Comparing microbial water quality in an intermittent and continuous piped water supply

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Abstract

Supplying piped water intermittently is a common practice throughout the world that increases the risk of microbial contamination through multiple mechanisms. Converting an intermittent supply to a continuous supply has the potential to improve the quality of water delivered to consumers. To understand the effects of this upgrade on water quality, we tested samples from reservoirs, consumer taps, and drinking water provided by households (e.g. from storage containers) from an intermittent and continuous supply in Hubli–Dharwad, India, over one year. Water samples were tested for total coliform, Escherichia coli, turbidity, free chlorine, and combined chlorine. While water quality was similar at service reservoirs supplying the continuous and intermittent sections of the network, indicator bacteria were detected more frequently and at higher concentrations in samples from taps supplied intermittently compared to those supplied continuously \( (p < 0.01) \). Detection of \( E. \) coli was rare in continuous supply, with 0.7% of tap samples positive compared to 31.7% of intermittent water supply tap samples positive for \( E. \) coli. In samples from both continuously and intermittently supplied taps, higher concentrations of total coliform were measured after rainfall events. While source water quality declined slightly during the rainy season, only tap water from intermittent supply had significantly more indicator bacteria throughout the rainy season compared to the dry season. Drinking water samples provided by households in both continuous and intermittent supplies had higher concentrations of indicator bacteria than samples collected directly from taps. Most households with continuous supply continued to store water for drinking, resulting in re-contamination, which may reduce the benefits to water quality of converting to continuous supply.

1. Introduction

In 2010, 73% of urban and 24% of rural populations in developing countries had access to piped water on their household premises (UNICEF and WHO, 2012). While piped water is an improved water source, recent studies suggest that many systems classified as improved may not provide water that is safe and reliable (Onda et al., 2012). Deficiencies in piped water distribution systems, common in many developing countries, have been linked to contamination of water at consumer taps and outbreaks of water-borne illnesses (Geldreich, 1996; Semenza et al., 1998; Lee and Schwab, 2005). One widespread deficiency is the practice of intermittent water supply (IWS). An estimated one-third of piped water supplies in Africa and Latin America and more than half in Asia supply water intermittently (WHO and UNICEF, 2000; van den Berg and Danilenko, 2011).
Previous studies have found evidence of impaired water quality at consumer taps in intermittently supplied systems (Raman et al., 1978; Tokajian and Hashwa, 2003; Ayoub and Malae, 2006; Yassin et al., 2006; Andey and Kelkar, 2007; Elala et al., 2011). When pipes are at low pressure or are empty when supply is off, contaminants from outside of pipes can enter pipes by backflow or intrusion. Additionally, intermittent delivery of water necessitates household collection and storage, a practice associated with recontamination (Wright et al., 2004; Levy et al., 2008; Elala et al., 2011; Eshcol et al., 2009).

No major city in India has continuous water supply (McKenzie and Ray, 2009), though several cities in India have implemented pilot projects or developed proposals to switch from intermittent to continuous supply (World Bank, 2010, 2003; McIntosh and Yiguez, 1997). Improved water quality is often mentioned as a benefit of upgrading an IWS to a continuous supply, but only one study has compared water quality between intermittent and continuous modes of operation, and its conclusions were limited by a small sample size (Andey and Kelkar, 2007). Because the costs of upgrading to continuous supply may be significant, it is important to provide quantitative evidence of whether the expected water quality benefits are actually achieved to aid decision-makers in identifying cost-effective strategies to upgrade intermittent supplies.

This research compares water quality at reservoirs, taps, and in drinking water in homes in intermittent and continuously operated distribution systems in the same cities in India. The results are useful for understanding the benefits of upgrading an intermittent to a continuous supply and can help inform investments to increase access to safe water through piped distribution systems.

2. Background

2.1. Study site

Hubli and Dharwad are twin cities with a combined population of over 900,000 in northern Karnataka, India (Registrar General of India, 2011). The bulk water supplies and distribution networks are managed by the Karnataka Urban Water Supply and Drainage Board (KUWS & DB) (Fig. 1). Surface water is drawn from two sources: the Renukasagar Reservoir, fed by the Malaprabha River and located 65 km northeast of Dharwad, and the rain-fed Neersagar lake located 20 km southwest of Hubli. The Amminbhavi and Kanvihonnapur water treatment plants (WTP) treat the water using aeration, coagulation and flocculation with alum, clarification, rapid sand filtration, and chlorination with Cl₂ gas. Treated water intended for drinking and domestic purposes is delivered via transmission/feeder mains (pumping or gravity) to service reservoirs and then to consumers through the distribution network pipes. Pipes are primarily cast iron mains and PVC service lines, with newer service lines made from HDPE. Additional chlorine is added sporadically at service reservoirs. During the time of the study, water was provided intermittently every one to eight days with a median frequency of five days. Consumers also commonly supplemented their water supply with groundwater from handpumps, electric borewells, tanker trucks, and neighborhood-scale piped groundwater systems. Wastewater infrastructure consisted of a combination of underground sewer networks (which cover 40% of Hubli’s area and 30% of Dharwad’s area), open drains, septic tanks, and pit latrines (Wilbur Smith Associates Private Limited, 2009).

