V_{s+u}—Median of the Storage and Direct Use Per Connection Multiplied by the Proportion of Households of Each Type Per Ward; (c) $V_{utility}$—The Flat Estimate of 15 kL/con/m Used by the KUWS&BD to Estimate a Standard Unmetered Connection

	Supply Volume (kL/con/m)	Consumption Volume (kL/con/m)						Unaccounted-For Water (UFW; %)					
Ward		25	38	57	58	63	Mean	25	38	57	58	63	Mean
Method													
a. V_m	28.6	14.5	14.8	13.1	13.4	12.5	13.7	49	48	54	53	56	52
b. V_{s+u}	28.6	16.6	16.8	13.5	13.9	11.6	14.5	42	41	53	51	59	49
c. $V_{utility}$	28.6			15.0						48			

13.7 kL/con/m per ward, and based on storage and direct use the mean was 14.5 kL/con/m per ward (Table 4). These are similar to the 15.0 kL/con/m fixed value assumed by KUWS&DB. These estimates were then compared to supply volume to estimate unaccounted-for water (UFW).

Based on these estimates of monthly use per connection, the estimated utility losses ranged from 48 to 56% using method a (metered), 41 to 59% per ward using method b (storage and use), and 48% using method c (utility) (Table 4). Overall, UFW estimates based on metered volumes were higher than estimates using the typology or a fixed consumption. There are many sources of uncertainty in this calculation. In particular, we know from our observations and utility-worker reports that supply volumes vary between wards, although no data were available on these variations. Measuring the supply to each ward could improve water loss estimates and help prioritize which areas to target for water loss reduction.

The UFW in the distribution system estimated using all three methods was high, and much larger than household-level waste. In industrialized country systems, average physical losses are 12%, while estimates of nonrevenue water in developing country systems overall are 35%, with approximately 60% of these as physical losses [*Kingdom et al.*, 2006, p. 200]. Our estimates are of a similar scale to the 25–40% UFW reported in many major Indian cities [*McKenzie and Ray*, 2009].

4. Conclusions

Towns and cities with IWS throughout the world are considering strategies for improving their urban water systems. While measurements of water use and loss are necessary for identifying how to achieve these goals, there are more than 450 similarly sized Indian cities which have challenges similar to those identified in Hubli-Dharwad: infrequent water delivery, many unmetered connections, frequent sharing of taps, and a range of household storage infrastructures [*Registrar General of India*, 2011]. We developed a practical method of estimating water use in Hubli-Dharwad's context by measuring storage container capacities and estimating direct use during supply.

While meters are the most common method of measuring household water consumption, metered data may lead to challenges in IWS regimes. First, metered data may be inaccurate in IWS due to underregistration of flow because of the low flow rates caused by the use of roof tanks or overregistration of flow due to air running through pipes [*Criminisi et al.*, 2009; *Mutikanga et al.*, 2011, 2013]. Second, many households in low- and middle-income countries (including those with continuous supply) share meters, therefore obscuring an individual household's consumption. Finally, average metering rates are low in many developing countries [*Kingdom et al.*, 2006]. Our estimates of per capita water use based on measured containers and observations of direct use were similar to data obtained through meters within each typology group; therefore, if metered data exist for some households, it appears reasonable to extrapolate to other households of the same type. However, we found that Type 1 households were less likely to be metered, and used very low quantities of water. Therefore, extrapolating metered data from one household type to another household type could lead to large errors.

Our estimates of per capita water use revealed large disparities between households. Households that shared a tap with many others and had limited storage capacity (Type 1) used only 21 LPCD, while households with their own tap and overhead storage tank (Type 4) used closer to 100 LPCD. Very few households

of any type were estimated to be using the Government of India design value of 135 LPCD for a city with Hubli-Dharwad's infrastructure (piped system with partial sewerage) [*CPHEEO*, 1999; *HPEC*, 2011]

The quantity of water consumed directly from the tap (without storage) also varied between types, revealing disparities not just in water use but also in water access. These findings highlight strategies that utilities could employ to improve equity of water use and access. Households that lacked an overhead tank but had good access to a tap (Type 2), used the most water during delivery periods; therefore, households that received very limited amounts of water (Type 1) were not necessarily limited because of unequal delivery durations but rather by access to time at the tap and by storage capacity. Strategies to improve equity in access to water could include reducing the number of households sharing a tap, or providing longer durations or more frequent delivery to neighborhoods with many shared taps and without household overhead storage tanks.

