

UC Berkeley

UC Berkeley Electronic Theses and Dissertations

Title

Water Quality and Quantity in Intermittent and Continuous Piped Water Supplies in Hubli-Dharwad, India

Permalink

<https://escholarship.org/uc/item/0br51246>

Author

Kumpel, Emily Katherine

Publication Date

2013

Peer reviewed|Thesis/dissertation

**Water Quality and Quantity in Intermittent and Continuous Piped Water
Supplies in Hubli-Dharwad, India**

by

Emily Kumpel

A dissertation submitted in partial satisfaction of the
requirements for the degree of
Doctor of Philosophy

in

Engineering - Civil and Environmental Engineering

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Kara L. Nelson, Chair
Professor Isha Ray
Professor Ashok Gadgil

Fall 2013

**Water Quality and Quantity in Intermittent and Continuous Piped Water
Supplies in Hubli-Dharwad, India**

Copyright 2013
by
Emily Kumpel

Abstract

Water Quality and Quantity in Intermittent and Continuous Piped Water Supplies in
Hubli-Dharwad, India

by

Emily Kumpel

Doctor of Philosophy in Engineering - Civil and Environmental Engineering

University of California, Berkeley

Professor Kara L. Nelson, Chair

In at least 45 low- and middle-income countries, piped water systems deliver water for limited durations. Few data are available of the impact of intermittent water supply (IWS) on the water quality and quantity delivered to households. This thesis examines the impact of intermittently supplied piped water on the quality and quantity of water delivered to residential taps in Hubli-Dharwad, India, when compared to continuous piped water supply. A framework for understanding the pathways through which IWS can impact water quality is first developed. The extent to which contamination occurs in Hubli-Dharwad is quantified by comparing microbial water quality throughout the distribution system in an intermittent system and a continuous system in the same city. The mechanisms affecting water quality in the IWS network in Hubli-Dharwad are identified by measuring changes in water quality over time using continuous measurements from pressure and physico-chemical sensors paired with grab samples tested for indicator bacteria. In the final chapter, a new method of measuring household water consumption in an IWS when supply durations are limited and few metered data are available is developed. This thesis showed that the intermittent supply was frequently subject to contamination in the distribution system and that households with intermittent supply consumed limited quantities of water. While these results demonstrated that converting to a continuous water supply can improve water quality when compared to intermittent supply, this conversion may not be possible in the near future for resource-constrained towns and cities. This thesis contributes to knowledge of the mechanisms causing contamination and constricting water access in IWS systems, which can help improve systems to ensure that people with piped water receive water that is reliable, safe, and sufficient.

To my family

Contents

Contents	ii
List of Figures	v
List of Tables	viii
1 Introduction	1
1.1 Location for research and rationale	2
1.2 Research objectives	3
1.3 Overview of dissertation	4
2 Microbial water quality in intermittent piped distribution systems: A review of the literature	5
2.1 Introduction	5
2.2 The practice of intermittent piped water supply	6
2.2.1 Description of intermittent water supplies	6
2.2.2 Microbial water quality in intermittent water supplies	7
2.3 Mechanisms when the water supply is off	9
2.3.1 Backflow and intrusion	9
2.3.2 Regrowth in bulk water	10
2.3.3 Biofilm regrowth and formation and particulate matter attachment	11
2.3.4 Corrosion and leaching	12
2.4 Mechanisms when water is turned on and off	13
2.4.1 Charge-up and charge-down	13
2.4.2 Particulate matter release and biofilm sloughing	14
2.4.3 Physical integrity	15
2.5 Mechanisms when water supply is on	15
2.5.1 Persistent low and negative pressure	16
2.5.2 Pressure transients	17
2.5.3 Backflow and intrusion	17
2.5.4 Regrowth, biofilm sloughing, and particulate matter release	18
2.6 Distribution system, environmental, and household features	18

2.7	Conclusions	21
3	Comparing microbial water quality in an intermittent and continuous piped water supply	23
3.1	Introduction	23
3.2	Background	23
3.2.1	Study site	23
3.2.2	Demonstration 24x7 Supply	24
3.2.3	Comparison of intermittent and 24x7 supply	25
3.3	Materials and Methods	26
3.3.1	Sample collection	26
3.3.2	Sample analysis	29
3.3.3	Data Analysis	29
3.4	Results and Discussion	29
3.4.1	Comparing 24x7 and intermittent supply at taps	29
3.4.2	Seasonal changes	34
3.4.3	Variability between wards	36
3.4.3.1	Interruptions to continuous supply	37
3.4.4	Variability within wards	37
3.4.5	Chlorine residual and indicator bacteria	40
3.4.6	Water quality in water treatment plants and reservoirs	40
3.4.7	Water quality at point-of-consumption	41
3.5	Conclusion	43
4	Mechanisms affecting water quality in an intermittent piped water supply	45
4.1	Introduction	45
4.2	Materials and Methods	46
4.3	Results	49
4.4	Discussion	59
5	Household water use and utility water loss in an intermittent piped water distribution system	62
5.1	Introduction	62
5.2	Accounting for water: Household and utility metrics under intermittent water supply	63
5.2.1	Household water accounting	63
5.2.2	Utility water accounting	64
5.2.3	Objectives	64
5.3	Methods	65
5.3.1	Study site	65
5.3.2	Typology	65
5.3.3	Measured water consumption	66

5.3.3.1	Metered volumes	66
5.3.3.2	Storage capacity	66
5.3.3.3	Consumption during supply	67
5.3.4	Distribution system losses	68
5.3.5	Statistical analysis	69
5.4	Results and Discussion	69
5.4.1	System description	69
5.4.2	Household Water Consumption	72
5.4.2.1	Storage capacity and metered volumes	72
5.5	Water losses	76
5.6	Distribution system losses	76
5.7	Conclusions and Policy Implications	78
6	Conclusions	79
	Bibliography	82

List of Figures

2.1	Hours of supply provided by utilities reporting intermittent supply. Data source: van den Berg and Danilenko (2011)	6
3.1	Hubli-Dharwad distribution system layout	25
3.2	Total coliform concentrations at each consumer tap sampling point in Hubli and Dharwad	27
3.3	Photos of consumer taps used for sampling showing taps above ground level (A-D) and at ground level (E). Taps located below ground level could be in an open drain (D; a hose is attached to the tap) or in tanks dug into the ground (F; a hose attached to the submerged tap.)	28
3.4	Comparison of all water quality parameters between 24x7 and IWS throughout the distribution system: water treatment plants (WTPs), service reservoirs, consumer taps, and point-of-consumption (PoC). 3.4(a) Box and whisker plots show the median, lower and upper quartiles, and outliers. 3.4(b) Percentage of samples in risk levels based on WHO guidelines.	32
3.5	Comparison of water quality parameters in 24x7 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	33
3.6	Water quality parameters over time in tap samples. Shaded rectangles denote the rainy season. The top line presents repeated plots of total monthly rainfall and a smoothed fitted cubic line of daily ambient temperature. Daily means are plotted for turbidity and free chlorine and daily medians plotted for total coliform and <i>E. coli</i> . Each ward is plotted with a different symbol.	35
3.7	Percent (%) of samples positive for total coliform and percent of samples with ≥ 0.2 mg/L free chlorine in each ward	36
3.8	CDFs of <i>E. coli</i> for each ward by day, with wards in the same order as in Fig. 3.7. Colors represent different rounds of data collection.	38
3.9	Percentage of samples meeting risk levels for total coliform and <i>E. coli</i> grouped by free chlorine concentrations.	40
3.10	Kernel density plot of conductivity for source waters (Aminbhavi and Neersagar water treatment plants), groundwater, and taps and reservoirs.	41

3.11	Total coliform and <i>E. coli</i> by risk group for tap and stored water. PoC: Point-of-consumption samples.	42
4.1	Study wards (14, 16, 25, 38, 57) and sampling sites in Hubli and Dharwad. Hubli is located 26 km southeast of Dharwad. Table lists sampling sites by ward (Ward), abbreviated site names (Site), neighborhood (Location), type of site (Type) distinguished as either a direct tap on a pipe (pipe) or a tap used by consumers (house), a description of the site (including story of house for consumer tap locations), and the estimated elevation (H) of the pressure sensor above the underground distribution pipes.	47
4.2	Sensors attached to direct tapping on pipe (Site: RADJ). YSI Sonde is on the left and Telog Line pressure monitor on the right.	48
4.3	Each column contains data from one ward (14, 25, 38, and 57). The top row displays turbidity and indicator bacteria data during the first two hours of example supply cycles. The grey vertical line marks the end of flushing. Bar charts display total coliform and <i>E. coli</i> concentrations during (dark grey) and after (light grey) flushing for each supply cycle, with the number of positive samples and total number of samples above each bar (+/n). The date is shown as month/day is below each bar, with years in Table 4.1.	51
4.4	The minimum (grey line) and maximum (black line) pressure recorded every 2 sec for all sampling locations located directly on distribution system pipes. Transients were identified only during one supply cycle (b).	53
4.5	Pressure transients identified during supply cycle at PATI (Ward 25) on 2011-07-15. The black trace represents the maximum recorded pressure and the grey trace represents the minimum recorded pressure (recorded every 2 sec). The dotted horizontal line is 10% greater than the maximum 2 sec mean pressure recorded during the supply cycle. Arrows at the top indicate transients.	54
4.6	Box and whisker plots show the median, lower and upper quartiles, and outliers of indicator bacteria concentrations from all supply cycles during supply (flushing and draining excluded), grouped by the average pressure and chlorine residual during the 30 minute period before each grab sample was collected and tested for total coliform and <i>E. coli</i>	55
4.7	Box and whisker plots show the median, lower and upper quartiles, and outliers of the log values of turbidity from all supply cycles, grouped by the pressure and chlorine residual recorded at the same time.	56
4.8	Mean pressure (P) every 2 sec, turbidity (T) every 1 sec, and grab samples tested for indicator bacteria concentrations (total coliform/ <i>E. coli</i> , TC/EC). A) (a) sustained pressure near 0 psi; (b) elevated indicator bacteria; (c) turbidity event after re-starting flow; (d) possible intrusion. B) (e) two turbidity and indicator bacteria spikes during draining (<10 psi). C) (g, h) turbidity spikes after sudden changes in pressure, (f) normal valve operation, D) (i) sudden pressure drop after turning valve off followed by (j) spike in turbidity.	57

4.9	Pressure (P) recorded as an average every 2 sec, turbidity (T) recorded every 1 sec, and indicator bacteria (total coliform/ <i>E. coli</i> , TC/EC) concentrations over time. A) (a) sudden drop in pressure without a subsequent turbidity event (b) turbidity event without a pressure change (possible intrusion). B) (c) series of events without a change in turbidity (d) elevated total coliform after first flush (e) turbidity changes that were not identified as events.	59
5.1	Average liters per capita per day (LPCD) based on estimates of storage capacity for each cluster within each ward. Pie charts in the bottom right of each plot show the makeup of each ward based on typology.	70
5.2	Box and whisker plots show the median, lower and upper quartiles, and outliers of liters per capita per day (LPCD), grouped by typology using two measurement methods (storage container measurements and meter records). Horizontal lines at 50 and 135 LPCD, representing guidelines for per capita consumption.	73
5.3	The geometric mean of total water consumption for type 2 and 3 households in units of per person per day (LPCD) using two methods of measurements: (1) measured storage volume augmented with an estimate of use while water is on using the mean use by flow rate (Use by Flow) and the medium estimate of use by time (Use by Time) and (2) metered volumes. The geometric mean of consumption volumes and sample sizes are printed above each bar.	75

List of Tables

2.1	Mechanisms affecting water quality in intermittent piped water distribution systems	8
2.2	National pressure guidelines.	16
2.3	Features frequently co-located with IWS which amplify effects on water quality	20
3.1	Descriptive statistics for samples collected from consumer taps including the number of samples (n), quantiles, percent of samples meeting criteria, and significance testing.	31
3.2	Mean of log concentrations transformed to counts (MPN/100mL) of total coliform. <i>p-values</i> from Kruskal-Wallis test.	39
3.3	Median values of water quality parameters for water at point of consumption, stratified by covariates. Significance determined by permutation ANOVA.	43
4.1	Site (ward and location), Date, duration of water supply (D), and mean pressure during supply (P) of all sampled cycles. The duration for charge-up (based on pressure) and flushing (based on turbidity) are presented in minutes (min) and percent of supply (%).	50
5.1	Number of surveyed households of each type within each ward. Characteristics include the percent of households sharing a tap, the percent of households with an overhead tank, and the percent of households with a functioning meter by ward and typology.	71
5.2	Table of water use factors (<i>UF</i>) as a fraction of the total storage capacity using 1) Flow rates and 2) Time at the tap available to households for using water.	74
5.3	Monthly consumption (Con) in liters per capita per day (LPCD) in Ward 25, 38, and 57 and unaccounted-for water (UFW) estimates using five models.	77

Acknowledgments

I could not have asked for a better teacher or more supportive adviser than I found in Kara Nelson. By example she showed me how to set and achieve high standards for research and by her mentorship showed me how to get there each step of the way. Her guidance helped me grow as a person and keep the challenges of graduate school in perspective. From enthusiastically supporting the small spark of an idea for a dissertation project, delving into bumpy bus rides and sampling trips in the field, editing dozens upon dozens of paper drafts, and sharing insights about development and teaching philosophies, I am grateful to have learned so much from a mentor I respect deeply.

I have also benefited greatly from Isha Ray's support and guidance. It was through her class in my first semester that my views on international development and my role in the world were turned on their heads. I am grateful to her for teaching me how to think critically from every perspective and process academic knowledge and field experiences side by side. Our conversations and her feedback always gave me a sense of clarity and direction.

I want to thank the role that the civil systems program played in finding me a home in Civil and Environmental Engineering at Berkeley, and I appreciated the years of conversations with and support from Raja Sengupta and Steve Glaser. Jack Colford provided me opportunities with and connections to the broader WASH field and has been a constant champion of my career. I also want to thank Ashok Gadgil for providing feedback on this dissertation.

This research would not have been possible without my colleagues Ayse Ercumen and Zach Burt. Our numerous days and nights arguing over survey questions and mapping wards while eating gobi manchurian and noodles taught me everything I need to know about field research and friendship. I admire Ayse's razor-sharp drive and focus that is coupled with genuine compassion for and love of the people around her. I am in awe of Zach's ability to ask the right questions and carefully uncover their answers while showing limitless kindness and consideration for other people. I will always treasure our time together in our Karella temple home and I look forward to being life-long colleagues.

This research was made possible by the support and dedication of colleagues in Hubli-Dharwad. Thank you to Mr. Jayaram, who first told me about the 24x7 project and invited me to stay and do my dissertation work in Hubli. His dedication to always learning more and doing the right thing, regardless of adversity, inspire me. Thank you to Professor Nayanatara Nayak and the staff at CMDR for all of their help with this project, gracefully accepting our every-expanding timeline, and providing a community in Dharwad. Professor Hegde and the students at SDM College of Engineering were enthusiastic and generous supporters and officemates. I owe a sincere thanks to the Deshpande Foundation, particularly Naveen Jha, for years of sharing resources, connections, and knowledge.

These data could not have been collected without the dedication of Madhu C H and his perseverance in collecting samples. I will never forget his tireless good humor and persistence as we worked to process supplies through customs and drive on long motorcycle rides through mud, monsoon rains, and early mornings. This study was also made possible through the

dedication and insight of Narayan Billava, whose work ethic and view of the world inspire me. I first knew he was special by his penchant for saying “no” in a world of “yes ma’am”’s; I have been continually amazed over the years by his incredible attention to detail and empathy. I am also thankful for the hard work of the enumerator team who collected the survey data and water samples: Suma, Sneha, Anasuya, Shobha, Reema, Tejal, Vijayalaxmi, Drakshayani, Neelama, Parvati, and Sunanda.

For much of graduate school, I was living two lives: one in Berkeley, and the other in India. I want to acknowledge the role that Haath Mein Sehat in leading me on this dissertation path. Anu Sridharan helped me find the joy of life in India, introduced me to idli sambar, and taught me how to get things done. She is an inspirational person who constantly reminds me to dream big. Thank you to Arvind Sadasivan and Krishna Sasidharan, who have let me stay at their homes one too many times and made me love India for my friends and want to keep coming back.

My time in Hubli and Dharwad was and always will be special, and I am grateful to patient rickshaw and bus drivers, to residents who gave me water samples and so many cups of chai, and to valvemmen and engineers who helped me while making sure I had had my breakfast. Sujata and her family gave me a safe and welcoming home away from home. Over the years, the Deshpande Foundation Sandbox fellows - particularly Arati, Dulcie, Genny, Emil, Suzanne, Xanthine, and Aliza - provided friendship, moral support, and great roommates. I also appreciated the help of the Berkeley students who came during the summer to assist with data collection: Sharada Prasad C S, John Erickson, and Cleo Woelfle-Erskine contributed substantially to collecting the data in this dissertation.

In Berkeley, graduate school was made both possible and fun because of a wonderful group of friends. Thank you to Lissette Jimenez for many years of moral support and cheerleading through classes, qualifying exams, and relationships of all kinds, and for being patient with an often-absentee roommate. Thanks to Kristen Parrish who taught me how to deal with the ups and downs of academia - and for the apartments. The wonderful group at Copa Colusa got me through the (almost) end with warm family dinners and always someone to talk to. Thank you also to my friends who helped me through classes and teaching: particularly Andrea Silverman, Corinne Scown, Lindsey Nolan, and Mi Nguyen. Thank you to the fantastic Nelson lab group and community of WASH researchers at Berkeley - in particular, conversations and support from Fermin Reygadas enriched my graduate school career and helped with the final push at the end.

I am grateful to have had a wonderful, supportive, and patient family throughout this process, who instilled in me from an early age a love of learning. The lives of Helen and Richard Jennings taught me that I could do anything but first and foremost I should be a good person. My sister Amy has always been an example of how to figure out what makes you happy and find joy in it, a message I took to heart many times to find the perseverance to finish my dissertation. My parents were patiently supportive and understanding of my wanderlust and have always told me they believed in me and believed in me doing what made me happy. They have been there every step of the way and cheering me on, and I am thankful for their support. I am grateful to Jay for making this journey by my side and

always challenging me to do and be my best.

-

This dissertation research was funded through the National Science Foundation Graduate Research Fellowship, the UC Berkeley Chancellor's Fellowship for Graduate Study, the Blum Center for Developing Economics at UC Berkeley, and the Deshpande Foundation.

-

The text and figures in Chapter 3, are partially a reprint of the material in *Water Research* 2013. Chapter 5 benefited greatly from the help of Cleo Woelfle-Erskine.

Chapter 1

Introduction

In 2010, over 4 billion people (60% of the world's population) accessed water through a piped supply on their premises or at public taps (WHO and UNICEF, 2012). This number is increasing: from 1990 to 2010, the number of people in urban areas with piped water increased from 1.8 billion people to 2.8 billion. In some regions of the world, access to piped water increased at least twice as fast as access to any other type of improved source (WHO and UNICEF, 2010). However, access to piped water is defined as access to a tap; this definition does not measure whether the water at the tap is reliable, safe, or sufficient. While improved water quality and increased water quantity from piped systems reduces waterborne illnesses and improves livelihoods, deficiencies in infrastructure or operations could reduce these benefits. The research presented in this thesis examines the impact of intermittent supply - a deficiency in piped water distribution systems common in resource-constrained settings - on the quality and quantity of water delivered to taps.

In many low- and middle-income countries, piped water systems deliver water for limited durations. At least 45 countries deliver intermittent water supply (IWS), serving at least 375 million people (van den Berg and Danilenko, 2011). An estimated 250 million of these people live in India, where no city has continuous supply (Desai et al., 2007; McKenzie and Ray, 2009; India, 2011). Supply durations have been declining in many low-income countries (Thompson et al., 2001; van den Berg and Danilenko, 2011). While the number of people with access to piped water is increasing with urbanization and population growth, increasing water scarcity, escalating demand, and rapid urbanization present challenges in meeting this growing demand and may make IWS an even more common operational mode (McDonald et al., 2011; Vairavamoorthy et al., 2008).

The social and economic costs borne by households and utilities of IWS compared to continuous water supply have been well studied (Choe et al., 1996; Dasgupta and Dasgupta, 2004; Dutta et al., 2005; Zerah, 1998). However, few data are available on the impact of IWS on the water quality and quantity delivered to households. The potential effect of IWS - where pipes are unpressurized for periods of time - on water quality was recognized in the literature as early as 1875, where a study linked typhoid cases to sewage backflow into an intermittent piped water system (Carpenter, 1875). While continuous positive pressure in

pipes is often considered the standard for providing safe water and adequate service, there has been limited research on how to improve IWS systems even though they supply water to hundreds of millions of people. Additionally, there are few data on how much water people consume in an IWS when meters are not present and whether strategies to reduce water losses should focus on the distribution system network or households.

In India, IWS is endemic and supply durations are limited: the average hours of supply reported by households in 2005 was 4.8 hours (there is no data on the number of days between delivery) (Desai et al., 2007; McKenzie and Ray, 2009). In India, the debate around improving urban water supplies has focused on converting from IWS to continuous water supply (known commonly as 24x7 in India). In addition to the benefits of increasing cost recovery for the utility and reducing coping costs for households, this upgrade was anticipated by policymakers to improve water quality (reducing waterborne diseases), increase water availability to households, and reduce water loss and waste at households. However, to date there has been only anecdotal evidence of whether any benefits have been achieved and whether they were worth the costs (World Bank, 2004; Sangameswaran et al., 2008; Seetharam and Bridges, 2005; Mitra, 2008).

In addition to questions of the benefits of 24x7 compared to IWS, it is not clear that a full conversion to 24x7 is the only path to improving water quality and quantity in IWS systems; there may be interim steps besides direct conversion to 24x7 that can improve the safety and sufficiency of water delivered through intermittent systems. This thesis approaches these questions from multiple angles and provides evidence quantifying the impact of IWS on water quality and quantity that is necessary for identifying how to improve urban water supplies in low- and middle-income countries.

There is also evidence that IWS results in negative health, social, and economic consequences for households when compared to continuous piped water supply. The work presented in this dissertation was complimented by the work of two other graduate students, Ayse Ercumen (Department of Public Health, UC Berkeley), who measured the impact of the conversion from IWS to 24x7 on the incidence of waterborne illnesses among children under five, and Zachary Burt (Energy and Resources Group, UC Berkeley), who compared the costs and benefits to households of the conversion. Together, our results present the first holistic picture of the conversion from intermittent to continuous supply, and through it provide insight into the true costs of intermittent supply.