2.2. Demonstration 24 × 7 supply

The Karnataka Urban Water Sector Improvement Project (KUWASIP) has provided approximately 81,000 consumers with continuous water supply (“24 × 7 supply”) through a demonstration project in Hubli and Dharwad since 2007 and 2008, respectively (World Bank, 2010, 2004). Four wards in each of Hubli and Dharwad have 24 × 7 supply while the remaining 59 wards continue to receive water intermittently. Wards were selected by KUWASIP for 24 × 7 supply based on criteria of a socio-economically diverse population and the ability to hydraulically isolate the ward’s network from the rest of the system (Sangameswaran et al., 2008).

The KUWS&DB provided bulk water from the Amminbhavi WTP to two reservoirs dedicated to supplying the 24 × 7 demonstration wards, one each in Hubli and Dharwad (Fig. 1). In the 24 × 7 areas, a private contractor operated and maintained the distribution networks that pipe water from the outlets of the service reservoirs to customers’ property lines; all of the pipes in these networks were replaced before launching 24 × 7 supply, with higher quality service line materials (high density polyethylene (HDPE)) and meters than those that existed in the intermittently supply network (World Bank, 2010). The results from a sanitary survey conducted along with our water sampling confirmed that infrastructure improvements in house service connections had accompanied the transition to 24 × 7 supply. Among households with IWS, 80% had taps located above ground and 34% had taps located indoors, while among households with 24 × 7 households, 99% of taps were above ground level and 43% were indoors. Only infrastructure relating to the water supply pipe network was improved as part of the 24 × 7 demonstration project; no changes were made to existing wastewater or drainage systems. In the household survey conducted as part of this study, 91% of households in 24 × 7 areas (n = 1794) and 92% in IWS areas (n = 1666) reported using private latrines and 6% of households in 24 × 7 and 4% in IWS areas reported using public latrines.

2.3. Comparison of intermittent and 24 × 7 supply

Leaks in distribution network pipes and poor quality materials and fittings in consumer service connections can allow contamination to enter a distribution system as intrusion when pipes are at low pressure. In the 24 × 7 network in 2011, an estimated 7–20% of the input water supply is lost through leaks, a rate similar to industrialized countries where these losses average 12% (Kingdom et al., 2006). Water loss estimates in the IWS network were not available, but non-revenue water in Indian cities averages 44% (World Bank, 2010) and 60% of water losses in developing countries are estimated to be physical losses (Kingdom et al., 2006). Based on the best available data, it appears that low pressure was more prevalent in the IWS network than the 24 × 7 network, with pressures reported to be between 0 and 5 m (0–7 psi) in the IWS network and 22–40 m (31–57 psi) in the 24 × 7 network (World Bank, 2010). Pressures in IWS service lines
measured by the authors ranged from –4 psi to 36 psi (Kumpel and Nelson, 2013).

The case of Hubli–Dharwad provides an opportunity to compare water quality between intermittent and 24 × 7 operation of water distribution systems given the same bulk water input, environment, and socio-economic context. However, since the 24 × 7 demonstration project also included use of dedicated reservoirs and extensive pipe replacements, it was not possible to isolate the effect of changing only modes of operation. Instead, the comparison presented in this paper is between IWS with the existing network and 24 × 7 supply that includes pipe and house service connection replacement and leak management. Current projects and proposals to convert from intermittent to 24 × 7 water supply in India include similar infrastructure improvements (World Bank, 2003).

3. Materials and methods

Samples were collected from reservoirs, household taps, and drinking water provided by households (points of consumption) and tested for total coliform, Escherichia coli, and physico-chemical parameters. Household storage container characteristics and information about the tap surroundings that could affect water quality were also collected and used in analyses.

3.1. Sample collection

Water samples were collected in parallel with a study of the effect of 24 × 7 water supply on child health and household economics that enrolled 3919 households (enrollment procedures and results reported elsewhere). For the survey, the eight wards with 24 × 7 water supply were matched with eight wards with intermittent supply that had similar demographic and infrastructure characteristics (including frequency of garbage collection and percent of households with latrines and water taps) in 2006, which was before implementation of 24 × 7 supply (CMDR, 2006). Using genetic matching (GM) the four wards in each of Hubli and Dharwad with 24 × 7 supply were matched with five wards in Hubli and three in Dharwad with IWS (Fig. 4) (Sekhon and Grieve, 2008).

Water samples were collected between November 9, 2010 and November 17, 2011 in three repeated rounds of data collection.