The relative importance of losses at different scales (utility versus household) is often debated. We found that most households were wasting very little water. These results call into question the gains that can be achieved by policies that aim to reduce household water losses in intermittent supplies, which is a stated goal for the World Bank and for government initiatives [*World Bank*, 2004]. In Hubli-Dharwad, for the many households that consume much less water than is deemed necessary for basic needs, policies should aim to increase water access. Efforts to reduce household water loss, or increase end-use conservation, are more appropriately targeted at households that have access to sufficient water supplies. In contrast, a focus on reducing losses in the Hubli-Dharwad distribution system could significantly increase available water and help to address the disparities in water use and access that we identified.

Water managers could use the methods we present in multiple ways, depending on their priorities. For example, a water manager interested in identifying how to allocate hours of supply to different neighborhoods more equitably may want to measure use and loss in select neighborhoods with a range of SES conditions, or focus on those areas suspected to have the most limited water use (e.g., high elevation or low-income areas). A water manager implementing a water conservation program may want to select areas anticipated to have the highest household-level water loss to evaluate a "worst-case" scenario. In contrast, a water manager in need of a statistically representative sample of an entire city would design a study based on standard sampling methods (i.e., using census data to randomly select households, or selecting random locations to sample within each administrative unit). Future research on measuring water use and loss in unmetered IWS systems should focus on replicating and refining these methods for other contexts, comparing these results with other measurement methods (e.g., water diaries), and incorporating quantitative measurements of flow (e.g., sensors or meters that have been modified to be accurate under IWS conditions).

References

Alegre, H., W. Hirner, J. M. Baptista, and R. Parena (2000), *Performance Indicators for Water Supply Services, IWA Manual of Best Practice*, Int. Water Assoc., London.

Bapat, M., and I. Agarwal (2003), Our needs, our priorities; women and men from the slums in Mumbai and Pune talk about their needs for water and sanitation, *Environ. Urbanization*, 15(2), 71–86, doi:10.1177/095624780301500221.

Beal, C. D., R. A. Stewart, and K. Fielding (2013), A novel mixed method smart metering approach to reconciling differences between perceived and actual residential end use water consumption, *J. Cleaner Production*, 60, 116–128, doi:10.1016/j.jclepro.2011.09.007.

Burt, Z., and I. Ray (2014), Storage and non-payment: Persistent informalities within the formal water supply of Hubli-Dharwad, India, *Water Alternatives*, 7, 106–120.

Christodoulou, S., and A. Agathokleous (2012), A study on the effects of intermittent water supply on the vulnerability of urban water distribution networks, *Water Sci. Technol.*, 12(4), 523–530, doi:10.2166/ws.2012.025.

CPHEEO (1999), *Manual on Water Supply and Treatment*, Cent. Public Health and Environ. Eng. Organ. in the Minist. of Urban Dev., Gov. of India, New Delhi.

Criminisi, A., C. M. Fontanazza, G. Freni, and G. L. Loggia (2009), Evaluation of the apparent losses caused by water meter under-registration in intermittent water supply, *Water Sci. Technol.*, 60(9), 2373–2382.

Ercumen, A., B. F. Arnold, E. Kumpel, Z. Burt, I. Ray, K. Nelson, and J. M. Colford Jr. (2015), Upgrading a piped water supply from intermittent to continuous delivery and association with waterborne illness: A matched cohort study in urban India, *PLoS Med*, 12(10), e1001892, doi:10.1371/journal.pmed.1001892.

Fan, L., F. Wang, G. Liu, X. Yang, and W. Qin (2014), Public perception of water consumption and its effects on water conservation behavior, *Water*, 6(6), 1771–1784, doi:10.3390/w6061771.

Galaitsi, S. E., R. Russell, A. Bishara, J. L. Durant, J. Bogle, and A. Huber-Lee (2016), Intermittent domestic water supply: A critical review and analysis of causal-consequential pathways, *Water*, 8(7), 274, doi:10.3390/w8070274.

Gleick, P. (1996) Basic Water Requirements for Human Activities: Meeting Basic Needs, *Water International*, 21(2), 83–92.

HPEC (2011), Report on Indian Urban Infrastructure and Services. [Available at http://icrier.org/pdf/FinalReport-hpec.pdf.]

Ismail, Z., and W. F. W. A. Puad (2007), Non-revenue water losses: A case study, *Asian J. Water Environ. Pollution*, 4(2), 113–117.