1.1 Location for research and rationale

Hubli-Dharwad, twin cities with a population of over 900,000 in Karnataka, India, were selected as a research site. They presented a typical case of intermittent water supply in India and were one of the first cities to pilot 24x7 supply (India, 2011; World Bank, 2010). Average supply duration in Hubli-Dharwad was 4.0 hr, which is similar to the average of many districts in India (4.8 hr), and its size of nearly one million is of a similar scale as more than 400 cities in India (Desai et al., 2007; India, 2011).

Bulk water was supplied to the distribution systems in Hubli-Dharwad from two surface water sources treated at two water treatment plants. This treated water was delivered to service reservoirs and then to consumers through distribution network pipes. Supply was provided rotationally through valve operations to more than 800 small areas throughout the cities. Consumers also commonly use supplementary water sources, including groundwater from handpumps, electric borewells, tanker trucks, bottled water, and neighborhood-scale piped groundwater systems. Wastewater infrastructure consisted of underground sewer networks (which cover 40% of Hubli's area and 30% of Dharwad's area), open drains, septic tanks, and pit latrines (CSE, 2012). The distribution system is described in more detail in Chapter Two.

Hubli-Dharwad was one of three cities in Karnataka selected for a pilot 24x7 water supply as part of the the Karnataka Urban Water Sector Improvement Project (KUWASIP), funded by a loan through the World Bank in partnership with state and local government. The goal of KUWASIP was to implement 24x7 water supply in demonstration zones through private sector participation (World Bank, 2004). A private contractor constructed the necessary infrastructure in the demonstration zones and supplied 24x7 water to 10% of residents (70,000 people) starting in late 2007 in Hubli and in mid-2008 in Dharwad while the remainder of the city received intermittent supply. Zones for pilot 24x7 supply were selected to contain a socio-economic mix of the population and on the ability to hydraulically isolate network sections (Sangameswaran et al., 2008; World Bank, 2010). The upgrade is discussed further in Chapter Two.

While this site is an extreme example of intermittency (there are many forms of intermittency, discussed in Chapter One), it is similar to that experienced by many cities in India. Additionally, the impacts of converting from extreme intermittency to 24x7 quantifies the maximum benefits that could be achieved by improving piped water delivery.

1.2 Research objectives

This thesis examines whether the water provided to residents is safe to drink (free from microbial contamination) and of sufficient quantity for drinking, cooking, and basic hygiene when it is delivered through piped distribution systems intermittently (WHO and UNICEF, 2006). The objectives are to:

- Compare microbial water quality between intermittent and continuous distribution systems at service reservoirs, household taps, and in water consumed in households.
- Understand and find evidence of the mechanisms affecting microbial water quality in intermittently supplied piped water distribution systems.
- Develop methods of measuring water consumption in unmetered households with intermittent supplies and use these estimates to understand water access and losses in the distribution system.

1.3 Overview of dissertation

Chapter One reviews the literature on microbial water quality in IWS, knowledge of hydraulics in IWS, and literature from continuous supplies to understand how IWS could affect water quality throughout the stages of a supply cycle. This critical review suggests that a host of complicated mechanisms can degrade water quality. Contamination likely enters pipes between supply cycles and is flushed out when water is turned back on. However, the risk of contamination continues during supply due to low pressure and a host of environmental and contextual issues that can allow backflow and intrusion into the pipe network.

Though the review in Chapter One suggests contamination in IWS systems is likely, there are few data available from these systems. Chapter Two quantifies the extent to which contamination occurs in an intermittent supply in Hubli-Dharwad, India by comparing microbial water quality in an intermittent system to a continuous system in the same city. I present microbial water quality data from throughout the distribution system (service reservoirs, household taps, and in household storage containers). Continuous supply provided consistent water quality while IWS was highly variable in space and time. Additionally, though continuous supply improved water quality overall at the tap, households continued to store water. Household water storage led to contamination, impairing the quality of water that people consumed.

Chapter Three follows from the evidence of contamination presented in intermittent supplies in Chapter Two. In this chapter, I explore the mechanisms causing contamination in IWS by measuring changes in water quality over time using new tools: pressure and physico-chemical sensors that sample continuously paired with frequent grab samples tested for microbial water quality. These data are used to identify mechanisms that may have caused contamination. Water was highly contaminated during flushing, when supplies were first turned on; however, contamination reduced after flushing had finished. Persistent low pressure, which could allow contamination through intrusion or backflow into the pipe network also led to frequent contamination. During supply, periodic contamination was common, though the mechanisms causing this contamination could not be separated. These methods and results can inform monitoring of and research on water quality in IWS systems.

Chapter Four focuses on water quantity in IWS by developing a new method of measuring household water consumption when supply is limited and metered data are not available and using these new methods to estimate losses in the distribution system. Water consumption is triangulated using metered data, measurements of storage capacity, and structured observation of use while supply is on. The results suggest that households are consuming small quantities of water, with many households consuming amounts below recommended minimums, while most water losses likely occur in the distribution system network.

In the Conclusions, I discuss research contributions and future work.

Chapter 2

Microbial water quality in intermittent piped distribution systems: A review of the literature

2.1 Introduction

Complex biological, physical, and chemical mechanisms can degrade water quality during transmission from a source to consumer taps (Geldreich, 1996; Kirmeyer et al., 2001a; Lechevallier et al., 2004; Payment et al., 1997). Millions of people in the developing world are supplied by piped water that is at risk of microbiological contamination due deficiencies in distribution systems (Onda et al., 2012; Lee and Schwab, 2005). While continuous positive pressure in piped distribution systems is the commonly accepted standard for protecting water from contamination (Ainsworth, 2004; AWWA, 2003), many low- and middle-income countries practice intermittent water supply (IWS), in which piped water is supplied for limited durations (Figure 2.1) (van den Berg and Danilenko, 2011; WHO and UNICEF, 2000). The hydraulics of operating a distribution system intermittently can influence the quality of water available at consumer taps.

There is currently no framework for understanding the causal pathways through IWS impacts water quality. While there is evidence that contamination occurs in IWS systems, it is not known whether these events are predominantly the result of persistent or momentary contamination (Lee and Schwab, 2005). A better understanding is needed for developing strategies that protect water quality in IWS. This review draws on the limited available data on water quality in IWS and the more extensive literature on water quality in continuous water supplies (CWS) which, combined with knowledge of hydraulics in IWS, can provide insight into how IWS affects water quality. In addition, the typical context in which IWS exists - low-income countries with under-resourced utilities and inadequate sanitation infrastructure - is discussed because these factors can exacerbate mechanisms causing contamination.

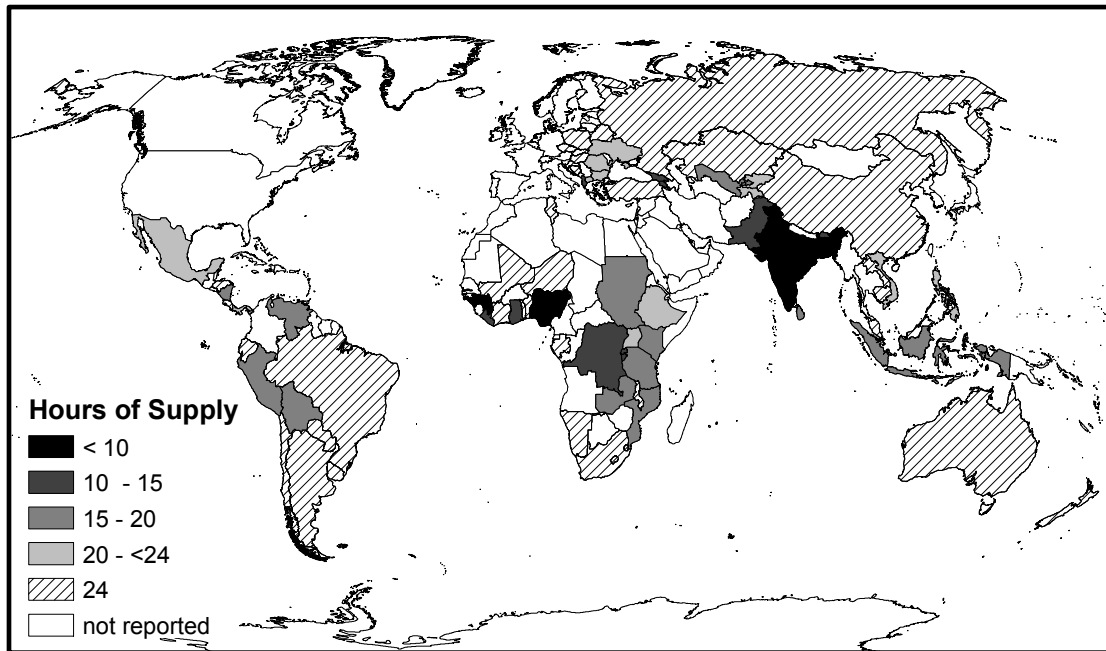


Figure 2.1: Hours of supply provided by utilities reporting intermittent supply. Data source: van den Berg and Danilenko (2011)

2.2 The practice of intermittent piped water supply

An estimated one-third of the population with piped water supply in Latin America and Africa and more than half in Asia receive water intermittently (WHO and UNICEF 2000). Though detailed data on the prevalence of IWS are scarce, over one billion people in the world are reported to have piped water in countries where IWS is common (van den Berg and Danilenko, 2011; WHO and UNICEF, 2012).

2.2.1 Description of intermittent water supplies

IWS encompasses a broad spectrum of practices with varying water delivery durations and patterns. Several cities in the Middle East supply 10 to 12 hours daily during the dry season and switch to 24 hour supply during the rainy season (Abu Amr and Yassin, 2008; Coelho

et al., 2003; Korfali and Jurdi, 2007). In South Asia, two to four hours daily or weekly is more common (McKenzie and Ray, 2005; Mohanty et al., 2002). The data that are available on IWS practices report supply durations but often do not report the number of days between supply cycles.

In larger distribution systems, intermittent delivery can be rotational, with water provided to hydraulically isolated parts of the network in sequence. In smaller systems, supply may be provided to an entire coverage area at the same time. Within the same distribution systems, the nature of intermittency experienced by different parts of the network can vary in space and time, with supply durations changing depending on population sizes, pressures, or pipe configurations (Sashikumar et al., 2003).

The reasons for providing water intermittently have not been systematically studied and vary significantly between systems and contexts. Totsuka et al. (2004) proposed that IWS is a method of rationing not only water quantity, but also of rationing economic, social, and technical inputs (e.g. power supply, chemicals for water treatment, lack of meters to control consumption). To our knowledge, no systems have been intentionally designed to provide intermittent supply; instead, a common scenario is that systems initially provided continuous supply but their ability to meet all demand throughout the system became limited by excessive leakages and/or unchecked network expansion.

Access to piped water is increasing faster than access to any other type of improved water source. At the same time, low-income countries are decreasing supply durations (Thompson et al., 2001; van den Berg and Danilenko, 2011; WHO and UNICEF, 2012). IWS will likely become more common as population growth, urbanization, and climate change are expected to adversely affect the quantity of water available to cities (McDonald et al., 2011; Vairavamoorthy et al., 2008).

2.2.2 Microbial water quality in intermittent water supplies

Water quality problems can be microbiological, chemical, physical, or aesthetic (Kirmeyer et al., 2001b; Geldreich, 1996; Spencer, 2012; Clark and Grayman, 1998). This review focuses on microbial contamination, which is the most common type of contaminant causing illness in developing countries (Gadgil, 1998). Microbiological contamination in distribution systems is often characterized using bacterial indicator organisms (e.g. heterotrophic plate count (HPC), total coliform, fecal coliform, and *E. coli*). However, indicator organisms do not always behave the same as actual pathogens. Actual pathogens can exist in the absence of indicator organisms if they are removed less efficiently by treatment processes, are more resistant to disinfection, or originate from a non-fecal source. On the other hand, indicator bacteria can potentially grow in the environment unlike enteric viruses and most protozoa; therefore regrowth, discussed in Section 2.3.2, is only possible for bacterial pathogens and free-living protozoa.

Chemical and physical parameters are discussed in this review when they could impact the survival or growth of pathogens. In particular, a disinfectant residual is frequently maintained in distribution systems to inactivate pathogens, and is therefore used as an

Table 2.1: Mechanisms affecting water quality in intermittent piped water distribution systems

Operation	Hydraulic effect	Mechanism	Water quality result
<i>Water off</i>	Empty pipes	Low/negative pressure	Backflow and intrusion
		Pipes exposed to air	Corrosion and leaching
	No flow	Stagnant water/biofilms	Regrowth
<i>Water turned on and off</i>	Charge-up/down	Shear stress changes	Release of particulates & biofilms from pipes
		Low pressure spikes	Backflow and intrusion
		High pressure spikes	Pipe damage
<i>Water on</i>	High demand	Low/negative pressure	Backflow and intrusion
	Pressure transients	Shear stress changes	Release of particulates & biofilms from pipes

indicator of water quality. The effects of IWS on physical integrity of the distribution system are also included in this review when they affect water quality.

Limited water quality data have been collected from IWS systems, though the evidence that exists suggests that contamination has occurred in IWS distribution systems. Indicator organisms have been detected at higher concentration at taps when they were at low concentrations or undetectable at the source (Swerdlow et al., 1992; Raman et al., 1978; Elala et al., 2011; Tokajian and Hashwa, 2004; Tokajian and Hashwa, 2003; Abu Amr and Yassin, 2008; Yassin et al., 2006). Other studies did not detect chlorine residual at taps when it had been expected based on the concentration at the treatment plant (Semenza et al., 1998; Egorov et al., 2002). In epidemiological investigations of outbreaks, IWS has been linked to amebiasis, typhoid, cholera, other diarrheal diseases, and infectious hepatitis (Barwick et al., 2002; Mermin et al., 1999; Swerdlow et al., 1992; Carpenter, 1875; Raman et al., 1978; Semenza et al., 1998). Momentary loss of pressure in continuous supplies and other inadequacies in distribution systems have been linked to water-borne illnesses (Hunter et al., 2005; Jakopanec et al., 2008; Nygard et al., 2007; Payment et al., 1997; Craun et al., 2002; Craun et al., 2010). However, in all of these cases, while the distribution system was considered the likely source of contamination, the mechanisms causing these contamination events were not identified.

Strategies have been proposed for the design and operation of IWS that overcome some problems, such as inequitable distribution and unreliable delivery timings (Vairavamoorthy et al., 2007; Totsuka et al., 2004). However, no system has been built specifically for intermittent operation and there is current insufficient understanding of the impact of intermittent operation on water quality to recommend IWS as a mode of operation. This review will improve understanding of contamination mechanisms in the distribution system and identify

knowledge gaps that need to be addressed so that strategies can be developed that minimize microbial contamination in IWS systems.

In IWS, pipes are typically empty (or partially empty) between supply cycles, charge up when water is turned on, are pressurized for the duration of supply (although low or negative pressure may occur during supply), and drain when supply is turned off. This paper reviews the hydraulics at each stage and their expected effects on the quality of water at consumer taps. The important hydraulic features of IWS systems and their expected effects on water quality are proposed in Table 2.1. These mechanisms are discussed in detail in the following sections.

2.3 Mechanisms when the water supply is off

In CWS, water supply is turned off and pipes lose pressure only during infrequent activities such as maintenance (e.g. pipe installation and repair) and emergencies. In contrast, the defining feature of IWS is regular loss of pressure. This section reviews potential effects on water quality that result from regular loss of pressure: backflow and intrusion into pipes, bacterial regrowth in bulk supply, microorganism attachment and bacterial regrowth in biofilms, particulate matter attachment to pipe walls, and corrosion. While water is not supplied to consumers during this stage, the bulk water left in pipes between supply cycles and the accumulated material on pipe walls can affect water quality at consumer taps when supply is re-started.

2.3.1 Backflow and intrusion

After supply is turned off in an IWS, water left in pipes drains through infrastructure deficiencies (e.g. cracks, breaks, leaky joints) and consumer taps or collects at dead ends, closed valves, or low elevations, leaving pipes at low or less than atmospheric pressure while they are empty or have stagnant water left in them between supply cycles. Contamination can enter a distribution system if there is an adverse pressure gradient, a pathway, and a source of contamination (LeChevallier et al., 2003; Lindley and Buchberger, 2002; Propato and Uber, 2004; Vairavamoorthy et al., 2007).

Contamination can enter distribution systems as backflow, defined as cross-connections that are plumbed connections between potable water and a non-potable source (e.g. chemical mixing tanks, storage tanks, sinks or bath tubs, or cooling towers), or as intrusion, defined as infrastructure deficiencies that connect potable water to the surrounding environment (e.g. air-vent vaults, pipeline cracks or breakages, leaking joints, or repairs and maintenance). Backflow can contain contaminants dangerous to human health (pathogens, metals, chemicals, etc) or organic material and other compounds that reduce chlorine residual. Intruded water can contain contaminants from sanitary, storm, and combined sewers, septic tanks, latrine pits, and water or soil surrounding pipelines (Besner et al., 2011; EPA, 2003; Kirmeyer et al., 2001a; LeChevallier et al., 2003; Lindley and Buchberger, 2002; AWWA, 2003). Both

backflow and intrusion are widely recognized as important potential mechanisms of contamination in CWS systems if proper conditions are not maintained to prevent them (EPA, 2002b; EPA, 2003; Craun et al., 2002; Craun et al., 2010; Besner et al., 2011).

Intrusion into an IWS distribution system when supply is off has not been studied directly; however, it is similar to pipe repairs in CWS, where evidence of intrusion when supply to pipes was off has been linked to episodes of waterborne illnesses and impaired water quality. Elevated gastrointestinal illnesses have reported after main break events (Nygard et al., 2007) and decreased chlorine residual and high turbidity at consumer taps and hydrants have been measured immediately after maintenance on pipes (Besner et al., 2008). A similar effect would be expected in IWS when supply is off.

Simulations in CWS networks have estimated that intrusion could enter in large volumes during momentary low pressure (Kirmeyer et al., 2001a; Boyd et al., 2004; Ebacher et al., 2012; Greyvenstein and Zyl, 2007). Kirmeyer et al. (2001a) estimated that 0.01-660 gallons (0.04-2500 L), or 1%-5% of bulk volume in pipes, can enter as intrusion during low pressure transients, with the range dependent on distribution system water pressure, contaminant source pressure, event duration, and orifice size. Another simulation by Ebacher et al. (2012) estimated a smaller range of 10-360 L, with the pressure of the contaminant source the most important factor affecting intrusion volume. Alternatively, in a model of the risk from intrusion to consumer health, Teunis et al. (2010) and Yang et al. (2011) found that the duration of low pressure and number of intrusion pathways posed a higher risk than other factors (orifice size, disinfectant residual, or pathogen concentrations outside of pipes), because longer durations of intrusion led to higher volumes of contaminants and lower dilution factors, while more pathways would expose more consumers.

In IWS with limited supply durations, the pipes are atmospheric pressure for long periods of time (on the order of hours or days), during which large volumes of backflow and intrusion could enter the distribution system between supply cycles. This is likely a important mechanism of contamination in IWS, particularly in supplies with short durations (and therefore long periods at atmospheric pressure) and poor infrastructure (resulting in many intrusion pathways). Section 2.6 reviews infrastructure deficiencies and contexts that can exacerbate the effects of backflow and intrusion. Contamination that enters when the supply is off can attach to pipe walls or regrow in bulk water, though it may be flushed out when supply is re-started (see Section 2.4).

2.3.2 Regrowth in bulk water

Bacterial growth can be fostered by long residence times that result in decay of disinfectant residuals, elevated temperatures, and stagnation. Regrowth in distribution systems can occur in finished water storage, bulk water in pipes, and biofilms; studies of regrowth throughout an entire distribution system do not usually distinguish between these locations of regrowth.

Bacteria can regrow in finished water storage facilities, with growth positively correlated with residence time. Residence times in finished water storage depend on design, capacity, and operations that determine mixing and stratification (Mays, 2000; EPA, 2005; Rossman

and Grayman, 1999; Grayman et al., 2004; Boulos et al., 1996; DOH, 2009). Operations and capacities of IWS service reservoirs can differ from those in CWS. In some IWS systems, reservoirs are drained entirely after each cycle, resulting in low water age as each cycle receives fresh water. Other IWS systems provide water to the entire distribution system every few days or once a week, leaving water stagnant between supply cycles. Guidelines for turnover in storage facilities to minimize regrowth and other water quality impairments associated with high water age are on the order of three to five days, which is shorter than most IWS supply cycles (EPA, 2005). Therefore, the importance of regrowth in finished water storage in IWS will depend on the supply regime.

Bacteria can also regrow in the bulk water in pipes when it stagnates (LeChevallier et al., 1996; Kerneis et al., 1995). Several studies of regrowth in reservoirs and in water in pipes in CWS found a positive correlation between concentrations of bacteria and distance from the treatment plant (Power and Nagy, 1999; Cordoba et al., 2010; LeChevallier et al., 1996). Water samples collected from household plumbing after overnight stagnation had significantly higher bacterial cell and HPC counts than water in main pipes (Prevost et al., 1997; Lautenschlager et al., 2010). This positive correlation between stagnation and high concentrations of bacteria would be expected in water left in pipes between supply cycles in IWS networks, potentially exacerbated by backflow and intrusion that could introduce additional bacterial contamination.

2.3.3 Biofilm regrowth and formation and particulate matter attachment

Biofilms and particulate matter can attach to pipe walls during stagnation. Microorganisms, including pathogens, can attach to biofilms, which provide protection from chlorine as well as an environment for bacteria to regrow. Microorganisms can then be released from biofilms into the bulk water through erosion (slowly) or sloughing (suddenly) (EPA, 2002a; Percival and Walker, 1999). Similarly, particles and sediments that accumulate on pipe walls can harbor pathogens and chemical contaminants, with their release affecting consumer health and water aesthetics (Boxall and Saul, 2005; Vreeburg and Boxall, 2007; Lehtola et al., 2004; Zacheus et al., 2001). Biofilms and particulate matter on pipe walls behave similarly (biofilms are often considered a component of particulate matter) and have similar effects on water quality.