3.1.1. Distribution system sampling

A total of 624 samples in 24 × 7 wards and 602 samples from IWS wards were collected from taps used by households. Ideally,
sampling locations would have been randomly selected from an entire ward to ensure balance between sampling locations in IWS and $24 \times 7$. However, this was not possible since in IWS wards, water delivery was unpredictable and only small subsections of the ward receive water at the same time. Therefore, 8–12 samples were collected during a visit to a ward from the areas where water was on at the time of sampling. The team conducted 3–4 visits to each ward per round to collect at least 25 samples per ward per round. Since the nature of IWS dictated the sampling strategy, the same procedure was emulated in $24 \times 7$ wards to achieve a balanced sample. In $24 \times 7$ wards, water samples taken on the same day were collected within the boundaries of clusters, which were subdivisions of wards drawn by the study team, to emulate IWS water supply areas.

Ideally, water samples would have been collected from households enrolled in the study to coordinate data collection; however, samples in the first round were collected before households were enrolled in this study. Therefore, during the first round, sampling locations were selected by walking along the streets of the area receiving supply and selecting the third structure on the left side of each street in the bounded area. During the second and third data collection rounds, samples were, where possible, collected using a similar walking pattern but by selecting the first household enrolled in the health and economics study that could be located. In these rounds, 366 (98.9%) of the samples from $24 \times 7$ household taps and 225 (64.8%) from IWS household taps were from households enrolled in the health and economics study. Fewer samples were collected from enrolled households with IWS because it was difficult to locate specific households within the short water supply durations. If an enrolled household could not be located or refused to participate, a non-enrolled household was selected using the first round procedure.

Taps were flushed for at least 1 min before sampling and sterilized by spraying a chlorine solution. GPS coordinates were recorded and a short sanitary survey administered for each tap sample. The sanitary survey included: tap location (indoors/outdoors and at/below ground level), whether the pipe before the tap was exposed, and presence of an open drain less than 5 m from the tap (examples in Supporting Information Fig. S1).

3.1.2. Service reservoirs
Where possible, one sample was collected from service reservoirs that supplied water to a tap sampling area. More samples were collected at the $24 \times 7$ reservoirs ($n = 69$) than IWS reservoirs ($n = 23$). Two reservoirs supplied all $24 \times 7$ wards, both of which were accessible for sampling, while seven reservoirs and transmission lines supplied the IWS wards in the study. Not all supplying reservoirs could be accessed (locked, unsafe ladder) and, in a few cases, the study team could not verify the origin of the water supplying sample neighborhoods. A limited number of samples were collected from the water treatment plants (WTPs), which were difficult to access and located at remote locations compared to study wards.

3.1.3. Point-of-consumption sampling
Enumerators collected water samples from households when they administered the health and economics survey by asking respondents for a glass of water as they would have given to their child. This glass of water was poured into sample bottles. Of the 611 samples collected, 68% were from stored water containers with no treatment, 21% from stored water that had been treated, and 11% were directly from taps. Enumerators also recorded characteristics of the storage containers and the method used to extract water. 135 of the second and third round tap ($n = 728$) and point-of-consumption ($n = 366$) water samples were collected from the same household (19% of tap and 37% of point-of-consumption water samples).

3.2. Sample analysis
Water samples for enumeration of bacteria were collected in sterile 100 mL bottles with sodium thiosulfate to neutralize residual chlorine. Samples were transported on ice to the laboratory for processing within 8 h. Samples were tested for total coliform and E. coli by the most probable number (MPN) method using Colilert Quanti-tray 2000 (IDEXX Laboratories Inc., Westbrook, ME, USA). Samples were incubated at 35 °C and counted after 24–28 h. Samples for physico-chemical analysis were collected in clean 100 mL bottles and tested for turbidity (Hach Portable Turbidimeter 2100Q) and conductivity (HANNA Instruments pH/conductivity/TDS tester or Extech ExStik II pH/conductivity meter) within 8 h of sampling. Free and total chlorine were tested on-site using a DPD method (Hach Colorimeter II). Duplicates were collected for every 15 samples and field and lab blanks for every 10.

3.3. Data analysis
Microbial detection limits had a lower bound of $<1$ MPN/100 mL and an upper bound of $2419.6$ MPN/100 mL. One half was substituted for values below the lower detection limit and 2420 MPN/100 mL was substituted for samples above the upper detection limit. Statistical tests using indicator bacteria data were performed on their rank values to account for censoring at lower and upper limits. Log transformations for total coliform and E. coli used a value of $\log_{10}(x + 1)$. Untransformed data were used for turbidity, free and combined chlorine, and conductivity. Tests for significance were performed using permutation tests, since this method does not require assumptions about the distribution of the data. To control for correlations among measurements taken within the same ward, permutations were restricted by ward (Anderson and Braak, 2003). Two-way analyses of variance (ANOVA) tests for continuous data and $\chi^2$ for binary data were performed within the permutation framework. Graphing and data analysis were carried out using R (R Core Team, 2012) and the permute package (Simpson, 2012). Values were considered significant at $p < 0.05$ level.