IWA (2003), Assessing non-revenue water and its components: A practical approach, *Water*, *21*, 50–51.

Karnataka Water Board, H. D. W. S. S. (2008), Water Audit: Unaccounted Water (UAW) of Hubli-Dharwad., Hubli-Dharwad.

Kingdom, B., R. Liemberger, and P. Marin (2006), *The Challenge of Reducing Non-Revenue Water (NRW) in Developing Countries*, Water Supply and Sanitation Sector Board Discussion Paper Series, World Bank, Washington, D. C.

Kumpel, E., and K. L. Nelson (2013), Comparing microbial water quality in an intermittent and continuous piped water supply, *Water Res.*, *47*(14), 5176–5188.

Kumpel, E., and K. L. Nelson (2014), Mechanisms affecting water quality in an intermittent piped water supply, *Environ. Sci. Technol.*, *48*(5), 2766–2775, doi:10.1021/es405054u.

Kumpel, E., and K. L. Nelson (2016), Intermittent water supply: Prevalence, practice, and microbial water quality, *Environ. Sci. Technol.*, *50*, 542–553, doi:10.1021/acs.est.5b03973.

McIntosh, A. C. (2003), *Asian Water Supplies: Reaching the Urban Poor*, Asian Dev. Bank and International Water Association, London.

McKenzie, D., and I. Ray (2009), Urban water supply in India: Status, reform options and possible lessons, *Water Policy*, *11*, 442–460.

Morrison, J., and E. Friedler (2015), A critical review of methods used to obtain flow patterns and volumes of individual domestic water using appliances, *Urban Water J.*, *12*(4), 328–343, doi:10.1080/1573062X.2014.900090.

Mutikanga, H., S. Sharma, and K. Vairavamoorthy (2011), Investigating water meter performance in developing countries: A case study of Kampala, Uganda, *Water SA*, *37*(4), 567–574, doi:10.4314/wsa.v37i4.18.

Mutikanga, H. E., S. K. Sharma, and K. Vairavamoorthy (2013), Methods and tools for managing losses in water distribution systems, *J. Water Resour. Plann. Manage.*, *139*(2), 166–174, doi:10.1061/(ASCE)WR.1943-5452.0000245.

R Core Team (2015), *R: A Language and Environment for Statistical Computing*, R Foundtion for Stat. Comput., Vienna.

Registrar General of India (2011), Census of India *2011*, New Delhi.

Rosenberg, D. E., T. Tarawneh, R. Abdel-Khaleq, and J. R. Lund (2007), Modeling integrated water user decisions in intermittent supply systems, *Water Resour. Res.*, *43*, W07425, doi:10.1029/2006WR005340.

Totsuka, N., N. Trifunovic, and K. Vairavamoorthy (2004), Intermittent urban water supply under water starving situations, paper presented at 30th WEDC International Conference, WEDC, Vientiane.

UNDP (2006), Human Development Report: Beyond scarcity: Power, poverty and the global water crisis, New York.

Vairavamoorthy, K., S. D. Gorantiwar, and S. Mohan (2007), Intermittent water supply under water scarcity situations, *Water Int.*, *32*(1), 121–132.

Van den Berg, C., and A. Danilenko (2011), The IBNET Water Supply and Sanitation Performance Blue Book: The International Benchmarking Network for Water and Sanitation Utilities Databook, World Bank, Washington, D. C.

WHO and UNICEF (2012), A Tool Kit for Monitoring and Evaluating Household Water Treatment and Storage Programmes (HWTS), Geneva, Switzerland.

Willis, R. M., R. A. Stewart, K. Panuwatwanich, P. R. Williams, and A. L. Hollingsworth (2011), Quantifying the influence of environmental and water conservation attitudes on household end use water consumption, *J. Environ. Manage.*, *92*(8), 1996–2009, doi:10.1016/j.jenvman.2011.03.023.

Woelfle-Erskine, C. (2012), The ''how much'' and ''why'' of household water use: Investigating waste during a transition from intermittent to continuous water service in Hubli-Dharwad, India, MS thesis, Univ. of Calif. at Berkeley, Berkeley.

World Bank (2004), Project Appraisal Document on a Proposed Loan in the Amount of US$39.5 Million to the Republic of India for the Karnataka Urban Water Sector Improvement Project, Washington, D. C.

Wutich, A. (2009), Estimating household water use: A comparison of diary, prompted recall, and free recall methods, *Field Methods*, *21*(49), 49–68.