Biofilms are composed of microorganisms and organic and inorganic matter enmeshed in matrix of extracellular polymeric substances (EPS). They form through deposition and attachment to the interior of pipe walls and fittings with different morphologies and compositions depending on their surrounding environmental and hydraulic conditions. Biofilms that developed in stagnant water in pipes were found to have more bacterial cells (Manuel et al., 2007) and detach readily when exposed to a change in shear stress (Douterelo et al., 2013) than biofilms that developed in flowing water. While chlorine is frequently used to reduce biofilm growth (Hallam et al., 2001; Codony et al., 2005), the disinfectant residual

will likely decay in stagnant water when supply is off in an IWS.

Biofilm morphology would likely be affected by intermittent wetting and drying in IWS, though this phenomenon has not been studied in drinking water distribution systems. A study in IWS pipes found that the scale on the inner walls of a PVC pipe were gelatinous when water was flowing but had a dry texture during first flush, suggesting that the morphology of layers on the interior of pipe walls changed when the supply was off (Cerrato, 2005). While an IWS system with frequent supply likely develops biofilms similar to those in CWS, an infrequent supply could have biofilms and layers of scale dry out completely or have multiple layers (water-saturated biofilms at the pipe bottom and unsaturated at the top). Their differing morphologies would be expected to influence water quality when water is turned on through erosion and sloughing (Section 2.4 and 2.5), though this has not been studied.

Particulate matter, which consists of minerals, organic matter, and microbial biomass, originates from many sources, including source water, water treatment plant processes, erosion of pipes and fittings, biological activity and biofilms, corrosion, intrusion, and backflow (Barbeau et al., 2005; Gauthier et al., 1999; Boxall and Saul, 2005). These particles tend to accumulate on pipe walls when and where flow is low in CWS, such as at night and in dead ends or oversized pipes, which are similar to conditions that exist when supply is off in an IWS. Like biofilms, these layers form with enough strength and bonding to withstand normally experienced hydraulic conditions; therefore, those developed in stagnant water are adjusted to quiescent conditions and may be easily released when shear stresses change as flow is re-started (Boxall and Saul, 2005; Husband et al., 2008).

It is likely that when supply is off in an IWS, microorganisms and particulate matter that entered as backflow and intrusion attach to pipe walls, with these layers and biofilms developing similar to what occurs in CWS under stagnant conditions. However, these layers may be flushed out when supply starts again in IWS (Section 2.4).

2.3.4 Corrosion and leaching

Corrosion in distribution system pipes can affect water quality by creating orifices for intrusion, providing sites for biofilm attachment, and reducing chlorine residual (Volk et al., 2000). Corrosion rates depend on many factors, including pipe material, flow velocity, and physico-chemical composition of water (e.g. pH, alkalinity, dissolved oxygen, total dissolved solids, temperature) (Volk et al., 2000). Biofilms can cause microbially-induced corrosion (MIC) (Volk et al., 2000; Annuk and Moran, 2010). Water with high dissolved oxygen is corrosive, which can lead to release of iron, pipe tuberculation, and pitting (Sarin et al., 2004; AWWA, 2011). Additionally, several studies have found that more iron is released to bulk water when it is stagnant than when it is flowing (Sarin et al., 2004; Nawrocki et al., 2010; Hayes, 2012). In IWS, the inside of pipe walls may be exposed to atmospheric oxygen which may lead to high rates of corrosion. Chemicals from pipe materials, such as vinyl chloride in PVC pipes, can leach into water during stagnation (Walter et al., 2011); water left in pipes when supply is off may then be contaminated with leachate.

2.4 Mechanisms when water is turned on and off

When water is first supplied to an area by opening a valve or turning on a pump, it rushes into the empty pipe network. Charge-up in a single pipe in IWS is similar to restarting a pipe section after a repair or replacement in a CWS; in a whole network, the process is similar to storm surges or valve operations in normally unpressurized sewer pipes. When supply is turned off, water left in the pipes drains or collects at low-lying points or dead ends. Similarly, charge-down for a single pipe resembles turning off a supply in CWS for pipe repairs; for a network, it resembles the return of a sewer pipe from surge conditions to open channel flow. The charge-down process can result in sudden change of pressure that can affect layers on pipe walls (Section 2.4.2) and result in very low pressure during draining; the effect of low pressure on water quality is described in Section 2.5.

This section reviews the hydraulics of charge-up and charge-down and their expected effect on water quality through velocity changes and air pockets that affect particulate matter and biofilms on pipe walls (the development of these were described previously in 2.3.3). The effect of these hydraulics on physical integrity of the distribution system is also reviewed. Backflow and intrusion can occur when pressure is low during charge-up as described in Section 2.3 and 2.5.

2.4.1 Charge-up and charge-down

Mathematical, numerical, and empirical models of pipe charge-up and charge-down have shown that air plays a complex role in pipe pressure dynamics (Benjamin, 1967; Wang et al., 2003; Zhang and Vairavamoorthy, 2006; Wilkinson, 1982; Vasconcelos and Wright, 2008). Air intrudes into a pipe during flow start-up until there is enough pressure to expel it (Vasconcelos and Wright, 2008). Air pockets can persist after pipes are filled, allowing open channel flow underneath or forming localized air cavities at boundaries (e.g. dead-end, high elevations), reducing pressure through excessive friction losses and reduced pipe capacity. These air pockets can also block flow completely or cause pipe bursts (Wang et al., 2003; Vasconcelos and Wright, 2008; Batish, 2003; Zhang and Vairavamoorthy, 2006). Additionally, air can scour pipe walls as it is expelled (discussed in the next section).

A study of friction loss in IWS measured a 27% increase in the Hazen-Williams C value as pipes progressed from empty to full; the authors hypothesized this change was the result of air being expelled from pipes during filling (Sashikumar et al., 2003; Batish, 2003). If all consumers located near the inflow to the network draw water at the same time, it will reduce overall pressure and networks will fill gradually (De Marchis et al., 2010). In an IWS that fills a large network area (most models are for a single pipe), pressure head may be too low to expel air during charge-up.

2.4.2 Particulate matter release and biofilm sloughing

Particulate matter on pipe walls may have been left from the previous supply cycle or accumulated from intrusion, backflow, or water left in pipes when supply is off. Biofilms are often considered a constituent of particulate matter that behaves similarly; the studies of particulate matter referenced here do not distinguish between the two.

Since layers of particulates and sediments on pipe walls develop to withstand normally experienced shear stresses, a change in shear stress, often triggered by a hydraulic event such as an increase in flow or a change in pressure, can cause their release (Boxall and Saul, 2005; Husband et al., 2008; Husband and Boxall, 2011; Husband and Boxall, 2010). Similarly, biofilm cohesiveness and detachment is affected by normally experienced hydraulics (Derlon et al., 2008). Biofilms that developed under steady state flow (as when water supply is off, see Section 2.3) have been found to detach readily when exposed to change shear stress through sloughing (release of large particles from only part of the surface) or erosion (from shear stress and affecting the whole surface) (Douterelo et al., 2013). Sudden increases in flow rate have been found to cause an immediate increase in suspended bacteria (Lehtola et al., 2006) and rapidly flowing water has been found to erode corrosion deposits (Volk et al., 2000).

Utilities often flush water at high velocities (1.8 m/s) through distribution system pipes to remove sediments, scale, and biofilms from pipe interiors (Chadderton et al., 1993; Antoun et al., 1999). In household plumbing, a few minutes of flushing has been shown to decrease the elevated concentrations of bacteria that had developed after overnight stagnation (Lautenschlager et al., 2010; Prevost et al., 1997). Scouring with air is also used to remove particulates from pipe walls (Ainsworth, 2004).

When flow re-starts in an IWS, pipe charge-up may emulate utility flushing, as shear stress increases as pipes transition from empty to pressurized and air is expelled. This phenomenon is a unique feature in IWS with both positive and negative implications for water quality that would depend on the nature of IWS (supply duration, frequency, and pressure). Therefore, particulate matter and microbes that accumulated in pipes when supply was off are likely flushed out at the beginning of each supply cycle. While several studies in CWS found that flushing led to only short-term gains to water quality due to quick re-accumulation (Barbeau et al., 2005; Lehtola et al., 2004; Zacheus et al., 2001), in IWS, given that flushing occurs at the beginning of each supply cycle, the improvement in water quality from flushing would likely persist throughout a supply cycle.

However, several factors may limit the effectiveness of this process. Pressures may be too low to provide a sufficient velocity for flushing (see Section 2.5) and parts of the distribution system may not be subject to the same variations in shear stress (e.g. high elevations, end of pipes). The effect can also vary with pipe material: a study in IWS found that less manganese was released from iron pipes than PVC pipes during the first flush because manganese had been incorporated into tubercles in iron pipes (Cerrato et al., 2006). Additionally, in CWS, utilities notify consumers to avoid using water from their taps during flushing; however, given the limited duration of water in IWS, consumers likely collect and store flush water that contains elevated levels of contamination.

This flushing behavior has been observed in IWS systems, with higher concentrations of indicator bacteria and turbidity detected during flushing than during the supply cycle (Kelkar et al., 2002). Similarly, Cerrato et al. (2006) found that iron and manganese was released when water was first on in an IWS, but that little release occurred later in the supply cycle.

Therefore, contamination that occurred from regrowth, backflow, and intrusion when supply was off may be flushed out at the beginning of each supply cycle during charge-up. However, the effectiveness of charge-up in removing this contamination may be limited by other features of IWS (e.g. low pressure). Flushing may not occur in systems with less intermittency and better pipe integrity.

2.4.3 Physical integrity

Pressurizing and depressurizing can cause wear and tear on pipes and fittings, which can affect water quality by creating pathways for intrusion to enter the distribution system. Christodoulou and Agathokleous (2012) found that pipe leak rates increased after switching from continuous to intermittent operation in a distribution system. In addition to regular wear and tear, Misra and Malhotra (2012) note that in a supply-driven IWS, the pressure drop created between beginning and end of pipe due to demand by all consumers at the same time may cause inconsistent wear and tear on pipes that can lead to bursts, though this effect has not been studied.

2.5 Mechanisms when water supply is on

When water supply is on, IWS distribution systems may behave similarly to CWS and therefore be subject to the same mechanisms affecting water quality. However, the likelihood of contamination entering the system, a significant risk in all distribution systems, may be exacerbated in some IWS due to persistent and transient low pressure.

Backflow and intrusion can occur when the distribution system is at negative pressure (backsiphonage) or when the distribution system has positive pressure but the contaminant source is at a higher pressure (backpressure). The minimum pressure in pipes necessary for preventing backflow depends on the pressure of the contaminant source. Guidelines for pressure are not based on preventing intrusion; minimum pressures and justifications from several countries are given in Table 2.2.

This section reviews the causes of persistent and transient low and negative pressure unique to IWS, the likelihood, source, and fate of intrusion and backflow, the potential for regrowth, and continued biofilm and particulate matter releases during supply.

Table 2.2: National pressure guidelines.

Min. pressure	Country	Reason
20 psi (14m)	USA	Fire fighting
28 psi (20m)	South Africa	Prevent consumer complaints
10/17/24 psi (7/12/17m) for 1, 2, and 3 stories	India	To reach the top of buildings

Sources: USA: AWWA (2003); National Fire Protection Association (2007); South Africa: Jacobs, Strijdom, et al. (2009); India: Batish (2003)

2.5.1 Persistent low and negative pressure

Persistent low pressure in distribution systems is caused by high demand (e.g. leakages, consumers drawing water), system expansion (e.g. new service connections), reduced pipe capacity (e.g. closed valves, corrosion, soft deposits, biofilms, trapped air, friction losses, etc), or changes in elevation or boundary pressures (e.g. reservoir levels, pump capacity) (AWWA, 2003). Though data are scarce, cities with IWS around the world have reported chronically low pressure (Lee and Schwab, 2005; Rahman et al., 1997; Mermin et al., 1999; Eshcol et al., 2009; Tokajian and Hashwa, 2003; Tokajian and Hashwa, 2004).

High consumer demand is likely a significant cause of reduced pressure in IWS systems. In CWS, consumers draw the amount of water they demand at the time they need it. In contrast, in IWS, consumers collect and store water when supply is on to meet their demand through supply off-hours. If the supply cycle is short, all consumers may draw their entire water demand within a limited duration, reducing distribution system pressure (Batish, 2003; Ingeduld et al., 2006; Sashikumar et al., 2003); these systems can become supply-driven, where households collect as much water as is available at their tap (Vairavamoorthy et al., 2007). Pressure can vary in time as well, with very low pressures at the beginning of supply as consumers collect and store water and increasing pressure later in the supply cycle as household storage tanks fill (Al-Ghamdi and Gutub, 2002; Sashikumar et al., 2003; De Marchis et al., 2010).

Trapped air and corrosion, both common in IWS (discussed in Section 2.3 and 2.4), can reduce pressure by reducing pipe capacity. Other factors contributing to low pressure that are frequent where IWS is common, though not features of IWS, are discussed in Section 2.6.

While high demand reduces pressure, it also has a potential advantage for water quality: low water age can reduce microbial regrowth in the bulk water supply (discussed in Section 2.3).

2.5.2 Pressure transients

A pressure transient, also known as a water hammer, is a sudden increase in pressure followed by oscillations until pressure returns to a steady state. Transients in distribution systems are caused by rapid changes in flow rate. They adversely affect water quality by causing momentary low or negative pressure that can allow intrusion or backflow, and they change shear at pipe walls that can cause release of accumulated material (see Section 2.4). Additionally, transients can cause physical damage and pipe wear from high pressures, local vacuums, cavitation, and hydraulic vibrations and resonance (Boulos et al., 2005). Pressure transients in CWS are most often caused by sudden pump shutdowns, as well as by sudden changes in boundary pressure and demand (e.g. valve closures, pipe leaks, flushing, fire-fighting, high consumer demand, filling storage tanks) (Besner et al., 2011; Besner et al., 2010; Gullick et al., 2004; Gullick et al., 2005; Hooper et al., 2006).

While IWS systems are subject to the same transients as CWS, several of these events - valve and pump operations to turn supply on and off, air intrusion, and use of consumer pumps - occur routinely in IWS and would be expected to lead to frequent transients. However, the high demand from consumers and leaks can dissipate the energy in pressure waves through frictional losses and by allowing the exchange of energy with the environment (Karney and Filion, 2003). This energy dissipation may dampen the effect of transients in IWS, though this has not been studied.

2.5.3 Backflow and intrusion

Backflow and intrusion can occur during low and negative pressure events (discussed previously); because such events are a rare and transient occurrence. They are difficult to empirically detect in CWS. However, several studies have detected possible intrusion (Cartier et al., 2009; Lambertini et al., 2012), and assessed likely intrusion by measuring fecal indicators and pathogens in soil and water exterior to the distribution system (Besner et al., 2009; Karim et al., 2003). Systems with IWS may have more contaminant sources exterior to infrastructure due to poor environmental conditions (Section 2.6). The effect of contaminant sources was illustrated by a GIS-based risk model of intrusion into IWS developed by Vairavamoorthy et al. (2007) that predicted the risk due to cracked sewer pipes, open drains and canals, surface water bodies, and other sources frequently found in the same places as IWS.

Indicator bacteria and pathogens that enter the distribution system can potentially be inactivated by a disinfectant residual. However, batch-reactor tests of indicator organisms and pathogen inactivation found that higher volumes of contaminants (5% sewage intrusion) required long contact times (Snead et al., 1980; Payment, 1999). Organic matter, often present in intrusion, further decreases the concentration of residual disinfectant (Betanzo et al., 2008). In a review of laboratory-, pilot-, and full-scale studies on the fate of microorganisms that enter the distribution system, Besner et al. (2008) concluded that while chlorine residual could inactivate intruded bacteria, it may not be sufficient to inactivate viruses and

protozoa that require longer contact times. Several studies have detected amoebic intestinal parasites (Basualdo et al., 2000) and viruses (He et al., 2009) in distribution systems in the absence of indicator bacteria, suggesting that intrusion had potentially occurred. In IWS, persistent low pressure may allow large volumes of intrusion into pipes while high water velocity reduces contact time, decreasing the effectiveness of disinfectant residual in the distribution system.

2.5.4 Regrowth, biofilm sloughing, and particulate matter release

Regrowth of bacteria in bulk water is often a concern in CWS (see Section 2.3). However, given that IWS is used to limit supply durations, high water age would be unlikely in bulk supply in pipes when supply is on; therefore, regrowth during supply is likely only an issue in IWS with long durations.

Biofilms and particulate matter, discussed previously in Section 2.4, can be removed from pipe walls while supply is on. In particular, IWS with shorter supply durations are often not at steady state due to high demands and regular exposure to valve and pump operations. Biofilms exposed regularly to changes in shear stress are young, thinner, and more porous, and therefore more resistant to removal (Rochex et al., 2008; Paul et al., 2012; Manuel et al., 2007; Douterelo et al., 2013). Biofilms exposed to changes in water composition (e.g. chlorination or a wastewater cross-connection that end abruptly), they released more cells or pathogenic organisms (Codony et al., 2005; Gibbs et al., 2003). Both of these conditions may occur in IWS given the unsteady hydraulics and likelihood of backflow and intrusion. Additionally, a biofilm sloughing event, affecting the entire biofilm surface, can lead to development of unstable biofilms that are then subject to random sloughing (Telgmann et al., 2004), an effect that could continue throughout the supply cycle.

2.6 Distribution system, environmental, and household features

Water distribution systems in low- and middle-income countries often have a host of deficiencies in their design, operation, and maintenance that amplify the effect of intermittency on water quality (Lee and Schwab, 2005; McIntosh, 2003; Banerjee and Morella, 2011; Gadgil, 1998). Table 2.3 presents a review of literature that describe intermittent supplies and reported co-existing problems.

Excessive leaks are reported widely in IWS distribution systems, which can reduce pressure in the network and provide pathways for intrusion. Though data on physical water losses are scarce, non-revenue water in developing country cities is estimated to be 35% with physical losses (e.g. leaks) accounting for 60% of these losses (Kingdom et al., 2006). Leakage rates in literature describing intermittent supplies have been estimated at around 30% in Makkah, Saudia Arabia and Hyderabad, India and 40% in Karachi, Pakistan (Al-Ghamdi and Gutub, 2002; Mohanty et al., 2002; Rahman et al., 1997). This is high compared to

industrialized countries, where average physical losses have been estimated at 12% (Kingdom et al., 2006). The average unaccounted-for water in the three studied wards was more than 50% of water input to the distribution system. Low pressure has been reportedly caused by undersized pipes from incorrect design or unchecked expansion to new consumers (Al-Ghamdi and Gutub, 2002).

Consumers cope with non-continuous water through a variety of strategies that have consequences for water quality upstream in the distribution system through increased cross-connections and intrusion pathways (Zerah, 1998; Choe et al., 1996; Dasgupta and Dasgupta, 2004; Rosenberg et al., 2008; Kudat et al., 1993). Households often use suction pumps (to draw more water from the distribution system or lift it to a roof tank) which can cause persistent negative pressure, surges, and cavitation. This practice has been reported anecdotally, though there are no data on its prevalence or effects (Batish, 2003; McIntosh, 2003). Additionally, poor quality fittings at household premises and illegal connections can increase friction losses by introducing bends and turbulent flow and intrusion pathways. Cross-connections are especially common in IWS due to consumers storing water to cope with the limited duration and unreliability of water delivery. Overhead and underground tanks, which can hold lower-quality water from a previous supply cycle or a different source, are often plumbed directly to the distribution system or have inlet pipes that become submerged (Zerah, 1998; Choe et al., 1996; Dasgupta and Dasgupta, 2004; Rosenberg et al., 2008; Kudat et al., 1993). Water from different sources (e.g. groundwater) is sometimes provided through the same distribution network that supplies treated water. This can create a cross-connection with water of poor quality, change rates of chlorine residual decay, and/or destabilize pipe deposits and biofilms (e.g. release iron by changing pH, alkalinity, sulphate, chloride, or oxygen concentrations) (Ainsworth, 2004; Hayes, 2012). Use of poor quality materials, common in resource-constrained utilities, can lead to faster decay of infrastructure, while illegal connections can damage pipe integrity, creating more pathways for intrusion.

Storing water in homes is a ubiquitous practice in IWS (Swerdlow et al., 1992; Eshcol et al., 2009; Andey and Kelkar, 2009; Rahman et al., 1997; Tokajian and Hashwa, 2003; Tokajian and Hashwa, 2004; Coelho et al., 2003; Al-Ghamdi and Gutub, 2002). Previous research has established that water stored in households is subject to recontamination and regrowth, and that water quality deteriorates between tap and household storage containers (Wright et al., 2004; Levy et al., 2008; Eshcol et al., 2009; Jagals et al., 1999; Elala et al., 2011).

Environmental contamination outside of pipes is a source of intrusion. Many of the same places where IWS is common lack a formal piped sewage network, with wastewater instead flowing in storm drains or seeping into the ground external to drinking water pipes (Abu Amr and Yassin, 2008). Sewage pipes have been reported to be under high pressure while drinking water pipes are at low pressure, while septic tanks or pit latrines are often inadequately maintained or located close to pipes (Rahman et al., 1997; Mohanty et al., 2002; Coelho et al., 2003; Raman et al., 1978). Drinking water pipes have been reportedly laid within drainage ditches, storm drains, and on the top of the ground where floods are common (Mermin et al., 1999). Several studies of IWS reported frequent flooding with sewage

Table 2.3: Features frequently co-located with IWS which amplify effects on water quality

Design, operations, and maintenance	
High leakage rate/water loss	Abu Amr and Yassin (2008); Al-Ghamdi and Gutub (2002); Kjellen (2006); Korfali and Jurdi (2007); Mohanty et al. (2002); Rahman et al. (1997)
Undersized pipes	Al-Ghamdi and Gutub (2002)
Aged infrastructure	Abu Amr and Yassin (2008)
Use of poor-quality fittings	Kjellen (2006)
Frequent pipe bursts	Kjellen (2006); Tokajian and Hashwa (2003); Tokajian and Hashwa (2004)
Low disinfectant residual	Abu Amr and Yassin (2008); Coelho et al. (2003); Mermin et al. (1999); Mohanty et al. (2002); Raman et al. (1978); Swerdlow et al. (1992); Tokajian and Hashwa (2003); Tokajian and Hashwa (2004)
Environmental and other infrastructure systems	
Limited sewerage system	Abu Amr and Yassin (2008)
Sewage flooding and ground infiltration	Mohanty et al. (2002); Swerdlow et al. (1992)
Inadequate solid waste disposal	Rahman et al. (1997)
Sewage pipes, septic tanks, and soak-aways close to drinking water pipes	Coelho et al. (2003); Mohanty et al. (2002); Raman et al. (1978); Rahman et al. (1997)
Potable water pipes within storm drains	Mermin et al. (1999)
Sewer lines at high capacity/pressure or broken to loosen blockages	Rahman et al. (1997)
Frequent cross-connections	Korfali and Jurdi (2007)
Household coping behaviors	
Household suction pumps	Kjellen (2006); Mermin et al. (1999); Misra and Malhotra (2012); Rahman et al. (1997)
Breaking/tapping pipes to access water	Kjellen (2006); Swerdlow et al. (1992)
Source switching	Al-Ghamdi and Gutub (2002); Andey and Kelkar (2009); Korfali and Jurdi (2007); Rahman et al. (1997)
Storing water in containers (overhead and underground tanks, small containers)	Al-Ghamdi and Gutub (2002); Coelho et al. (2003); Eshcol et al. (2009); Rahman et al. (1997); Swerdlow et al. (1992); Tokajian and Hashwa (2004)

(Mohanty et al., 2002; Swerdlow et al., 1992).