4. Results and discussion
4.1. Comparing $24 \times 7$ and intermittent supply at taps
Water provided to the continuous ($24 \times 7$) and intermittent (IWS) distribution networks was of similar quality, based on a comparison of water quality at the reservoirs (see Section 4.6). Thus, differences in water quality at taps can be attributed to
the distribution system. Results from water samples collected at consumer taps and tested for physico-chemical parameters and indicator bacteria are presented in Table 1 and Fig. 2.

The geometric mean of turbidity in all samples collected from consumer taps was 4.9 NTU (range 0.95–113.00 NTU). More than half of the samples in both IWS and 24 × 7 supplies were above the Indian Drinking Water Standards aesthetic guideline of <5 NTU (Fig. 2b), though most samples (99.2% in 24 × 7 and 91.7% in IWS) were below the maximum permissible limit of <10 NTU (BIS, 2004). There was no significant difference in the percent of samples meeting the standard in IWS compared to 24 × 7 ($\chi^2, p > 0.05$) (Table 1). There were more high and low turbidity outliers among IWS samples (Fig. 2a), but there was no significant difference between 24 × 7 and IWS tap sample means (ANOVA, $p > 0.05$) (Table 1).

Free chlorine in all tap samples ranged from <0.02 to 2.20 mg/L with an arithmetic mean concentration of 0.28 mg/L. A significantly higher proportion of samples from 24 × 7 taps met the minimum standard concentration of 0.20 mg/L (BIS, 2004) compared to samples from IWS taps ($\chi^2, p < 0.01$) (Table 1). While the median free chlorine concentration was higher in 24 × 7 than IWS taps (0.27 mg/L compared to 0.13 mg/L), this difference was not significant (ANOVA, $p > 0.05$) (Table 1). This result is likely influenced by high value outliers in IWS taps (Fig. 2a); 18.8% of IWS samples were above 0.5 mg/L free chlorine while only 5.0% of 24 × 7 samples were above this value (Fig. 2b). This suggests that there was uneven or irregular dosing at IWS service reservoirs. Mean combined chlorine in all tap samples was 0.14 mg/L (range 0–1.26 mg/L), and there were no significant differences in combined chlorine at 24 × 7 and IWS taps (ANOVA, $p > 0.5$) (Table 1).

Fig. 2b shows the percent of samples grouped by World Health Organization guidelines for risk posed by E. coli (WHO, 1997); here they are also applied to total coliform. Overall, indicator bacteria were detected more frequently and in higher concentrations in IWS tap samples compared to 24 × 7 tap samples. A significantly higher proportion of samples were positive for total coliform in IWS (64.9%) than 24 × 7 (17.7%) ($\chi^2, p < 0.01$). Concentrations of total coliform were higher at IWS taps (ANOVA, $p < 0.01$) (Fig. 2a). 15.9% of samples from IWS were at or above the detection limit of 2419.6 MPN/100 mL, compared to 0.7% in 24 × 7. Significantly more samples were positive for E. coli in IWS samples than in 24 × 7 samples ($\chi^2, <0.01$). 1.2% of samples from IWS were at or above the detection limit for E. coli of 2419.6 MPN/100 mL, while the maximum concentration in 24 × 7 samples was 3.1 MPN/100 mL.

Indian Drinking Water Standards for piped water supplies recommend that no more than 5% of samples should contain coliform organisms and no sample should have a concentration greater than 10 CFU/100 mL (BIS, 2004). 8.4% of 24 × 7 samples and 53.1% of IWS samples had concentrations of total coliform greater than 10 MPN/100 mL. The standards also recommend that E. coli should not be present in any samples; 99.3% of samples from 24 × 7 taps met the standard for E. coli compared to 68.3% of samples from IWS taps.

Water quality parameters in IWS samples were variable, with large ranges and frequent outliers (Fig. 2a). More frequent detection of indicator bacteria in the IWS network than in the 24 × 7 networks suggest that contamination occurred in the IWS distribution system. This contamination could be from backflow (e.g. intrusion from the environment or back-siphonage from cross-connections) into pipe networks when supply is off or during low-pressure events when the supply is on (Karim et al., 2003; Besner et al., 2011), resuspension or scouring of particulate matter harboring bacteria from pipe walls (Lehtola et al., 2004; Zacheus et al., 2001), or release from biofilms (van der Wende et al., 1989; Telgmann et al., 2004). These results are consistent with Andey and Kelkar (2007), which found more samples positive for fecal indicator bacteria in IWS and CWS, though this study was limited by a small sample size. The presence of total coliform in 24 × 7 tap water suggests there are still factors compromising the 24 × 7 distribution system, including high turbidity, low free chlorine residual, and interruptions to supply (discussed in Section 4.3.1).