Additionally, deficiencies in other infrastructure systems (e.g. energy, transportation) can exacerbate the ability to provide treated water (e.g. electricity to operate a treatment plant or pump station, transportation for equipment, supply chains for chemicals), though these have not been studied. Many distribution systems report low levels of disinfectant residual, either from insufficient addition at treatment plants or lack of booster stations or supply of the required chemicals.

2.7 Conclusions

While the literature on water quality in IWS is sparse, knowledge of intermittent supply hydraulics and the literature on continuous water supplies can be used to provide insight into the mechanisms affecting water quality in intermittent systems.

Contamination likely enters pipes through intrusion and backflow when supply is off, where intruded particulate matter and microorganisms can then adhere to pipe walls and regrow in biofilms. When water supply starts again, the resulting rapid change in shear stress at pipe walls can readily detach these accumulated layers of particulates and biofilms. As pipes fill when supply is started, air is expelled, likely scouring pipe walls. These effects at the pipe wall, as well as the rapid change in velocity caused by start-up flow, results in flushing at the beginning of each supply cycle that can remove contamination that intruded when supply was off.

While flushing at the beginning of each supply cycle can improve water quality throughout the remainder of the cycle, there are several limitations. There may not be enough shear stress at pipe walls to remove intruded contamination when pipes fill slowly or to only a low steady-state pressure, both likely in IWS systems. While air scouring as it is expelled during charge-up can help remove accumulated layers, air that is trapped may damage pipes or reduce pressure. Changing operations (e.g. operating valves slowly) and infrastructure (e.g. air release valves) can help release trapped air to both maximum the efficacy of flushing and reduce the risk of pipe damage, though there has been little research in this area. Additionally, this flush water is highly contaminated; measures that protect consumers from using flush water could help mitigate health risks.

Low pressure during supply is likely the most important mechanism affecting water quality, as it can allow contamination through backflow or intrusion. When supply is on, IWS are likely to have persistent low or negative pressure. Managing pressure in IWS systems is challenging due to spatio-temporal variation during a supply cycle and within a network, particularly when very limited supply durations create supply-driven hydraulics. While current guidelines for minimum pressures are often not based on preventing backflow and intrusion, research to identify minimum required pressure and strategies to improve pressure management in IWS could help reduce the risk of contamination. Additionally, this risk could be mitigated by controlling contaminant sources, intrusion pathways, and cross-connections.

Other mechanisms that affect water quality in distribution systems during supply - pressure transients, release of biofilms and particulate matter from pipe walls, and microbial regrowth - may not be as important in IWS as they are in CWS. While pressure transients in IWS may occur with each supply operation, it is possible they may not propagate far, particularly in supply-driven systems, though this has not been studied. The risk of particulate matter release or biofilm sloughing during supply is potentially reduced by flushing at the beginning of each supply cycle. IWS with short supply durations will minimize the time for regrowth during supply.

The context in which IWS occurs - distribution system infrastructure, the surrounding environment, and household connections and storage - can amplify the mechanisms affecting water quality in IWS. Poor quality infrastructure with numerous contamination pathways and environments with wastewater and sewage have been frequently reported in the places with IWS. Strategies consumers use to cope with limited supply durations likely interact with the distribution system by creating cross-connections with storage infrastructure and negative pressure in the distribution system by attaching pumps to taps.

While there are some potential advantages to water quality in IWS, including the self-cleaning effect of flushing and low water age, there is not enough evidence to recommend IWS based on available data. Given that IWS is used throughout the world, there is a need for research to identify the importance of mechanisms affecting water quality and understanding differing risks within and between systems with varying operations and contexts. In particular, understanding of the effects on water quality of different intermittent supply regimes (e.g. longer durations less frequently, vs. frequent, short supply cycles) on water quality could provide insight into operational strategies that could lead to improvements in water quality.

Chapter 3

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

3.1 Introduction

Several cities in India have implemented pilot projects or developed proposals to switch from intermittent to continuous supply (World Bank, 2010; World Bank, 2003; McIntosh and Yiguez, 1997). Though improved water quality is often mentioned as a benefit of upgrading an IWS to a continuous supply, 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 chapter 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.

3.2 Background

3.2.1 Study site

Hubli and Dharwad are twin cities with a combined population of over 900,000 in northern Karnataka, India (India, 2011). The bulk water supplies and distribution networks are managed by the Karnataka Urban Water Supply and Drainage Board (KUWS&DB) (Fig. 3.1). 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 Cl_2 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, intervals between consecutive water supply cycles ranged from one to eight days, with a median 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).

3.2.2 Demonstration 24x7 Supply

The Karnataka Urban Water Sector Improvement Project (KUWASIP) has provided approximately 81,000 consumers with continuous water supply ("24x7" supply) through a demonstration project in Hubli and Dharwad since 2007 and 2008, respectively (World Bank, 2010; World Bank, 2004). Four wards in each of Hubli and Dharwad have 24x7 supply while the remaining 59 wards continue to receive water intermittently. Wards were selected by KUWASIP for 24x7 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 24x7 demonstration wards, one each in Hubli and Dharwad (Fig. 3.1). In the 24x7 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 24x7 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 24x7 supply. Among households with IWS, 80% had taps located above ground and 34% had taps located indoors, while among households with 24x7 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 24x7 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 24x7 areas (n=1794) and 92% in IWS areas (n=1666) reported using private latrines and 6% in 24x7 and 4% in IWS areas reported using public latrines.

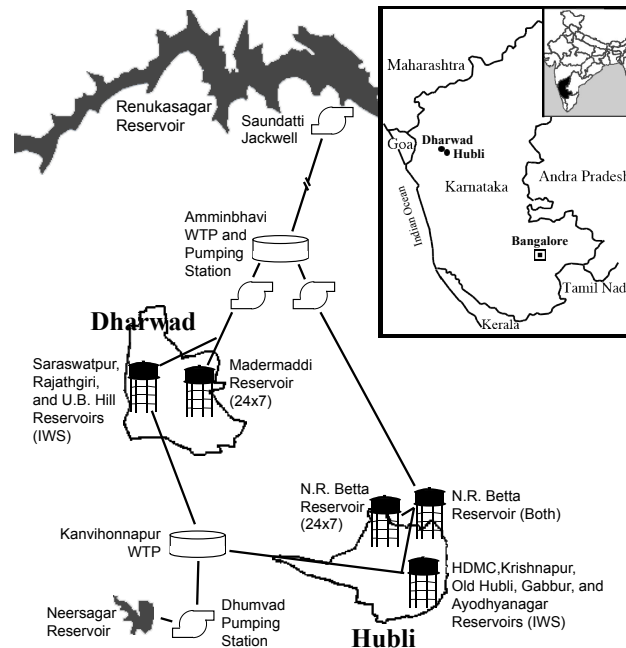


Figure 3.1: Hubli-Dharwad distribution system layout

3.2.3 Comparison of intermittent and 24x7 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 24x7 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 24x7 network, with pressures reported to be between 0-5 m (0-7 psi) in the IWS network and 22-40 m (31-57 psi) in the 24x7 network (World Bank, 2010). Pressures in IWS service lines measured in the course of this research ranged from -4 psi to 36 psi (Chapter 4).

The case of Hubli-Dharwad provides an opportunity to compare water quality between 24x7 and intermittent operation of water distribution systems given the same bulk water input, environment, and socio-economic context. However, since the 24x7 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 24x7 supply that includes pipe and house service connection replacement and leak management. Current

projects and proposals to convert from intermittent to 24x7 water supply in India include similar infrastructure improvements (World Bank, 2003).

3.3 Materials and Methods

Samples were collected from reservoirs, household taps, and drinking water provided by households (points of consumption) and tested for total coliform, *E. 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.

3.3.1 Sample collection

Water samples were collected in parallel with a study of the effect of 24x7 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 24x7 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 24x7 supply (CMDR, 2006). Using genetic matching (GM) the four wards in each of Hubli and Dharwad with 24x7 supply were matched with five wards in Hubli and three in Dharwad with IWS (Fig. 4.1) (Sekhon and Grieve, 2008). Water samples were collected between November 9, 2010 and November 17, 2011 in three repeated rounds of data collection.

Distribution system sampling. A total of 624 samples in 24x7 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 24x7. However, this was not possible since in IWS wards, water delivery was unpredictable and only small sub-sections 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 24x7 wards to achieve a balanced sample. In 24x7 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 taken 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

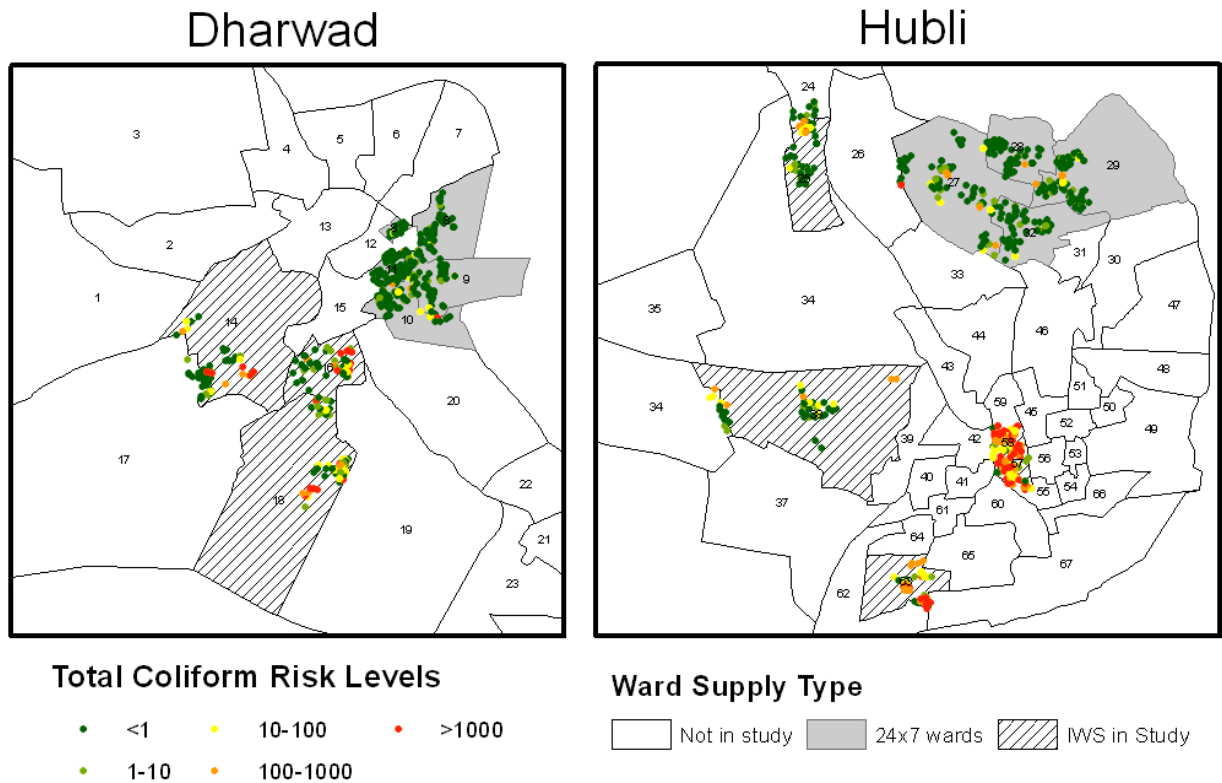


Figure 3.2: Total coliform concentrations at each consumer tap sampling point in Hubli and Dharwad

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 24x7 household taps and 225 (64.8%) from IWS household taps were from households enrolled in the health and economics study. Fewer samples were taken 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 one 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 was exposed before the tap, and presence of an open drain less than five meters from the tap (Fig. 3.3).

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 24x7 reservoirs than IWS reservoirs. Two reservoirs supplied all 24x7 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,

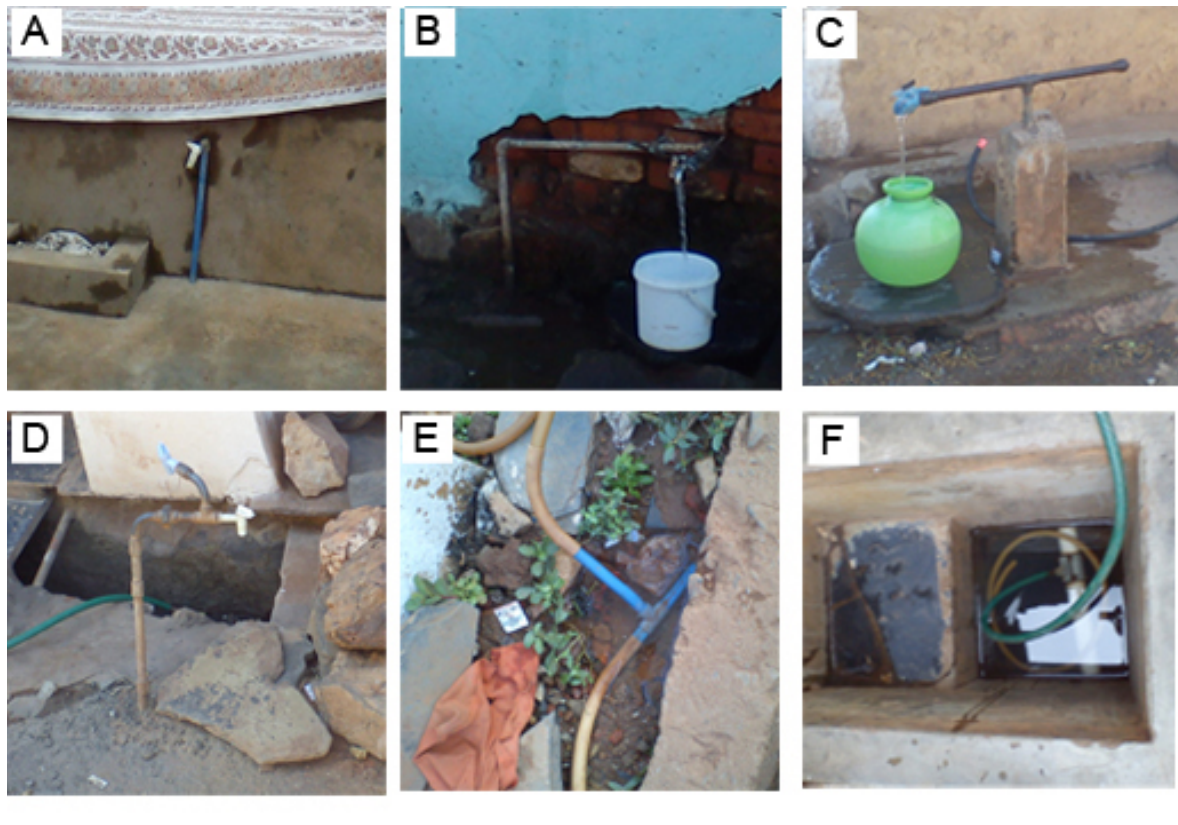


Figure 3.3: Photos of consumer taps used for sampling showing taps above ground level (A-D) and at ground level (E). Taps located below ground level could be in an open drain (D; a hose is attached to the tap) or in tanks dug into the ground (F; a hose attached to the submerged tap.)

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.

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. While this sampling method does not distinguish whether contamination observed at point-of-consumption originated from the tap, storage, or from the glass itself, it does represent the quality of water consumed by children in the households. 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).

3.3.2 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 hours. 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 taken for every 15 samples and field and lab blanks for every 10.

3.3.3 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 χ^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.

3.4 Results and Discussion

3.4.1 Comparing 24x7 and intermittent supply at taps

Water provided to the continuous (24x7) and intermittent (IWS) distribution networks was of similar quality, based on a comparison of water quality at the reservoirs (see Section 3.4.6). 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 3.1 and Fig. 3.5.

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 24x7 supplies were above the Indian Drinking Water Standards aesthetic guideline of < 5 NTU (Fig. 3.5b), though most samples (99.2% in 24x7 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 24x7 (χ^2 , $p>0.05$) (Table 3.1). There were more high and low turbidity outliers among IWS samples (Fig. 3.5a), but there was no significant difference between 24x7 and IWS tap sample means (ANOVA, $p>0.05$) (Table 3.1).

Free chlorine in all tap samples ranged from <0.02-2.20 mg/L with an arithmetic mean concentration of 0.28 mg/L. A significantly higher proportion of samples from 24x7 taps met the minimum standard concentration of 0.20 mg/L (BIS, 2004) compared to samples from IWS taps (χ^2 , $p<0.01$) (Table 3.1). While the median free chlorine concentration was higher in 24x7 than IWS taps (0.27 mg/L compared to 0.13 mg/L), this difference was not significant (ANOVA, $p>0.05$) (Table 3.1). This result is likely influenced by high value outliers in IWS taps (Fig. 3.5a); 18.8% of IWS samples were above 0.5 mg/L free chlorine while only 5.0% of 24x7 samples were above this value (Fig. 3.5b). 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 24x7 and IWS taps (ANOVA, $p>0.5$) (Table 3.1).

Table 3.1: Descriptive statistics for samples collected from consumer taps including the number of samples (n), quantiles, percent of samples meeting criteria, and significance testing.

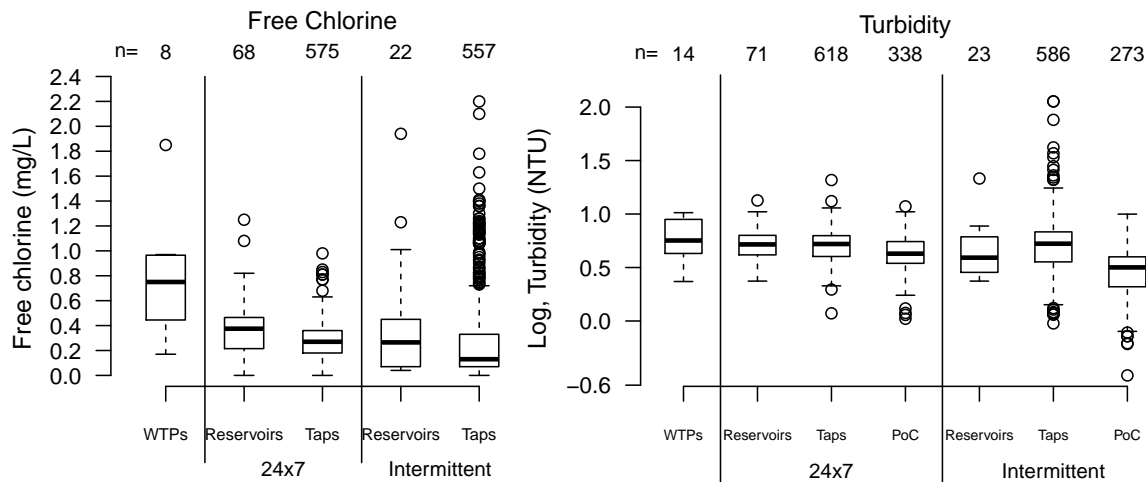
	Supply	n	Quantiles					Meeting Standards			
			min	25%	median	75%	max	p-value ^a	criteria ^b	%	p-value ^c
Turbidity (NTU)	24x7 IWS	618 586	1.18 0.95	4.02 3.57	5.25 5.28	6.28 6.81	20.8 113	0.18	<5	44.5	0.98
Free Chlorine (mg/L)	24x7 IWS	575	<0.02	0.18	0.27	0.36	0.98	0.48	>0.2	68.3	0.02*
Combined Chlorine (mg/L)	24x7 IWS	563 551	<0.02 <0.02	0.07 0.1	0.13 0.14	0.33 0.18	2.2 0.57	0.91		39.9 84.4	
Total Coliform (MPN/100 mL)	24x7 IWS	586 589	<0.02 <1	<1 <1	<1 18.5	<1 648.8	>2419.6 >2419.6	<0.01** <0.01**	<1 <1	82.3 35.1	<0.01** <0.01**
<i>E. coli</i> (MPN/100 mL)	24x7 IWS	587 589	<1 <1	<1 <1	<1 <1	<1 4.1	>2419.6 >2419.6	<0.01** <0.01**	<1 <1	99.3 68.3	<0.01** <0.01**

* p = <0.05; ** p = <0.01

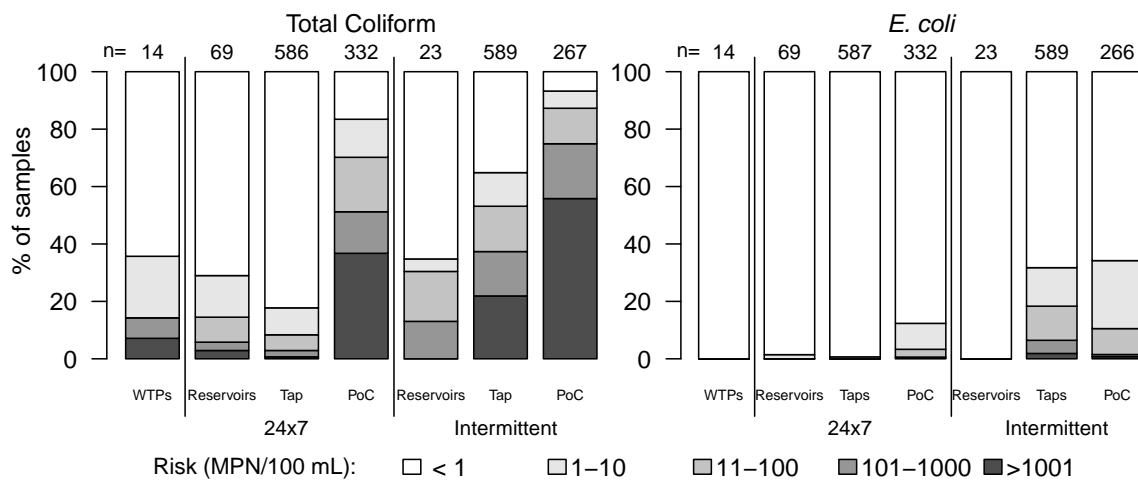
a permutation ANOVA using ranks of data

b 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 are based on the free chlorine standard.

c permutation χ^2 using percentage meeting water quality guidelines



(a) Turbidity and free chlorine along the distribution system



(b) Total coliform and *E. coli* by risk group along the distribution system

Figure 3.4: Comparison of all water quality parameters between 24x7 and IWS throughout the distribution system: water treatment plants (WTPs), service reservoirs, consumer taps, and point-of-consumption (PoC). 3.4(a) Box and whisker plots show the median, lower and upper quartiles, and outliers. 3.4(b) Percentage of samples in risk levels based on WHO guidelines.

Fig. 3.5b 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 24x7 tap samples. A significantly higher proportion of samples were positive for total coliform in IWS (64.9%) than 24x7 (17.7%) (χ^2 , $p < 0.01$). Concentrations of total coliform were higher at IWS taps (ANOVA, $p < 0.01$) (Fig. 3.5a). 15.9% of samples

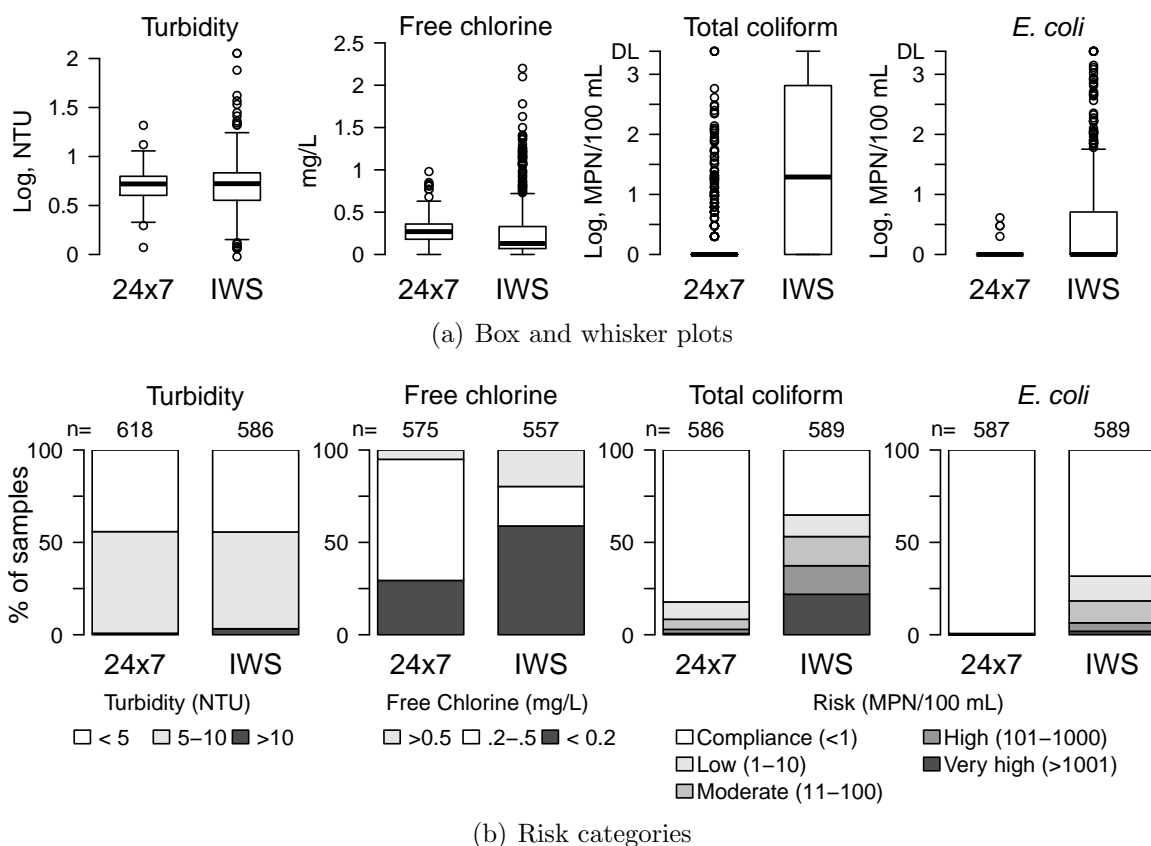


Figure 3.5: Comparison of water quality parameters in 24x7 and IWS at taps. (a) Box and whisker plots show the median, lower and upper quartiles, and outliers. (b) Percentage of samples in different risk categories. DL: Detection limit

from IWS were at or above the detection limit of 2419.6 MPN/100 mL, compared to 0.7% in 24x7. Significantly more samples were positive for *E. coli* in IWS samples than in 24x7 samples (χ^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 24x7 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 24x7 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 24x7 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. 3.5a). More frequent detection of indicator bacteria in the IWS network than in the 24x7 networks suggest that contamination occurred in the IWS distribution

system. This contamination could be from backflow (e.g. intrusion from the environment or backsiphonage 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 24x7 tap water suggests there are still factors compromising the 24x7 distribution system, including high turbidity and low free chlorine residual, as well as interruptions to supply (discussed in Section 3.4.3.1).

3.4.2 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 during the northeast monsoon from October to December (CGWB, 2008).

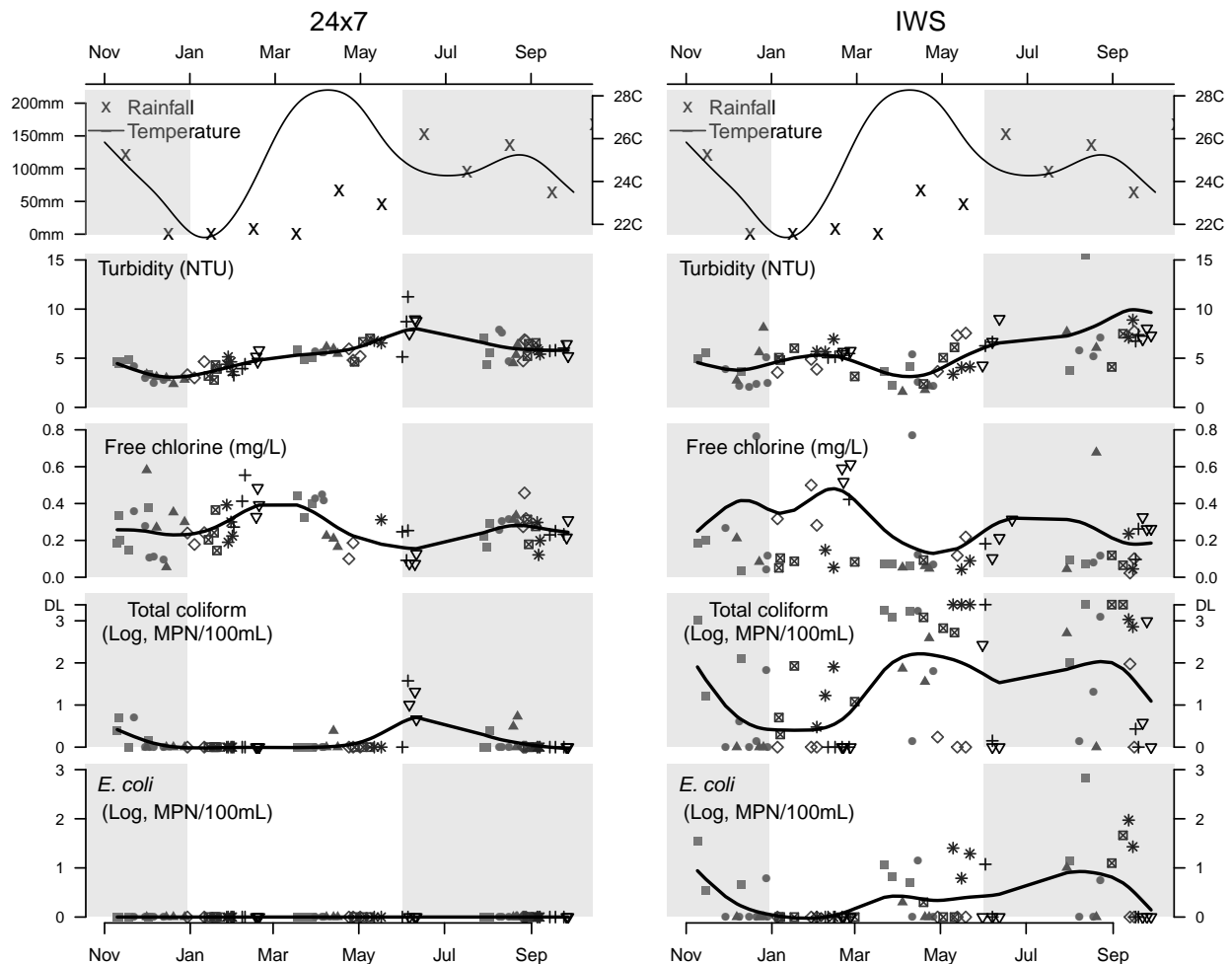
Unique conditions during both dry and rainy seasons can potentially adversely affect water quality. At the end of the dry season, water levels in the raw water reservoirs were low and sediments may have been drawn in with the bulk water. During the wet season, runoff likely introduced sediments into source water from the watershed. Ambient temperatures are at their highest during the end of the dry season (Fig. 3.6). High temperatures have been shown to be positively related to bacteria concentrations and inversely related to free chlorine concentrations (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. 3.6 along with daily means of turbidity and free chlorine and daily medians of indicator bacteria. Temperature in tap samples ranged from 23-29°C during round 1 of data collection (Nov 2010 - Feb 2011) and from 28-30°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 hours 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 24x7 and IWS taps occurred during the rainy season (ANOVA, $p < 0.01$) (Fig. 3.6). Lower concentrations of free chlorine during the rainy season were likely due to higher chlorine demand from organic matter in source water.

In 24x7 wards, there was an increase in total coliform concentration at the start of the rainy season in June (Fig. 3.6), though there was no significant difference in total



Temperature data: meteorological station in Gadag, India (<http://www.wunderground.com/global/stations/43201.html>)
 Rainfall data: India Meteorological Department Hydromet Division (*District Rainfall (mm.) for Last Five Years*)

Figure 3.6: Water quality parameters over time in tap samples. Shaded rectangles denote the rainy season. The top line presents repeated plots of total monthly rainfall and a smoothed fitted cubic line of daily ambient temperature. Daily means are plotted for turbidity and free chlorine and daily medians plotted for total coliform and *E. coli*. Each ward is plotted with a different symbol.

coliform concentration between the dry and rainy seasons. Samples taken from 24x7 taps after rain had occurred in the previous 24 hours 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. 3.6). 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 hours of sampling at IWS taps (ANOVA, $p < 0.01$); differences in turbidity were not significant.

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.

3.4.3 Variability between wards

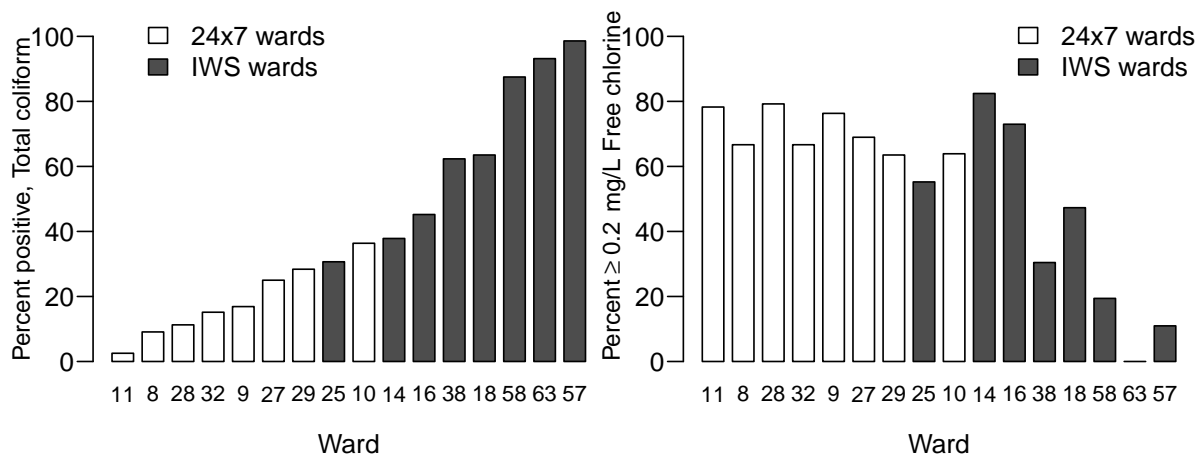


Figure 3.7: Percent (%) of samples positive for total coliform and percent of samples with ≥ 0.2 mg/L free chlorine in each ward

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. 4.1). 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. 3.7), is adjacent to ward 11 (Fig. 4.1), which had the lowest percent of positive samples (Fig. 3.7). 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. 3.7). 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. 3.7).

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 (see Chapter 4). 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 (where water stagnates as it is left in pipes for long periods of time), which would vary by ward, can result in regrowth of bacteria and loss of chlorine residual. The following section discusses interruptions in 24x7, and a more detailed investigation of contamination mechanisms in IWS is reported in a separate manuscript.

3.4.3.1 Interruptions to continuous supply

Supply in the 24x7 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 24x7 supply reported at least one outage during the study period. 9% of these outages lasted for less than 1 hour, 42% for 1-6 hours, 45% for 6-24 hours, and the remaining 4% for more than 24 hours. 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 24x7 taps resulted from supply interruptions, but since households did not report dates of supply outages, it cannot be confirmed.

3.4.4 Variability within wards

The distribution of *E. coli* in each ward varied by sampling day (Fig. 3.8). Five of the eight 24x7 wards had no samples positive for *E. coli*.

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. 3.7) had samples positive for *E.*

coli occur on only a few sampling days and at lower concentrations than other wards (Fig. 3.8). 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.

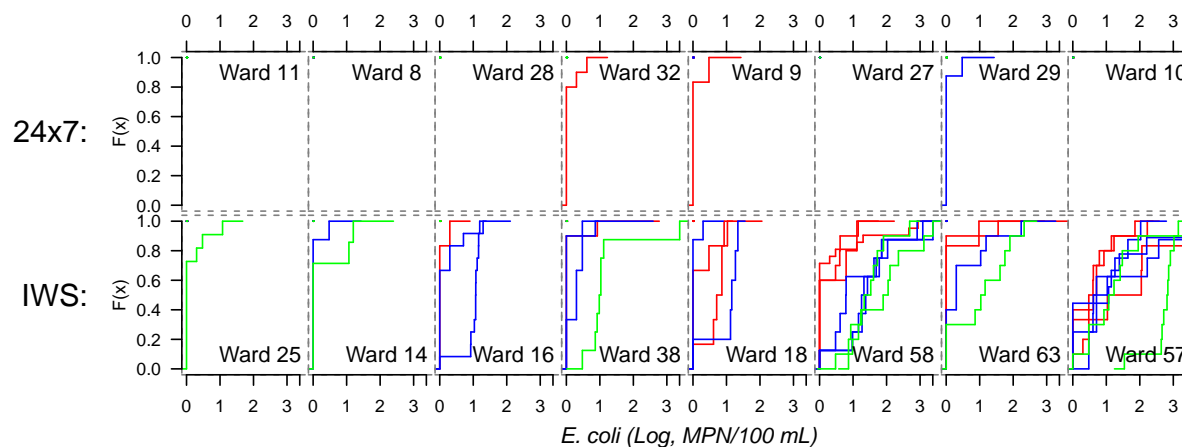


Figure 3.8: CDFs of *E. coli* for each ward by day, with wards in the same order as in Fig. 3.7. Colors represent different rounds of data collection.

Wards 38 and 18 had a similar percentage of samples positive for total coliform (Fig. 3.7), however Fig. 3.8 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 3.2), 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.

Table 3.2: Mean of log concentrations transformed to counts (MPN/100mL) of total coliform. *p-values* from Kruskal-Wallis test.

	24x7											IWS				
	8	9	10	11	27	28	29	32	14	16	18	25	38	57	58	63
Drainage																
Underground	<1	<1	2.4	<1	1	1	1.8	<1	1.9	16.9	25.5	<1	16.3	703.1	876.4	266.7
Visible	<1	<1	1.2	<1	1.4	<1	<1	<1	3.7	1.8	6.7	4.6	10.6	181.4	99.6	112.9
<i>p-value</i>	0.37	0.52	0.92	0.35	0.71	0.06	0.02*	0.34	0.08	0.24	0.19	< 0.01 *	0.63	0.05	0.71	< 0.01 *
Tap Location																
Indoors	<1	<1	2.6	<1	1.1	1.1	3.3	<1	<1	53.6	70.2	<1	83	1008.1	1627.3	612.7
Outdoors	<1	<1	1	<1	1.1	<1	<1	<1	3.8	1.4	7.1	3.1	5	177.6	95.1	86.2
<i>p-value</i>	0.37	0.52	0.92	0.35	0.71	0.06	0.02*	0.34	0.08	0.24	0.19	< 0.01 *	0.63	0.05	0.71	< 0.01 *
House Pipe																
Buried	<1	<1	2.2	<1	1.2	<1	1.5	<1	1.4	13.8	25.1	1.4	28.2	466.7	363.1	127.9
Exposed	<1	<1	1.3	<1	1	<1	<1	<1	7.6	1.5	5.5	4.3	1.3	135.5	131.1	475.7
<i>p-value</i>	0.45	0.26	0.38	0.36	0.82	0.07	0.01*	0.07	0.01*	0.11	0.01*	< 0.01 *	< 0.01 *	< 0.01 *	0.69	< 0.01 *
Level																
Below	-	-	-	-	-	-	-	-	1.9	8.3	-	-	19.3	396	265.9	205.8
Above	-	-	-	-	-	-	-	-	6.7	2.6	-	-	2.6	274	175.3	74.1
<i>p-value</i>	0.45	0.26	0.38	0.36	0.82	0.07	0.01*	0.07	0.01*	0.11	0.01*	< 0.01 *	< 0.01 *	< 0.01 *	0.69	< 0.01 *
Leak																
No Leak	<1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Leak	1.9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>p-value</i>	0.35	0.65	0.67	0.55	0.9	0.23	0.38	0.13	< 0.01 *	0.35	0.11	< 0.01 *	< 0.01 *	0.11	0.57	< 0.01 *

** p < 0.01, Kruskal-Wallis * p < 0.05, Kruskal-Wallis

3.4.5 Chlorine residual and indicator bacteria

In both 24x7 and IWS tap samples, indicator bacteria were detected less frequently and at lower concentrations when there was higher chlorine residual (Fig. 3.9). Three of the four samples positive for *E. coli* at 24x7 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.

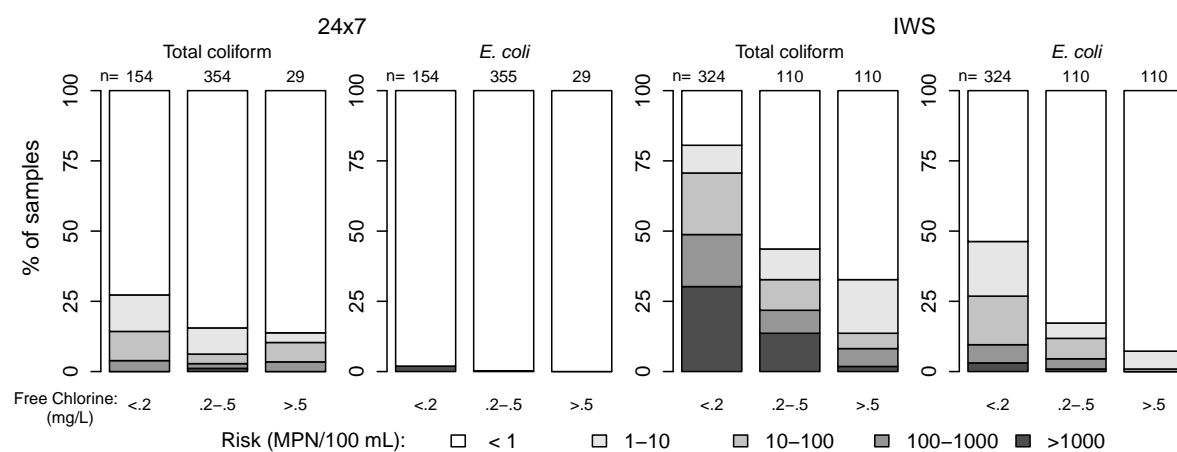


Figure 3.9: Percentage of samples meeting risk levels for total coliform and *E. coli* grouped by free chlorine concentrations.

3.4.6 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 147-267 $\mu\text{S}/\text{cm}$ and at the Kanvihonnapur WTP ranged from 415-488 $\mu\text{S}/\text{cm}$ (see Supporting Information Fig. 3.10). Thus, conductivity was a convenient tracer for source water. Since IWS wards were supplied with water from both WTPs while 24x7 wards received water from only the Amminbhavi WTP, conductivity was used to distinguish sources and assess whether treated water quality from WTPs was comparable.