### Table 1 – Descriptive statistics for samples collected from consumer taps including the number of samples (n), quantiles, percent of samples meeting criteria, and significance testing.

<table>
<thead>
<tr>
<th>Supply</th>
<th>n</th>
<th>Quantiles</th>
<th>Meeting standards</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>25%</td>
<td>Median</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 × 7</td>
<td>618</td>
<td>1.18</td>
<td>4.02</td>
</tr>
<tr>
<td>IWS</td>
<td>586</td>
<td>0.95</td>
<td>3.57</td>
</tr>
<tr>
<td>Free chlorine (mg/L)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 × 7</td>
<td>575</td>
<td>&lt;0.02</td>
<td>0.18</td>
</tr>
<tr>
<td>IWS</td>
<td>557</td>
<td>&lt;0.02</td>
<td>0.07</td>
</tr>
<tr>
<td>Combined chlorine (mg/L)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 × 7</td>
<td>563</td>
<td>&lt;0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>IWS</td>
<td>551</td>
<td>&lt;0.02</td>
<td>0.09</td>
</tr>
<tr>
<td>Total coliform (MPN/100 mL)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 × 7</td>
<td>586</td>
<td>&lt;0.02</td>
<td>&lt;1</td>
</tr>
<tr>
<td>IWS</td>
<td>589</td>
<td>&lt;1</td>
<td>1</td>
</tr>
<tr>
<td>E. coli (MPN/100 mL)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 × 7</td>
<td>587</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>IWS</td>
<td>589</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

<sup>a</sup>Permutation ANOVA using ranks of data.

<sup>b</sup>Criteria for water quality set by Indian Drinking Water Standards BIS 10500 or World Health Organization guidelines for E. coli. There are no guidelines for combined chlorine, therefore criteria were based on the guideline for free chlorine.

<sup>c</sup>Permutation, $\chi^2$ using percentage meeting water quality guidelines.
4.2. Seasonal changes

Hubli–Dharwad receives rainfall seasonally, with a dry season from January–May (comprising of winter from January–February and summer from March–May) and a rainy season from June–December. Historically, 65% of annual rainfall accumulates during the southwest monsoon from June to September and the remaining accumulates during the northeast monsoon from October to December (CGWB, 2008).

Unique conditions during both dry and rainy seasons can potentially adversely affect water quality. At the end of the dry season, water levels in the raw water reservoirs were low and sediments may have been drawn in with the bulk water. During the wet season, runoff likely introduced sediments into source water. Ambient temperatures are at their lowest during the end of the dry season (Francisque et al., 2009; LeChevallier et al., 1996). However, throughout the rainy season or when rain occurs in any season, soil surrounding pipes can become saturated and drains and sewers can overflow, providing backpressure that can force intrusion of contaminants into pipes.

Monthly precipitation and mean daily ambient temperatures are presented in Fig. 3 along with daily means of turbidity and free chlorine and daily medians of indicator bacteria. Temperature in tap samples ranged from 23 to 29 °C during round 1 of data collection (Nov 2010–Feb 2011) and from 28 to 30 °C during round 2 (Mar–Jun 2011).

Among service reservoirs, there was higher turbidity during the rainy season than in the dry season (ANOVA, p < 0.05), and after rain occurred in the 24 h before sampling in any season (ANOVA, p < 0.01) (data not shown). No other water quality parameter was significantly different during the rainy season compared to the dry season in service reservoirs.

Higher turbidity and lower free chlorine concentrations in samples from both 24 × 7 and IWS taps occurred during the rainy season (ANOVA, p < 0.01) (Fig. 3). Lower concentrations of free chlorine during the rainy season were likely due to higher chlorine demand from organic matter in source water. In 24 × 7 wards, there was an increase in total coliform concentration at the start of the rainy season in June (Fig. 3), though there was no significant difference in total coliform concentration between the dry and rainy seasons. Samples taken from 24 × 7 taps after rain had occurred in the previous 24 h had lower free chlorine concentration and higher turbidity (ANOVA, p < 0.01), as well as higher total coliform concentration (ANOVA, p < 0.05).

In IWS wards, concentrations of indicator bacteria were lower during the winter months and increased in April, which was also when the first rains began, the ambient temperature was highest and the water levels in the sources were at their lowest (Fig. 3). Concentrations of total coliform and E. coli were significantly higher in the rainy seasons (ANOVA, p < 0.01). Free chlorine was significantly lower and total coliform and E. coli concentrations were higher when rain occurred within 24 h of sampling at IWS taps (ANOVA, p < 0.01); differences in turbidity were not significant.