There were no significant differences between turbidity, free chlorine, total coliform, and *E. coli* concentration between service reservoirs supplying 24x7 and IWS wards (ANOVA, $p > 0.05$) (Fig. 3.4). Total coliform were detected in both 24x7 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

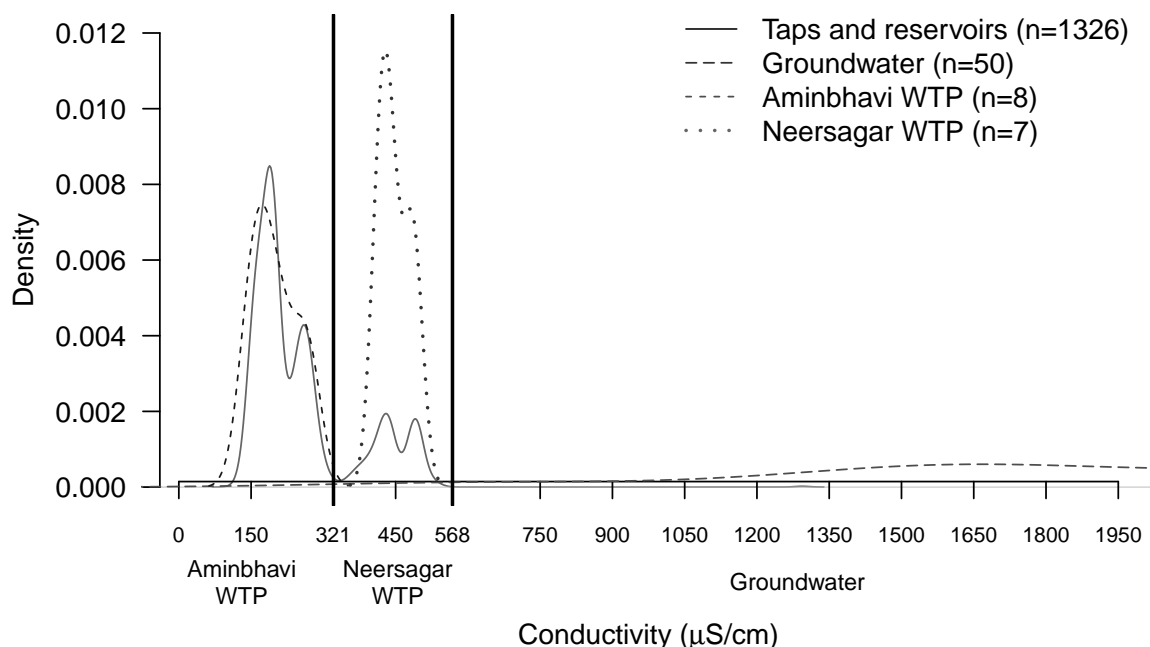


Figure 3.10: Kernel density plot of conductivity for source waters (Aminbhavi and Neersagar water treatment plants), groundwater, and taps and reservoirs.

site of contamination (Grayman et al., 2004; Edwards and Maher, 2008; Lee et al., 2006). While there is not sufficient data to assess risks or causes of contamination at individual reservoirs, these data suggest that 24x7 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 *E. coli* from 24x7 reservoirs to 24x7 taps, possibly due to inactivation by chlorine residual, while there was an increase in both total coliform and *E. coli* between IWS reservoirs and IWS taps (Fig. 3.4a and 3.4b); data for tap samples is the same as presented in Fig. 3.5).

3.4.7 Water quality at point-of-consumption

While households with IWS always store water, 94% of 24x7 households where water samples were collected for point-of-consumption testing reported storing water at the time of visit. In households with 24x7, there were higher concentrations of total coliform and *E. coli* in point-of-consumption samples than tap samples (ANOVA, $p < 0.01$) (Fig. 3.4b). In households with IWS, point-of-consumption samples had higher total coliform concentrations (ANOVA, $p < 0.01$), but slightly lower *E. coli* concentrations than tap samples (ANOVA, $p < 0.05$) (Fig. 3.4b). 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 taken directly from consumer taps (ANOVA, $p < 0.01$) (Fig. 3.11). 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.

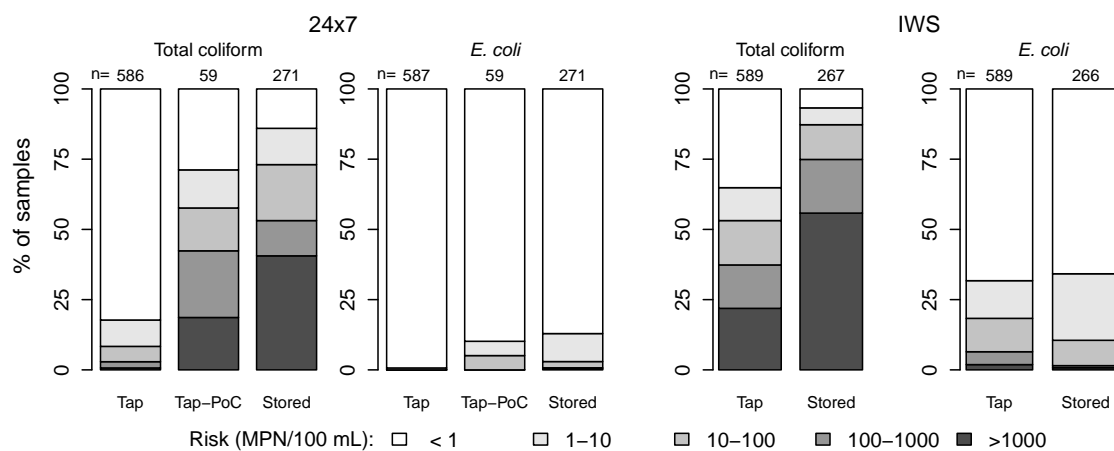


Figure 3.11: Total coliform and *E. coli* by risk group for tap and stored water. PoC: Point-of-consumption samples.

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 taken from household storage containers, 24% of households in each of IWS and 24x7 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 24x7 and 27% of visits in IWS. In the health and economic study, 46% of households in 24x7 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 3.3) (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 3.3). The only significant association was between time in storage and *E. coli* concentrations in IWS, where storing for more than a day was associated with higher *E. coli* concentrations.

The distribution system operation (24x7 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 3.3: Median values of water quality parameters for water at point of consumption, stratified by covariates. Significance determined by permutation ANOVA.

	No.	Total coliform		<i>E. coli</i>	
		24x7	IWS	24x7	IWS
Treatment					
untreated	402	100	1414	<1	<1
treated	126	980	1733	<1	<1
<i>p-value</i>		0.10	0.48	0.08	0.22
Container Location					
on floor	139	105	689	<1	<1
above ground	323	191	1733	<1	<1
<i>p-value</i>		0.12	0.48	0.27	0.41
Container mouth					
wide mouth	161	411	921	<1	<1
narrow mouth	276	93	>2420	<1	<1
<i>p-value</i>		0.26	0.27	0.14	0.44
Extraction					
dipped	432	191	1733	<1	<1
pour/tap	155	68	183	<1	<1
<i>p-value</i>		0.38	0.21	0.22	0.18
Storage Time					
> 1 days	67	>2420	>2420	<1	<1
≤ 1 days	166	563	>2420	<1	<1
<i>p-value</i>		0.08	0.34	0.12	0.02*

* p = <0.05

3.5 Conclusion

- The continuous water supply (24x7) 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 24x7 system did not meet the Indian standard for total coliform and *E. coli* respectively. A significantly higher percentage of tap samples from the 24x7 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 24x7.
- 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 24x7 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 24x7 households was more contaminated than water from the taps. Most households with 24x7 supply continued to store water, and therefore were not realizing the full water quality benefits of 24x7 supply. Future 24x7 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.

Chapter 4

Mechanisms affecting water quality in an intermittent piped water supply

4.1 Introduction

Maintaining continuous positive pressure in drinking water distribution systems can protect water from contamination as it flows to consumer taps (Ainsworth, 2004; AWWA, 2003; Geldreich, 1996). In contrast to systems with continuous water supply (CWS), distribution systems with IWS provide water through supply cycles, during which pipes are at atmospheric pressure when water is off, charge up when water supply is turned on, are repressurized during supply, and depressurize and drain when supply is turned off.

Minimum recommended pressure in distribution systems are 20 psi (14 m) in the U.S., 28 psi (20 m) in South Africa, and 10/17/24 psi (7/12/17 m) for each story of a building in India. Between IWS supply cycles, pipes are at atmospheric pressure (0 psi). When supply is on in IWS, excessive leaks and high demand (from all consumers drawing water during limited supply durations) can cause low pressure (Lee and Schwab, 2005; Batish, 2003; Ingeduld et al., 2006; Sashikumar et al., 2003; van den Berg and Danilenko, 2011; Christodoulou and Agathokleous, 2012), while surges can cause transient low pressure (Kirmeyer et al., 2001a). Additionally, many cities and towns with IWS also lack adequate sanitation systems, increasing the likelihood that potential contamination sources contain pathogens (Lee and Schwab, 2005; Vairavamoorthy et al., 2007). Though intrusion and backflow have been studied in CWS, the frequency and fate of contamination from these mechanisms have not been studied in IWS.

When an IWS is first turned on, pressure increases rapidly and water flows at high velocities. Flushing water at high velocities through distribution system pipes is a regular maintenance activity in many CWS systems remove stagnant water and accumulated particulates and biofilms from pipe walls (Barbeau et al., 2005; Choi and E, 2003; Lehtola et al., 2006; Gauthier et al., 1999; Lehtola et al., 2004; Prevost et al., 1997; Vreeburg and Boxall, 2007; Zacheus et al., 2001). Air trapped in the network as empty pipes fill can scour pipe

walls, reduce pressure, block flow, or cause pipe bursts (Vasconcelos and Wright, 2008; Zhang and Vairavamoorthy, 2006; Sashikumar et al., 2003). Similar effects would be expected at the beginning of each IWS supply cycle as pipes fill and flush out stagnant water, intruded contamination, and accumulated particulates and biofilms on pipe walls; however, while previous studies have suggested impaired water quality at the start of supply in IWS, their conclusions were limited by small sample sizes (Coelho et al., 2003; Kelkar et al., 2002).

Water quality in distribution systems is usually monitored through grab samples tested for bacterial indicator organisms (e.g. HPC, total coliform, fecal coliform, and *E. coli*) and physico-chemical parameters (e.g. turbidity, free chlorine). While these bacterial indicator organisms do not always behave the same as actual pathogens, they are useful for identifying contamination that could potentially contain pathogens. However, grab samples collected in previous studies of water quality in IWS have not accounted for temporal variations likely during supply cycles. Recent studies in CWS have used continuous measurements of water quality to detect deliberate contamination or changes in operating parameters (Skadsen et al., 2008; Ostfeld and Salomons, 2005; Mustonen et al., 2008; Storey et al., 2011). Continuous measurements, informed by testing indicator bacteria in grab samples, can aid in understanding the effect of hydraulic transitions in IWS on water quality throughout supply cycles.

The objectives of this chapter were to understand the mechanisms affecting water quality throughout supply cycles in IWS, detect evidence of contamination, and inform and evaluate tools for measuring water quality in these systems. To our knowledge, this is the first attempt to measure temporal variability in water quality in an IWS and identify the predominant mechanisms causing contamination.

4.2 Materials and Methods

Sampling Locations. This study was conducted in Hubli-Dharwad between April 2010 and July 2012. Eight wards with intermittent supply were selected as part of the larger study of the effect of intermittent and continuous water supply on water quality, health, and economics (see Chapter 3). Five of these wards (14 and 16 in Dharwad and 25, 38, and 57 in Hubli) were selected for sampling (Fig. 4.1). Seven sampling points were selected in consultation with the water utility and installed by tapping main lines in wards 25, 38, and 57. Consumer taps in wards 14, 16, 25, and 38 were selected for sampling based on their availability during a supply cycle (most taps are used by consumers to draw water and are thus not available for continuous sampling) (Fig. 4.1).

Water quality and pressure monitoring. Three methods were used for sampling: a multi-parameter physico-chemical sensor, a pressure sensor, and grab samples tested for indicator bacteria.

Turbidity, conductivity, free chlorine, temperature, and pH were measured and recorded every one to four seconds (depending on the supply duration) with a YSI 6920DW Sonde (YSI Inc., Yellow Springs, OH, USA). Pressure was measured every 250 milliseconds and

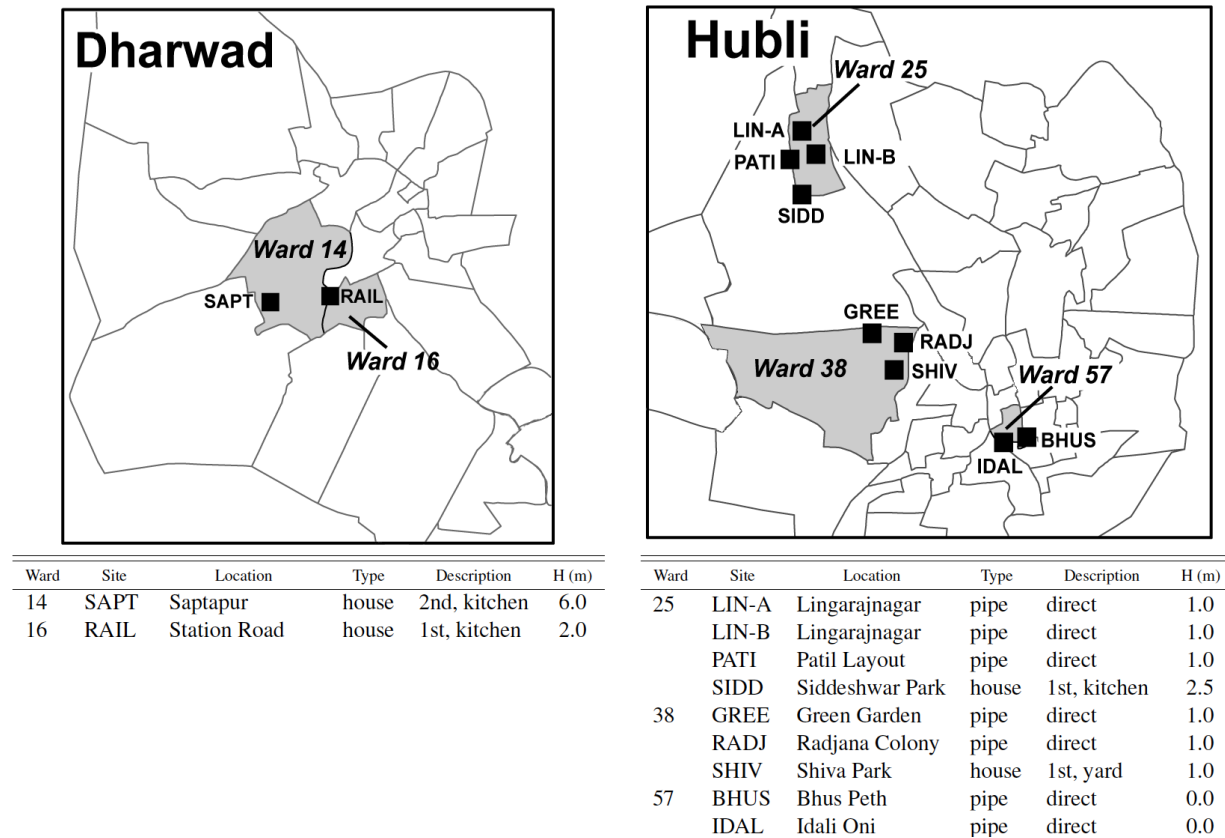


Figure 4.1: Study wards (14, 16, 25, 38, 57) and sampling sites in Hubli and Dharwad. Hubli is located 26 km southeast of Dharwad. Table lists sampling sites by ward (Ward), abbreviated site names (Site), neighborhood (Location), type of site (Type) distinguished as either a direct tap on a pipe (pipe) or a tap used by consumers (house), a description of the site (including story of house for consumer tap locations), and the estimated elevation (H) of the pressure sensor above the underground distribution pipes.

the mean, maximum, and minimum values were recorded every two seconds with a Telog LPR31 line pressure monitor (Telog Instruments, Victor, NY, USA). Where possible, these two sensors were installed at the same location (Fig. 4.2). Pressure measurements were corrected for elevation to estimate pressure in the underground distribution system pipes located approximately 1 m below ground (Fig. 4.1).

Grab samples were collected from the Sonde outlet in sterile 100 mL bottles containing sodium thiosulfate. The Sonde outlet was first disinfected with a chlorine solution. Samples were transported on ice to the laboratory and 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 hours. Samples were collected when water first started flowing, every 5 min for the first 15 min,



Figure 4.2: Sensors attached to direct tapping on pipe (Site: RADJ). YSI Sonde is on the left and Telog Line pressure monitor on the right.

every 15 min for the first hour, and every 30 min throughout the supply cycle.

It was not always possible to sample with all three methods (Sonde, pressure sensor, and grab samples) or throughout an entire supply cycle due to excessive air, leaks close to the sampling location, and unreliable start and end timings. The final data set includes nineteen supply cycles sampled with both sensors, two with only the Telog pressure sensor, and eight with only the Sonde (Table 4.1). 250 grab samples were collected and tested for total coliform and indicator bacteria. 127 grab samples were tested for free chlorine using a DPD method (Hach Colorimeter II) when the chlorine probe on the Sonde malfunctioned.

Steady-state detection. Charge-up (based on pressure data) and flushing (based on turbidity data) durations were identified using a method of detecting steady-state conditions. Steady-state can be defined as when a system experiences few changes besides noise and identified as when the standard deviation of a signal is within a threshold (based on typical operational standards) of its mean value (Kim et al., 2008). Because these study sites did not have standard operations, the system was defined as reaching steady-state when the rolling 1-min standard deviation of measurements was first within a threshold of the overall mean, with thresholds of 0.5% for pressure and 1% for turbidity based on identifying universal values for all supply cycles that could be verified by visual inspection. Data from supply cycles with observed air bubbles, which caused spikes in turbidity readings, were first smoothed with a cubic spline.

Event detection. Pressure data were analyzed to identify events that could degrade water quality by changing shear stress at pipe walls through: (1) sudden changes in operating pressure and (2) pressure transients. Sudden changes in operating pressure were defined as when the mean pressure recorded every 2 sec changed by more than 1 psi within 30 sec. Pressure transients resulting in excessively high or low pressure (which then have negative effects on pipe integrity and water quality) are caused by rapid change in flow from a transient

surge. Transient analyses identify events with consequences most relevant for a particular system; pressure data was analyzed to identify events that produced vacuum (atmospheric) or excessively high pressure. Excessively high pressure can be defined as when pressure reaches or exceeds the design pressure, with international standards from 0 - 50% greater than design pressure (Boulos et al., 2005; Pothof and Karney, 2012). Since design pressures of the sampled pipes were unknown, transients were defined as when the maximum pressure recorded every two sec exceeded 10% of the maximum of the mean pressure recorded every 2 sec during the entire cycle.

Turbidity data were analyzed to identify potential contamination events by identifying when observations differed from predictions based on previously observed data (general procedure outlined by (Murray et al., 2010)). Turbidity data were adjusted to 2 sec time intervals and normalized by subtracting the mean and dividing by the standard deviation of all previous data. Normalized data were then used to predict turbidity at the next time step using an auto-regressive moving average (ARIMA) model. Residuals that exceeded a standard deviation were classified as events. Multiple events within one min were categorized as the same event. Events were excluded if the turbidity changed < 0.5 NTU within one min to filter noise at low standard deviations. Events were excluded when air had been visually observed in the flow cell, turbidity decreased more than 10 NTU in one time step (likely from a wiper on the probe surface activating to clear bubbles), or when conductivity measured $< 100 \mu\text{S}/\text{cm}$ (likely from air bubbles). These procedures resulted in a conservative classification of turbidity events.

Statistical Analysis. Microbial detection limits had a lower bound of < 1 MPN/100 mL (substituted with zero) and an upper bound of > 2419.6 MPN/100 mL (substituted with 2420 MPN/100 mL). Log transformations for total coliform and *E. coli* used a value of $\log_{10}(x+1)$. Statistical tests using indicator bacteria data were performed on their rank values to account for censoring at lower and upper limits. Graphing and data analysis were carried out using R (R Core Team, 2012).

4.3 Results

Contamination during flushing. Water quality during flushing was analyzed using measurements taken immediately after supply was first turned. This data set consisted of 23 traces of turbidity at 10 sampling sites, 22 traces of pressure at 9 sites, and 70 grab samples tested for indicator bacteria collected during 15 supply cycles at 9 sites (Table 4.1). Charge-up and flushing periods were identified using the procedure described in the methods section for all cycles with available pressure or turbidity data.

Atmospheric pressure was recorded in pipes between supply cycles. When supply was turned on, pressure charged up and reached steady-state after 2-33 min (1-14% of supply durations) (Table 4.1). Visual observations confirmed that air was expelled from pipes. Pressure changes and expelled air were expected to increase shear stress or scour the pipe walls.

Table 4.1: Site (ward and location), Date, duration of water supply (D), and mean pressure during supply (P) of all sampled cycles. The duration for charge-up (based on pressure) and flushing (based on turbidity) are presented in minutes (min) and percent of supply (%).

Site	Date m/d/y	D hr	P psi	Charging		Flushing	
				min	%	min	%
Ward 14							
SAPT	9/17/10	1.3	-	-	-	2	2
SAPT	12/2/10	2.2	-	-	-	31	23
SAPT	2/10/11	3.9	-	-	-	3	1
SAPT	7/31/11	2.4	-	-	-	1	0
SAPT	6/27/12	3.4	-	-	-	15	7
SAPT	6/30/12	3.3	16	10	5	55	27
SAPT	7/3/12	3.3	12	2	1	25	12
SAPT	7/21/12	-	-	-	-	10	-
SAPT	7/30/12	2.6	21	2	1	6	4
Ward 16							
RAIL	2/15/11	5.9	20	-	-	-	-
RAIL	3/2/11	7.4	17	6	1	-	-
Ward 25							
LIN-A	7/9/11	6.8	5	14	3	28	7
LIN-A	7/21/11	4.7	7	2	1	13	5
LIN-A	6/23/12	5.7	16	17	5	-	-
LIN-A	6/29/12	5.5	20	14	4	27	8
LIN-A	7/8/12	5.7	18	17	5	31	9
LIN-B	7/20/12	6.6	12	16	4	25	6
PATI	7/15/11	4	0	-	-	-	-
SIDD	7/17/12	2.9	17	7	4	14	7
SIDD	7/26/12	2.5	17	6	5	3	2
Ward 38							
GREE	7/20/11	4.6	11	6	2	22	8
GREE	7/30/11	7.5	23	-	-	-	-
GREE	8/9/11	4	15	11	4	32	13
GREE	7/1/12	-	15	7	-	31	-
RADJ	8/4/11	5.4	14	7	2	71	20
SHIV	7/15/11	4.3	-	-	-	5	2
Ward 57							
BHUS	8/6/11	-	1	10	-	19	-
IDAL	8/1/11	3.2	0	33	17	-	-
IDAL	8/12/11	2.5	-	-	-	42	27

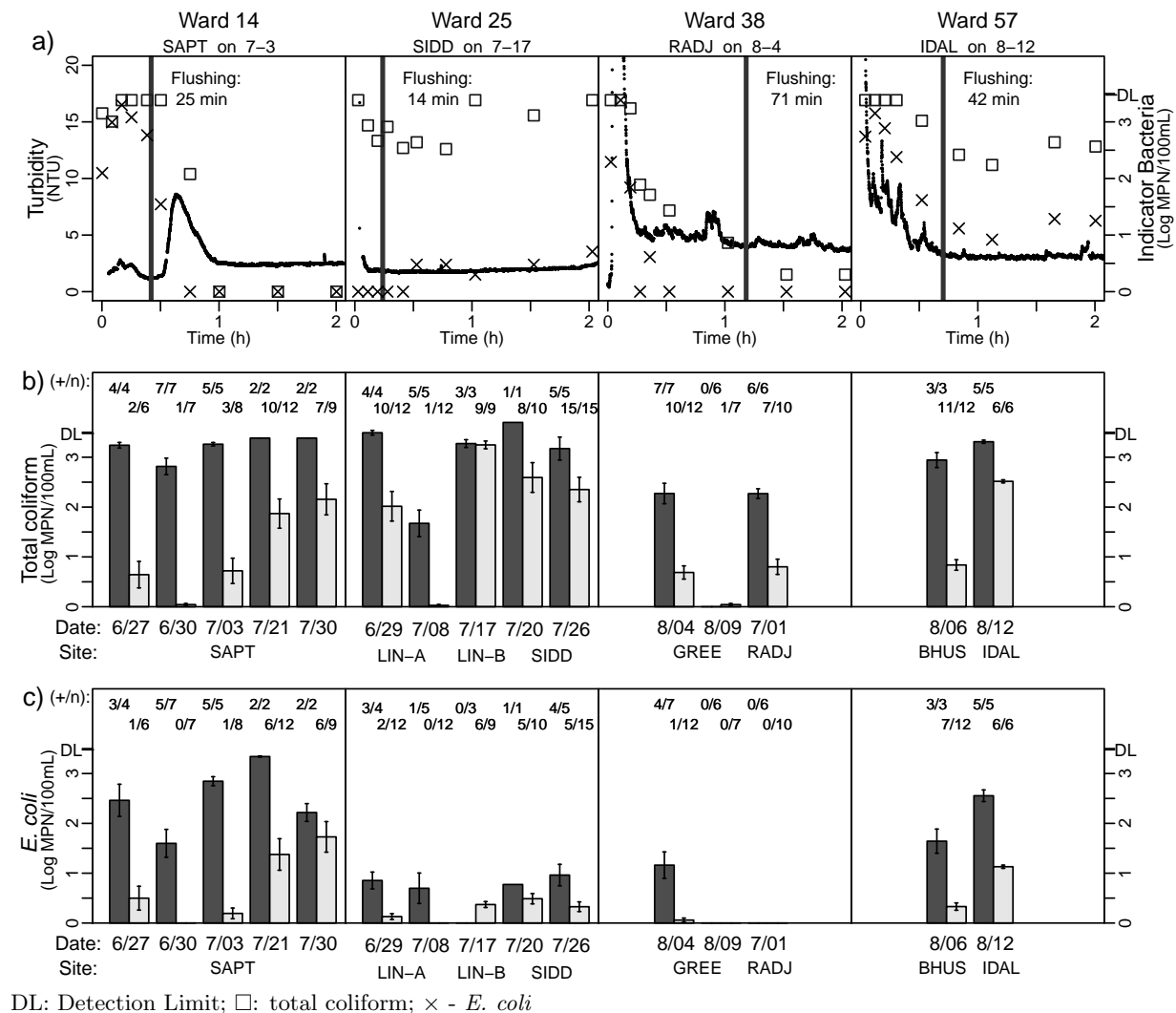


Figure 4.3: Each column contains data from one ward (14, 25, 38, and 57). The top row displays turbidity and indicator bacteria data during the first two hours of example supply cycles. The grey vertical line marks the end of flushing. Bar charts display total coliform and *E. coli* concentrations during (dark grey) and after (light grey) flushing for each supply cycle, with the number of positive samples and total number of samples above each bar (+/n). The date is shown as month/day is below each bar, with years in Table 4.1.

Researchers and utilities often use turbidity to indicate the effectiveness of flushing when used as a maintenance activity in CWS (Barbeau et al., 2005; Lehtola et al., 2004; Husband et al., 2008). Flushing lasted 1-71 minutes (<1-27% of supply cycle durations), which was longer than charge-up during all but one sampled cycle (Table 4.1). Average flushing durations were

longer at pipes (31 min) than at house taps (14 min). At sampling points on pipes, turbidity was very high when supplies first turned on and decreased until reaching a local steady-state (overall mean was 242 NTU during the first 30 sec and 24 NTU after) (Fig. 4.3). Turbidity trends were more variable at sampling points at house taps. While the first few readings were often high, turbidity was often already at steady-state or increased later in the supply cycle (overall mean was 21 NTU during the first 30 sec and 27 NTU after).

Conductivity and temperature measurements confirmed these general findings. Groundwater had higher conductivity than treated municipal water (see Chapter 3). Conductivity during flushing was significantly higher in 15 of the 23 supply cycles (ANOVA, $p < 0.01$) with a mean difference of 121 $\mu\text{S}/\text{cm}$, suggesting groundwater was a possible source of intrusion when supply was off at these sites. In two supply cycles, average conductivity during flushing was $>1000 \mu\text{S}/\text{cm}$; at these sites, groundwater was supplied through the local distribution system on alternate days. In the remaining cycles, there was no difference between conductivity before or after flushing, or conductivity was lower during flushing.

Temperatures during flushing were significantly lower than after flushing in 15 of the 23 cycles (ANOVA, $p < 0.01$), though the mean difference was small (0.26°C). While it was expected that temperature in stagnant water in pipes would be higher than inflow water, it is possible that only a small volume of water was left in pipes when supply was off, as temperature reached a steady-state value much faster than pressure, turbidity, or conductivity.

During flushing, the geometric mean concentration was 341 MPN/100 mL for total coliform and 18 MPN/100 mL for *E. coli* compared to 17 MPN/100 mL and 1 MPN/100 mL, respectively, after flushing (Fig. 4.3). Total coliform were detected in every sample during flushing in all but one supply cycle and *E. coli* were detected during flushing in all but three cycles. Concentrations were above the detection limit ($>2419.6 \text{ MPN}/100\text{mL}$) at several locations during flushing.

Pipes charged down when supply was turned off, with rapid decreases in pressure followed by draining at low or negative pressures (Fig. 4.8B,C,D).

Conditions likely to cause contamination during supply. A similar approach as reported in literature from CWS systems was used to identify the potential for intrusion or backflow by assessing the presence of pathways, sources of contamination, and the frequency of low pressure (Besner et al., 2011; Kirmeyer et al., 2001a; LeChevallier et al., 2003). Other mechanisms that potentially caused contamination are discussed in the next section.

Infrastructure deficiencies such as leaks are pathways for intrusion; in Hubli-Dharwad, 50% of water is estimated to be lost in the distribution system. Contaminant sources were common, as only approximately 30% of the area of the city is sewered. 30% of the city's sewage is collected in septic tanks and the remaining is disposed of in households pit latrines, open drains, and natural water sources (CSE, 2012). Although data on the state of underground assets are scarce, much of the sewer infrastructure is quite old and therefore contaminant sources are likely near potable water pipes.

Pressure was categorized based on Indian guidelines for first, second, and third story buildings (7, 12, and 17 m, respectively) as low ($<10\text{psi}$), medium (10-17psi), and high ($>17\text{psi}$) (CPHEEO, 1999). Persistent low and negative pressures were measured frequently,

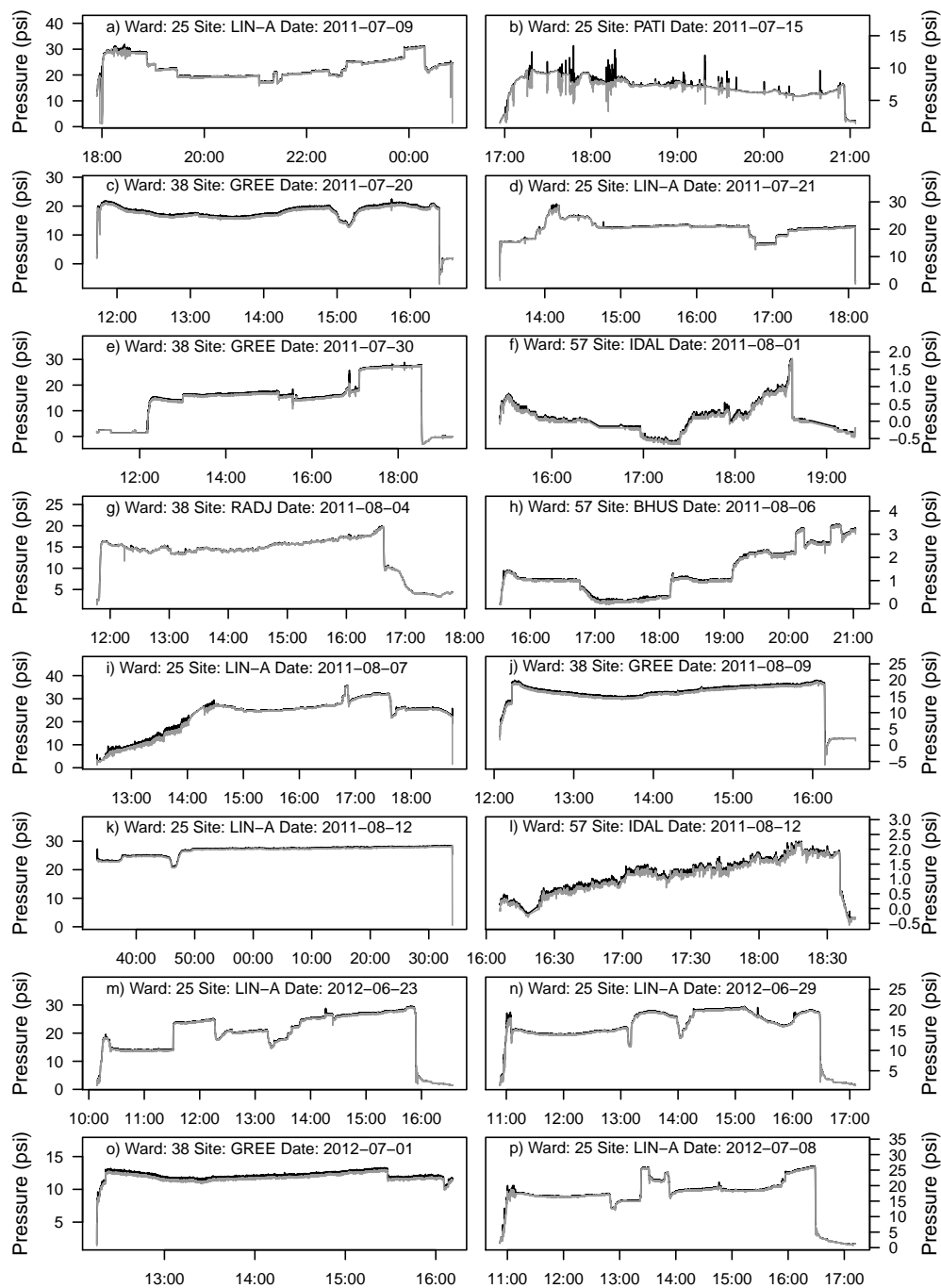


Figure 4.4: The minimum (grey line) and maximum (black line) pressure recorded every 2 sec for all sampling locations located directly on distribution system pipes. Transients were identified only during one supply cycle (b).

with pressure <10 psi recorded in five of the seven sampled sites that were directly on distribution system pipes. All sampling days in ward 57 experienced pressure < 0 psi for 2 sec - 39 min (the latter caused by a leak on the same pipe).

Pressure transients were expected when pipes charged up or down and when valves or pumps were operated nearby (valve operations are frequent in rotational IWS) (an example valve operation is shown in Fig. 4.8(f)). However, valve operations did not cause transients at any site (sites were located both down- and upstream of valves). Transients were identified during only one of 16 supply cycles (Fig. 4.4). The eight transients recorded during the 4 hr supply at a site located near the end of a line with few outlets resulted from expelled air (Fig. 4.5).

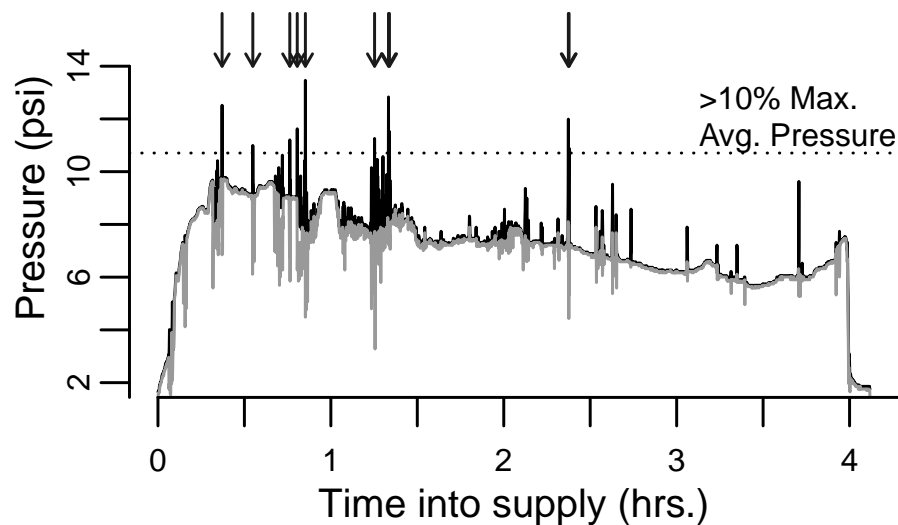


Figure 4.5: Pressure transients identified during supply cycle at PATI (Ward 25) on 2011-07-15. The black trace represents the maximum recorded pressure and the grey trace represents the minimum recorded pressure (recorded every 2 sec). The dotted horizontal line is 10% greater than the maximum 2 sec mean pressure recorded during the supply cycle. Arrows at the top indicate transients.

Roof and underground tanks used by consumers to store water can become cross-connections if taps are submerged. 35% of households (n=1951) surveyed as part of the health and economic study had rooftanks and 8% had taps inside storage tanks that had been submerged in the past month. 17% of households had taps at or below ground level (where they would be vulnerable to intrusion from soil, surface runoff, or ponded water) and more than half (62%) of these reported that the street had flooded above their tap within the previous month. At consumer taps, < 5 psi was recorded during five of the eight cycles while < 0 psi was recorded at every location immediately after supply was turned off. Roof tanks can be

potential cross-connections if taps become submerged; during one cycle, pressure (adjusted for roof tank elevation) was < 0 psi for the entire cycle.

Evidence of contamination during supply. Low pressure and contamination after flushing were observed frequently enough to explore the mechanisms affecting water quality in the distribution system. Evidence of contamination was defined as high turbidity or high concentrations of indicator bacteria.

Influence of pressure and chlorine residual on water quality. Factors contributing to persistent contamination were examined by calculating the mean pressure and mean free chlorine residual during the 30 min before each grab sample was collected (changing the window size did not significantly affect relationships) (Fig. 4.6).

Total coliform concentrations were significantly lower in grab samples with measurable free chlorine residual (≥ 0.1 mg/L) than in those without (< 0.1 mg/L) at any pressure (Wilcoxon rank-sum, $p < 0.01$) (Fig. 4.6). *E. coli* concentrations were significantly lower in samples with chlorine residual than those without only at medium pressures (10-17 psi) (Wilcoxon rank-sum, $p < 0.01$). *E. coli* was present both with and without chlorine in samples collected at low pressure, while few *E. coli* were detected in samples collected at high pressure. These data confirm the expected result that the lowest concentrations of indicator bacteria occurred when water was delivered at high pressure (> 17 psi) with a free chlorine residual.

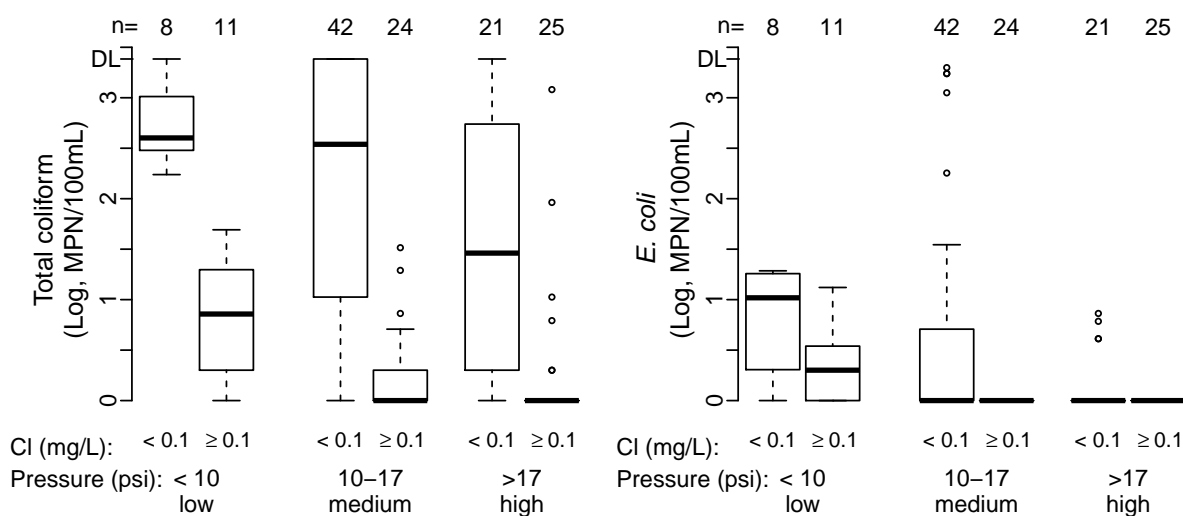


Figure 4.6: Box and whisker plots show the median, lower and upper quartiles, and outliers of indicator bacteria concentrations from all supply cycles during supply (flushing and draining excluded), grouped by the average pressure and chlorine residual during the 30 minute period before each grab sample was collected and tested for total coliform and *E. coli*.

At medium pressure (10-17 psi), total coliform were detected in 86% ($n=42$) of samples without chlorine and 46% ($n=24$) of samples with chlorine (Fig. 4.6). Concentrations of total coliform were low when there was a chlorine residual. This variability in contamination

levels suggest that water delivered at these pressures were subject to periodic contamination in the distribution system.

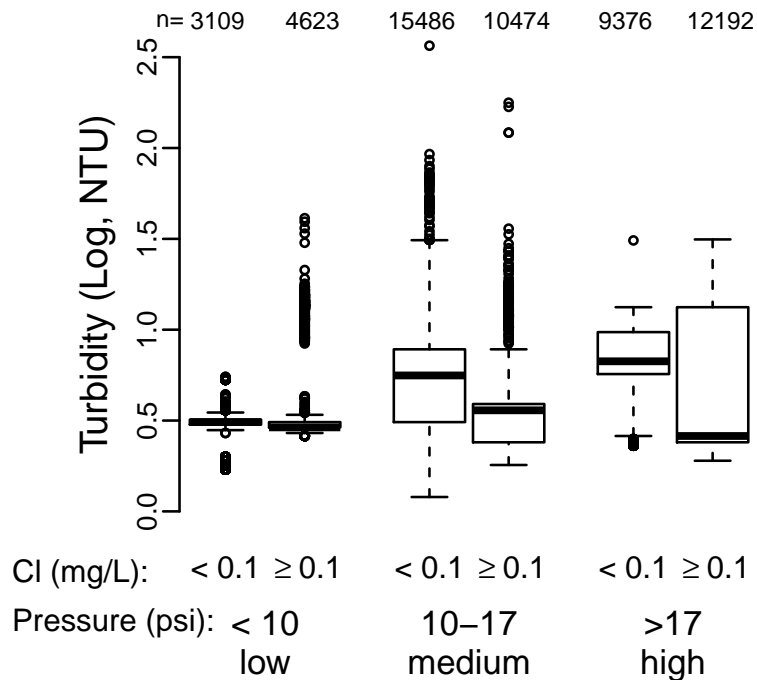


Figure 4.7: Box and whisker plots show the median, lower and upper quartiles, and outliers of the log values of turbidity from all supply cycles, grouped by the pressure and chlorine residual recorded at the same time.

The only samples positive for *E. coli* when chlorine was also present occurred when pressure was low (<10 psi) (Fig. 4.6). At low pressure (<10 psi), total coliform were present in all but one sample and *E. coli* were present in 6 samples both with (n=11) and without (n=9) chlorine. This frequent detection of indicator bacteria suggests contamination was persistent at low pressure (an example is presented in Fig. 4.8A). Turbidity of > 5 NTU likely interfered with maintaining chlorine residual at medium and high > 10 psi (Fig. 4.7).

While some of the detected indicator bacteria may have originated from inadequate source water treatment, water provided to all areas originated from the same treatment plants and similar service reservoirs. Therefore, it is likely that the observed contamination occurred in the distribution system. Detecting indicator bacteria in the presence of a chlorine residual suggests contamination was localized or bacteria had been protected by aggregating with other particles (Herson et al., 1987; Ridgway and Olson, 1982). Additionally, detecting total coliform at concentrations >2419.6 MPN/100 mL frequently and detecting *E. coli* concentrations >100 MPN/100 mL in 9% (n=43) of samples indicate that wastewater may have entered the distribution system as intrusion.