Fig. 2 – Comparison of water quality parameters in 24 × 7 and IWS at taps. (a) Box and whisker plots show the median, lower and upper quartiles, and outliers. (b) Percentage of samples in different risk categories. DL: Detection limit.
Overall, the seasonal analysis suggests that source water quality declined slightly (indicated by higher turbidity) during the rainy season, resulting in lower chlorine residuals. In 24x7, the sampling frequency was not high enough to identify whether the total coliform after rainfall events came from service reservoirs or the distribution network. In IWS, greater concentrations of indicator bacteria in every season, which increased on average in both the rainy season as well as after specific rainfall events, provide strong evidence that intrusion occurred in the distribution system.

4.3. Variability between wards

Each ward has different operations, infrastructure, and environments that could affect water quality; therefore, it is useful to compare water quality between wards. The spatial distribution of total coliform concentrations in tap samples shows this heterogeneity (Fig. 4). These data suggest that water quality in both IWS and 24x7 wards was highly dependent on local factors.

Ward 10, which had the highest percentage of samples positive for total coliform among 24x7 wards (Fig. 5), is adjacent to ward 11 (Fig. 4), which had the lowest percent of positive samples (Fig. 5). Given that source water quality and water distribution system infrastructure should be similar in 24x7 wards, the differences were likely due to the local environment or operational factors in wards 10 and 11.

A similar percentage of samples were positive for total coliform with similar concentrations in IWS wards 14 and 25 as in 24x7 ward 10, illustrating that IWS can potentially provide water with similar levels of indicator bacteria as 24x7 (similar trends were observed with E. coli; data not shown) (Fig. 5). Differences in the percent of samples with >0.2 mg/L free chlorine could not explain the total coliform results, except that the IWS wards where total coliform was detected more frequently also had persistent low or non-detectable chlorine (Fig. 5).
However, it is important to note that IWS samples were collected after supply had been turned on for at least a few minutes. Therefore, the water quality data presented here do not capture the lower water quality observed during the initial flushing period (documented in a separate study by Kumpel and Nelson (2013)). Elevated concentrations of indicator bacteria during flushing in IWS can have important implications for the quality of water available to consumers.

Potential factors that could have been different between wards include environmental conditions that provide sources of contamination, and operations such as outages or changes in upstream supply pressure that cause low pressure. Also, high water age, which would vary by ward, can result in regrowth of bacteria and loss of chlorine residual. The following section discusses interruptions in 24/7, and a more detailed investigation of contamination mechanisms in IWS is reported in a separate manuscript.

4.3.1. Interruptions to continuous supply
Supply in the 24 × 7 distribution network was occasionally interrupted during the sampling period. In the health and economic survey, households reported the frequency and duration of interruptions they experienced in the last month. 51% of these households with 24 × 7 supply reported at least one outage during the study period. 9% of these outages lasted for less than 1 h, 42% for 1–6 h, 45% for 6–24 h, and the remaining 4% for more than 24 h. These interruptions varied from a single household to street or ward-level outages (likely caused by repairs or insufficient water in the reservoir).

During the first round of data collection, all wards except 8 and 11 reportedly experienced at least one interruption, while in subsequent rounds, interruptions were reported in every ward. It is possible that some of the observed contamination in 24 × 7 taps resulted from supply interruptions, but since households did not report dates of supply outages, it cannot be confirmed.

4.4. Variability within wards
The distribution of E. coli in each ward varied by sampling day (Fig. 6). Five of the eight 24 × 7 wards had no samples positive for E. coli.

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**Fig. 4** – Total coliform concentrations at each consumer tap sampling point in Hubli and Dharwad.

**Fig. 5** – Percent (%) of samples positive for total coliform and percent of samples with ≥0.2 mg/L free chlorine in each ward.
All IWS wards were subject to similar supply durations and frequencies, though they resulted in a wide range of water quality parameter values. IWS wards that had fewer samples positive for total coliform (wards 25, 14, Fig. 5) had samples positive for E. coli occur on only a few sampling days and at lower concentrations than other wards (Fig. 6). Wards 16 and 38 had one day with most or all samples positive for E. coli, suggesting contamination from environmental or operational changes on a particular day.

Wards 38 and 18 had a similar percentage of samples positive for total coliform (Fig. 5), however Fig. 6 reveals different patterns of contamination. Half of sampling days in both wards had at least one positive sample, however, in ward 38, contamination occurred in different clusters and on different days while in ward 18, several clusters repeatedly had positive samples over multiple sampling days. This suggests that contamination in ward 38 may have been due to environmental or operational changes in a particular location on a particular day, while ward 18 may have been subject to chronic problems in sections of the distribution network.

In wards 57 and 58, E. coli were detected on every sampling day, with similar frequencies and concentrations observed in every cluster and round. This pattern suggests chronic problems with the distribution network infrastructure, environmental conditions, or operations in these wards.

A sanitary survey of each house service connection was conducted to collect data on factors hypothesized to contribute to localized intrusion before the tap. A Kruskal–Wallis test was performed for each sanitary survey factor within each ward. The association between each sanitary survey factor and total coliform concentration was inconsistent across wards (Table S1), suggesting that the sanitary survey was not informative about water quality at taps. It appears that underground infrastructure, such as pipe condition, and operational features, such as pressures and flow rates, play a more important role in determining water quality at the taps than the factors assessed in the sanitary survey.
4.5. Chlorine residual and indicator bacteria

In both 24×7 and IWS tap samples, indicator bacteria were detected less frequently and at lower concentrations when there was higher chlorine residual (Fig. 7). Three of the four samples positive for E. coli at 24×7 taps occurred when chlorine was below the recommended guideline of <0.2 mg/L. The detection of indicator bacteria when free chlorine was still present, particularly at levels >0.5 mg/L, suggest that indicator bacteria were protected from inactivation through aggregation with other particles (Herson et al., 1987; Ridgway and Olson, 1982) or that water became contaminated through very local intrusion or sloughing or scouring of biofilms.

4.6. Water quality in water treatment plants and reservoirs

The two surface water sources supplying water to Hubli-Dharwad had different conductivity ranges: conductivity at the Amminbhavi WTP ranged from 147 to 267 µS/cm and at the Kanvihonnapur WTP ranged from 415 to 488 µS/cm (see Supporting Information Fig. S2). Thus, conductivity was a convenient tracer for source water. Since IWS wards were supplied with water from both WTPs while 24×7 wards received water from only the Amminbhavi WTP, conductivity was used to distinguish sources and assess whether treated water quality from WTPs was comparable.

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**Fig. 8** – Comparison of all water quality parameters between 24×7 and IWS throughout the distribution system: water treatment plants (WTPs), service reservoirs, consumer taps, and point-of-consumption (PoC). 8(a) Box and whisker plots show the median, lower and upper quartiles, and outliers. 8(b) Percentage of samples in risk levels based on WHO guidelines.
There were no significant differences between turbidity, free chlorine, total coliform, and \textit{E}. \textit{coli} concentration between service reservoirs supplying $24 \times 7$ and IWS wards (ANOVA, $p > 0.05$) (Fig. 8). Total coliform were detected in both $24 \times 7$ and IWS reservoirs. There are three possible reasons: 1) inadequacies at the water treatment plant; 2) contamination in transmission lines between the WTPs and the reservoirs, which were operated intermittently; or 3) contamination at the reservoirs, as distribution system storage facilities are a common site of contamination (Grayman et al., 2004; Edwards and Maher, 2008; Lee et al., 2006). While we do not have sufficient data to assess risks or causes of contamination at individual reservoirs, these data suggest that $24 \times 7$ and IWS networks were provided with water of roughly similar quality despite being supplied by different reservoirs.

There was a decrease in total coliform and \textit{E}. \textit{coli} from $24 \times 7$ reservoirs to $24 \times 7$ taps, possibly due to inactivation by chlorine residual, while there was an increase in both total coliform and \textit{E}. \textit{coli} between IWS reservoirs and IWS taps (Fig. 8a and b); data for tap samples is the same as presented in Fig. 2.

### 4.7. Water quality at point-of-consumption

While households with IWS always store water, 94% of $24 \times 7$ households where water samples were collected for point-of-consumption testing reported storing water at the time of visit. In households with $24 \times 7$, there were higher concentrations of total coliform and \textit{E}. \textit{coli} in point-of-consumption samples than tap samples (ANOVA, $p < 0.01$) (Fig. 8b). In households with IWS, point-of-consumption samples had higher total coliform concentrations (ANOVA, $p < 0.01$), but slightly lower \textit{E}. \textit{coli} concentrations than tap samples (ANOVA, $p < 0.05$) (Fig. 8b). These results are consistent with other studies that compared water quality between tap and point-of-consumption in IWS (Tokajian and Hashwa, 2003; Elala et al., 2011).

18% of point-of-consumption water samples collected in households were provided directly from the consumers’ tap. Contamination in these samples was higher than in samples collected directly from consumer taps (ANOVA, $p < 0.01$) (Fig. 53). This difference is likely the result of the sampling method: tap samples were collected in sterile bottles after pipes were flushed and taps were sterilized, while point-of-collection samples were collected from a cup given by a member of the household. In the latter case, there was no flushing or sterilization, and water was first poured into a drinking cup before sampling. Therefore, the observed contamination could be the result of stagnation in pipes, a dirty tap, or the cup itself.

Water was considered treated if the household reported having boiled, chlorinated, filtered, or used a commercial device to treat their water and offered this water to enumerators at that time of the visit. Among point-of-consumption samples collected from household storage containers, 24% of households in each of IWS and $24 \times 7$ reported that the stored water had been treated. This is similar to the health and economics survey, where participants offered a cup of water that was reportedly treated in 29% of visits in $24 \times 7$ and 27% of visits in IWS. In the health and economic study, 46% of households in $24 \times 7$ and 47% in IWS reported treating their water at least once during the study. Treatment was not significantly associated with indicator bacteria in samples at the point of consumption (Table 2) (ANOVA, $p > 0.05$).

Covariates potentially associated with recontamination were analyzed to explore whether storage container characteristics or method of extracting water affected water quality (Table 2). The only significant association was between time in storage and \textit{E}. \textit{coli} concentrations in IWS, where storing for more than a day was associated with higher \textit{E}. \textit{coli} concentrations.

The distribution system operation ($24 \times 7$ vs. IWS) was significant for all water quality indicators ($p < 0.01$), suggesting that water quality at the tap was still the most important determinant of water quality at point-of-consumption.

### Table 2 – Median values of water quality parameters for water at point of consumption, stratified by covariates. Significance determined by permutation ANOVA.

<table>
<thead>
<tr>
<th>No.</th>
<th>Total coliform</th>
<th>E. coli</th>
</tr>
</thead>
<tbody>
<tr>
<td>$24 \times 7$</td>
<td>IWS</td>
<td>$24 \times 7$</td>
</tr>
<tr>
<td>Treatment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Untreated</td>
<td>402</td>
<td>100</td>
</tr>
<tr>
<td>Treated</td>
<td>126</td>
<td>980</td>
</tr>
<tr>
<td>p-value</td>
<td>0.10</td>
<td>0.48</td>
</tr>
<tr>
<td>Container location</td>
<td></td>
<td></td>
</tr>
<tr>
<td>On floor</td>
<td>139</td>
<td>105</td>
</tr>
<tr>
<td>Above ground</td>
<td>323</td>
<td>191</td>
</tr>
<tr>
<td>p-value</td>
<td>0.12</td>
<td>0.48</td>
</tr>
<tr>
<td>Container mouth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wide mouth</td>
<td>161</td>
<td>411</td>
</tr>
<tr>
<td>Narrow mouth</td>
<td>276</td>
<td>93</td>
</tr>
<tr>
<td>p-value</td>
<td>0.26</td>
<td>0.27</td>
</tr>
<tr>
<td>Extraction</td>
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<td></td>
</tr>
<tr>
<td>Dipped</td>
<td>432</td>
<td>191</td>
</tr>
<tr>
<td>Pour/tap</td>
<td>155</td>
<td>68</td>
</tr>
<tr>
<td>p-value</td>
<td>0.38</td>
<td>0.21</td>
</tr>
<tr>
<td>Storage time</td>
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<td></td>
</tr>
<tr>
<td>&gt;1 days</td>
<td>67</td>
<td>&gt;2420</td>
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<tr>
<td>≤1 days</td>
<td>166</td>
<td>563</td>
</tr>
<tr>
<td>p-value</td>
<td>0.08</td>
<td>0.34</td>
</tr>
</tbody>
</table>

*p = <0.05.

### 5. Conclusion

- The continuous water supply ($24 \times 7$) network provided water at consumer taps that was less frequently contaminated and had lower concentrations of indicator bacteria than the intermittent water supply (IWS) network. Nonetheless, 18% and 1% of samples in the $24 \times 7$ system did not meet the Indian standard for total coliform and \textit{E}. \textit{coli} respectively. A significantly higher percentage of tap samples from the $24 \times 7$ network (68.3%) than from the IWS network (39.9%) met the guidelines for chlorine residual of >0.2 mg/L. There were no significant differences between the two networks in turbidity, but turbidity was higher than recommended levels in both types of supplies. Improved treatment processes that reduce turbidity and improved management of chlorine residual would be expected to reduce concentrations of indicator bacteria in $24 \times 7$. 
Contamination occurred in the IWS distribution network between reservoirs and taps, with more contamination and higher concentrations of indicator bacteria occurring in the rainy season. The results provide strong evidence that intrusion from the environment into the pipe network was an important mechanism of contamination.

• Variations in water quality parameters were observed between wards, where differing environmental or operational factors influenced water quality. IWS had wide variations in free chlorine concentrations and frequent outlier values of turbidity. While total coliform and E. coli were frequently detected in IWS tap samples, there were some locations and days with no positive samples.

• IWS provided water quality similar to 24 × 7 in some cases. However, tap samples did not represent the water quality when supply was first turned on in IWS networks, during which more contamination would be expected as a result of flushing.

• Water stored in both IWS and 24 × 7 households was more contaminated than water from the taps. Most households with 24 × 7 supply continued to store water, and therefore were not realizing the full water quality benefits of 24 × 7 supply. Future 24 × 7 implementation in areas transitioning from IWS should consider the ways in which people access and store water before drinking, including whether promoting in-house plumbing can improve the quality of water people consume.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.watres.2013.05.058.

References