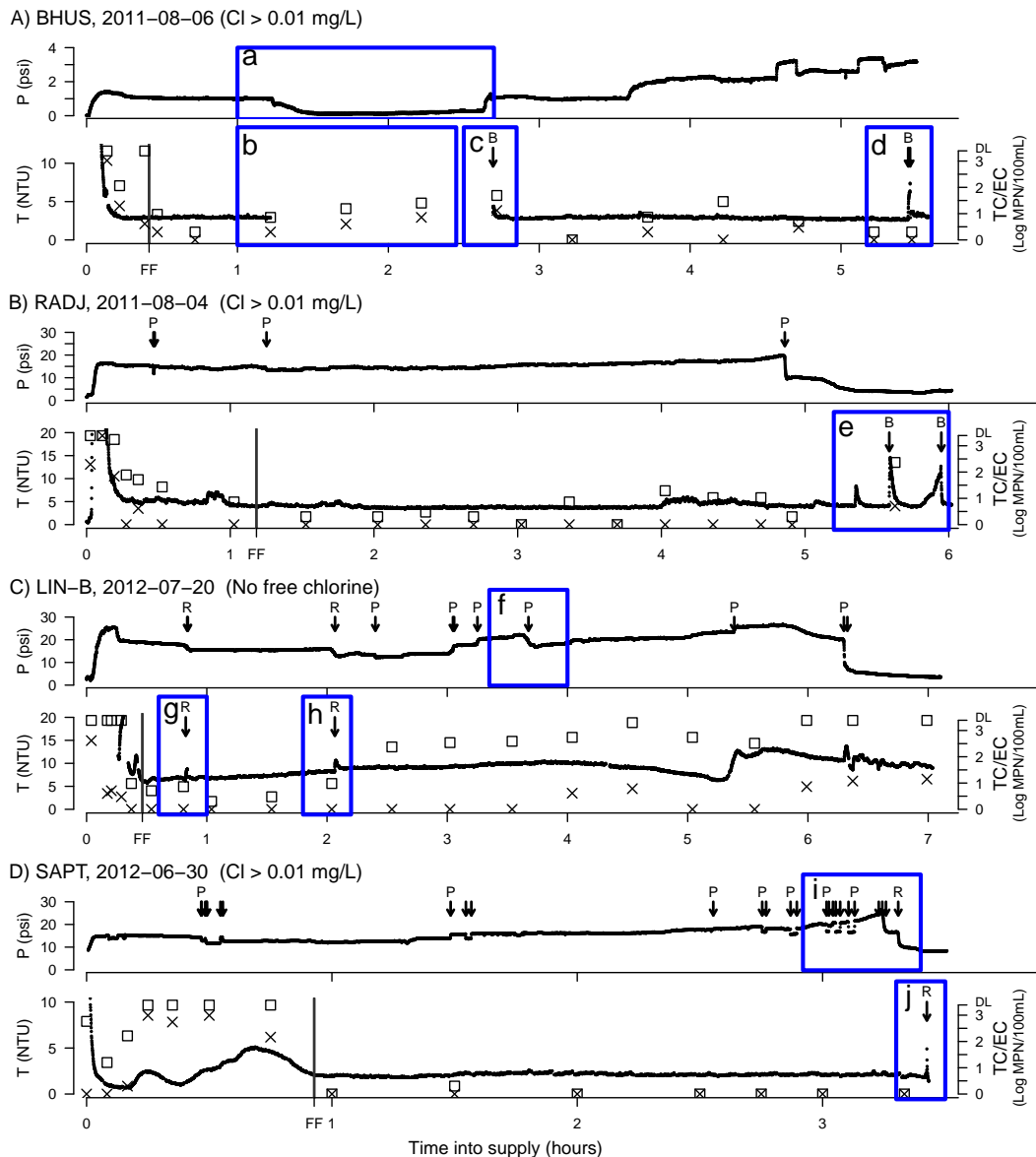


Figure 4.8: Mean pressure (P) every 2 sec, turbidity (T) every 1 sec, and grab samples tested for indicator bacteria concentrations (total coliform/*E. coli*, TC/EC). A) (a) sustained pressure near 0 psi; (b) elevated indicator bacteria; (c) turbidity event after re-starting flow; (d) possible intrusion. B) (e) two turbidity and indicator bacteria spikes during draining (<10 psi). C) (g, h) turbidity spikes after sudden changes in pressure, (f) normal valve operation, D) (i) sudden pressure drop after turning valve off followed by (j) spike in turbidity.

Continuous time series data. While analysis of real-time data provided further insight into water quality, this distribution system was highly dynamic with unique data from each site and supply cycle. Pressure and water quality indicators varied over time and between days due to changing valve operations and consumer demands (e.g. turbidity, which is typically steady in CWS, was highly variable). Though given this variability it was not possible to identify overall trends, in this section I present evidence of likely contamination events and hypothesized the mechanisms causing these events.

84 hours of pressure and turbidity data during 18 supply cycles were analyzed for events. Likely contamination, indicated by turbidity spikes, were differentiated by possible causal mechanism: if a sudden change in operating pressure had occurred in the ten minutes before a turbidity spike, this was considered an event that may have been particulate release or biofilm sloughing (R), while a turbidity spike without a hydraulic trigger indicated likely backflow or intrusion (B). Changes in operating without a subsequent turbidity event were also identified (P) (Fig. 4.8) (additional examples are presented in Fig. 4.9). Since indicator bacteria were collected as grab samples, correlations with continuous measurements were not possible. However, the data provided insight into other contamination events.

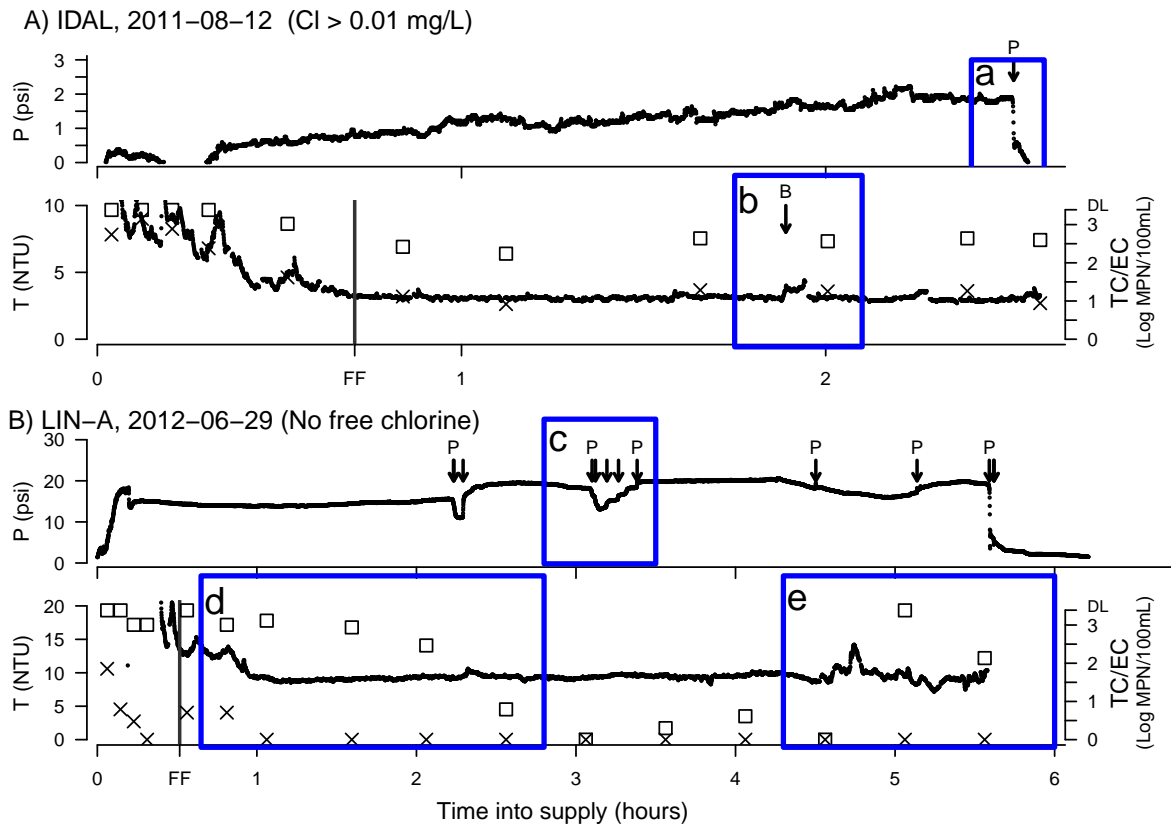
During one sampled cycle at BHUS, elevated total coliform and *E. coli* concentrations were detected throughout despite chlorine residual (Fig. 4.8A). Pressure was near 0 psi for 1 hr 28 minutes Fig. 4.8(a) during which indicator bacteria concentrations increased (Fig. 4.8(b)) (since there was no flow to the Sonde cell, turbidity could not be measured). A turbidity spike was detected when flow re-started (Fig. 4.8(c)). Given the overall very low pressure, intrusion or backflow may have persisted or there may have been insufficient shear stress during flushing such that contamination that was instead released continuously during supply.

During the same cycle, a 50-sec turbidity spike without a change in operating pressure was detected when pressure was < 10 psi, which could indicate intrusion or backflow (Fig. 4.8(d)). A similar phenomenon occurred at RADJ, where two spikes lasting 2-3 min were detected when pressure was 6 psi during draining along with elevated total coliform and *E. coli* (Fig. 4.8(e)).

Two turbidity spikes after changes in pressure when pressure was an average of 18 psi suggested likely release of particulates or sloughing of biofilms (Fig. 4.8(g,h)). During this supply, the highly variable turbidity may have reduced chlorine residual and been related to elevated indicator bacteria concentrations (Fig. 4.8C). Pressure events also occurred without a subsequent turbidity spike (Fig. 4.8C and D); in these instances, there may have been no contamination to release or contamination may not have been indicated by turbidity.

Turning supply off (as reported by the valve operator) caused a rapid decrease in pressure and persistent low pressure which was associated with a turbidity event during one sampled supply (Fig. 4.8(i,j)) that may have signaled intrusion or particulate release or biofilm sloughing.

While transients would have been expected to cause a sudden change in shear stress that could affect water quality, they occurred in only one observed supply cycle (Fig. 4.5). During this cycle, it was not possible to measure turbidity due to excessive air in the flow cell.



□ - total coliform; × - *E. coli*; DL - Detection Limit (2419.6); FF - First flush; P - Pressure event; R - Event with match (turbidity and pressure); B - Turbidity spike without change in pressure

Figure 4.9: Pressure (P) recorded as an average every 2 sec, turbidity (T) recorded every 1 sec, and indicator bacteria (total coliform/*E. coli*, TC/EC) concentrations over time. A) (a) sudden drop in pressure without a subsequent turbidity event (b) turbidity event without a pressure change (possible intrusion). B) (c) series of events without a change in turbidity (d) elevated total coliform after first flush (e) turbidity changes that were not identified as events.

4.4 Discussion

Flushing. When supply was first turned on, water emerged from the pipes with elevated turbidity and indicator bacteria concentrations. This is consistent with studies in CWS that measured elevated turbidity and indicator bacteria during flushing from turning over stagnant water and scouring particulates and biofilms from pipe walls (Vreeburg and Boxall, 2007; Lehtola et al., 2004; Zacheus et al., 2001). Though bacteria could have grown in stagnant water left in pipes between supply cycles, the extremely concentrations measured in some cases are strong evidence that contamination had entered the distribution system pipes while the supply was off.

The flushing observed at the beginning of each supply cycle is potentially beneficial for water quality, as contaminated water and accumulated materials on pipe walls can be flushed out. However, the data suggest several features that may limit the benefits of flushing. Sustained high or variable shear stress at pipe walls are necessary to remove accumulated particulates and biofilms; in some cases, short charge-up durations or low pressure could limit the change in shear stress. During planned flushing in CWS, the flush water is treated as wastewater while in the system studied, consumers were observed using or storing highly contaminated flush water. The long flushing durations measured (up to 25% of the supply cycle) suggest consumers would need to wait long durations to avoid flush water. Despite these limitations, flushing could be optimized to be a tool for improving water quality in IWS by increasing pressure or diverting and avoiding use of flush water (e.g. keeping consumer taps closed when supply starts).

Contamination during supply. The evidence suggested that the main mechanisms that likely caused contamination in the distribution system during supply - intrusion, backflow, resuspension of particulate matter, or sloughing of biofilms from pipes walls - occurred during the observed supply cycles.

Pathways, contaminant sources, and frequent low pressure - all conditions likely to lead to intrusion or backflow - were common in this distribution system. Water delivered at pressure <10 psi (low by most international standards) had consistently high concentrations of indicator bacteria, suggesting that persistent contamination occurred in the distribution system. At these low pressures, chlorine was insufficient to inactivate intruded indicator bacteria.

Sporadic contamination was also observed when water was delivered between 10-17 psi. Turbidity or indicator bacteria spikes measured after a sudden change in operating pressure suggest biofilm sloughing or particulate release, while turbidity spikes that did not follow a hydraulic event may have resulted from intrusion, backflow, or spontaneous releases from pipe walls.

This research confirmed the expected result that water delivered at high pressure (>17 psi) with a detectable disinfectant residual (≥ 0.1 mg/L) had low concentrations of indicator bacteria. While water delivered at high pressure had the lowest levels of contamination, our data suggest that a minimum of 10 psi may still protect against persistent contamination, though higher pressures may be necessary to prevent momentary intrusion or backflow. Future research should be directed toward identifying the minimum pressures for preventing both persistent and periodic contamination events.

While valve operations both up and downstream from sampling sites were frequent, these operations did not produce detectable pressure transients. A likely explanation is that the high demand and numerous pathways to the environment, dissipating pressure waves and potentially dampening the effect of transients (Karney and Filion, 2003). The only observed transients resulted from expelling trapped air.

Other mechanisms affecting water quality in CWS - bacterial regrowth or accumulation on pipe walls during stagnation - were unlikely important in this system given the short supply durations, though they may be more important with longer supply durations.

Measuring water quality in intermittent systems. To our knowledge, this is the first study of water quality throughout IWS supply cycles. It is important to note that this distribution system represents severe intermittency: water delivery was infrequent and supply durations were short. While this is fairly representative of other cities in India, the dynamics may differ in cities with more moderate intermittency.

These results suggest that water quality monitoring in a dynamic IWS requires special considerations. The temporal variability measured - particularly that water is most contaminated at the beginning of a supply cycle - would change interpretations of monitoring data. In addition to measuring indicator bacteria (commonly a part of monitoring programs), periodic chlorine residual and pressure were important for assessing potential risk to water quality (continuous, high-frequency monitoring are likely not useful).

These results also inform and highlight the challenges of research on water quality in dynamic IWS systems. Since each supply cycle in this system was unique, human observations and information on distribution system assets and operations were necessary to interpret and validate data (e.g. supplies started and stopped, air bubbles persisted, etc.). Continuous turbidity measurements were the most useful indicator of flushing, a finding consistent with studies in CWS, and an empirical approach for measuring charge-up and flushing durations was useful when hydraulic models were unavailable. Turbidity was also somewhat useful for detecting potential contamination events, though air bubbles interfered with readings and indicator bacteria were often detected in the absence of turbidity events. Continuous measurements of conductivity, temperature, and pH (discussed in SI) provided minimal insight into mechanisms affecting contamination, and continuous chlorine measurements may be more useful indicator in systems where chlorine residual is regularly maintained. Indicator bacteria were useful for detecting persistent contamination and understanding varying risks to water quality over time and between locations; however, since these are collected as grab samples, they could not be used to detect short contamination events.

The tools and analysis techniques developed in this research can be applied to other systems. Similar methods to data from other types of IWS systems would help with understanding the spectrum of IWS practices and their differential impacts on water quality, while research on more controlled IWS conditions could be used to distinguish between mechanisms causing contamination.

Chapter 5

Household water use and utility water loss in an intermittent piped water distribution system

5.1 Introduction

In intermittent piped water supply (IWS) systems, water consumption can be restricted by short supply durations and low pressure at taps, as well as residents' ability to collect, store, and use that water. Measurements of how much water residents consume are necessary for understanding water access, equity, and losses. However, data collection on household water consumption in IWS is often haphazard because meters are lacking or inaccurate. Together, constrained supply and poor data pose significant challenges in measuring and understanding household water use.

Intermittent supply regimes can be improved by increasing the frequency and reliability or intermittent water delivery or by converting to continuous supply; both paths require that utilities reduce water loss (Ismail and Puad, 2007; Vairavamoorthy et al., 2007). Water loss and waste can occur in the utility network or in households; in IWS systems, the relative importance of losses at each scale (before and after the tap) is debated, but few data are available (McIntosh, 2003). Complicating the problem of loss reduction, definitions of water loss vary by sociopolitical and institutional context, though conceptions of what constitutes waste are important for developing water accounting metrics. Uneven delivery of and access to water in cities and towns with IWS can result in inequities among residential consumers; therefore, equity and sufficiency of water supply also factor in conceptions of loss.

Volumetric accounting, also known as a mass or water balance, compares the volume of water input to a system to the output volumes at the output. Municipal utilities perform these audits at the micro scale (household) or mezzo scale (service level, e.g. a water supply system), while regional and national agencies perform audits at macro scale (catchment or basin). Water accounting methods used to derive metrics of household water consumption

and utility performance (e.g. unaccounted-for water) are well developed for fully pressurized and metered water systems typical of industrialized nations. However, these methods fail in many developing world contexts for two reasons: (1) many supply lines and households are not metered, and (2) supplying water for limited durations complicates measurements of pressure and flow rates.

To address this, I estimated household water consumption under infrequent intermittent water delivery in a city where meters are scarce by using several methods to triangulate consumption: metered data, storage container inventory, and structured observations of water collection and use. These new estimates of per person water consumption are used to assess household water consumption and compare physical losses in the utility network with losses after household taps.

5.2 Accounting for water: Household and utility metrics under intermittent water supply

Below, I discuss the methods and challenges in accounting for water at the household and utility scales in intermittent systems and motivate methods of measuring water consumption.

5.2.1 Household water accounting

Household water accounting usually assumes that the utility provides enough water to meet household demand (“demand-driven regime”) and that water meters accurately measure use at households. Where these assumptions hold, measurements of volumetric consumption are used to compare water use between households, set and enforce block tariffs, target demand reduction programs, and quantify water loss in the distribution system. However, in IWS systems with short supply durations and infrequent water delivery, the system can shift from a demand-driven regime to a supply-driven regime. In a supply-driven regime, the quantity of water delivered to a household is a function of utility allocation (supply duration and frequency) and water pressure. In practice, allocation is often uneven within and between supply areas and is influenced by topography, valve operations, leakage, and household modifications such as booster pumps (Vairavamoorthy et al., 2007).

Micro-scale factors may also constrain the volume of water available to a particular household. Households with their own tap and a hose can access water for the entire delivery period. As the number of households sharing a connection increases, a household's access to the water at a connection declines. The need to carry water from a tap in pots will further limit access, depending on the queue to fill pots and 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 of low socio-economic status (SES) often lack roofs strong enough to support an overhead storage tank or lack space to store containers water inside, while high SES households can install large roof tanks. These systems of infrastructure intersect with behaviors that include using alternate water sources

and shifting water intensive uses to supply periods (Rosenberg et al., 2007). These layers of coping infrastructure and behavior complicate the task of measuring household water consumption.

5.2.2 Utility water accounting

Utility water accounting compares measured inflow into the distribution system with measured consumption to estimate losses. 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). The International Water Association water balance approach (Alegre et al., 2000; Pilcher et al., 2008) separates real/physical losses (e.g. water lost through leaks or overflows from storage tanks) from apparent/commercial losses (e.g. inaccurate meters, illegal consumption). Water accounting is used to derive several metrics that are used to compare and monitor utility performance. Unaccounted-for water (UFW or UAW) is the difference between water production and consumption, expressed as a percentage of production; however, this metric does not provide information about whether losses are real or apparent. A more broad definition of loss, non-revenue water (NRW), measures water produced and distributed for which no revenue is collected (this includes UFW).

However, existing accounting methods rely on two key assumptions: (1) data from meters is available at both production sites and consumer connections, and (2) water supply is continuous. These assumptions do not hold in intermittent systems, which include an estimated one-third of African and Latin American cities and more than half of Asian cities (WHO and UNICEF, 2000; van den Berg and Danilenko, 2011). Most methods of measuring utility water loss require detailed data that are often scarce or inaccurate in many developing countries (e.g. production or distribution system meters, maps, and records of pipe material and meters) (Jeffcoate and Saravanapavan, 1987; Kandra et al., 2004; Schouten and Halim, 2010). Residential consumption meters, where they exist, may have been damaged by intermittent pressure or underestimate consumption when pressures are low (Criminisi et al., 2009). Connections are often shared between multiple households or are tapped illicitly, making the calculation of per-capita daily usage highly uncertain. Additionally, reporting water loss estimates calculated based on limited supply periods can mask the true extent of pipe problems and may incentivize shortening supply durations.

5.2.3 Objectives

Measuring water use and losses in intermittently supplied distribution systems with few meters is not straightforward and existing methods developed for continuous supplies are inadequate. In the next section, I describe a strategy of triangulation to measure household water consumption. These results are used to compare measurement methods to gain a more accurate understanding of consumption in an intermittent supply system. These methods are based on characteristics of household water access and infrastructure that can be identified

relatively rapidly and without costly equipment, and thus should be transferable to other developing world cities.

5.3 Methods

A typology of likely per household water consumption was developed based on characteristics contributing to differential water access and storage capacity. The quantity of water that households collected from taps (consumption) was measured using meters and storage container inventories. These measurements were then augmented with structured interviews and household survey data to estimate water used directly from the tap during delivery. Distribution system water loss was then calculated using these average monthly household water consumption estimates.

5.3.1 Study site

Data on demographics, water connections, supply frequency and duration, and water storage and pumping infrastructure (including overhead and underground tank volumes) were collected from household respondents in Hubli-Dharwad as part of the household survey during the first of four rounds of data collection (November 2010 - February 2011).

5.3.2 Typology

Unstructured interviews among a subsample of households enrolled in the study (n=40) and conversations with local water managers were used to define a typology of water access and use. Households enrolled in the study were then classified into a typology along a scarcity gradient based on their coping infrastructure and social factors (e.g. low pressure, many users sharing a tap, a short delivery period) that influenced the total volume of water they consumed. The key characteristics used in the final typology definition (all of which were easy to collect data on) were: 1) number of households sharing a tap and who owned the tap and 2) presence or absence of an overhead tank.

- Type 1: Consumers without an overhead tank that access water from (a) a public connection, or (b) a neighbor's connection shared with more than two other households, or (c) their own connection shared with more than three households.
- Type 2: Consumers without an overhead tank that access water from (a) their own connection that is not shared, or (b) a neighbor's connection shared with one or two other households, or (c) their own connection shared with between one and three other households.
- Type 3: Consumers with an overhead tank that access water from their own connection shared with at least one other household.

- Type 4: Consumers with an overhead tank that access water from their own connection that is not shared with any other households.

5.3.3 Measured water consumption

When municipal water supply was delivered through taps, flow rates varied throughout supply periods (0-5.5 liters per minute) and water users filled myriad storage containers and performed water-intensive tasks. Given these complicated pressure, storage, and water-use behaviors, three methods of measuring household water consumption were used to triangulate total water consumption, as no one method was accurate alone. These methods included: (1) metered data, (2) measured storage containers, (3) structured observations of use directly from the tap, and (4) survey data reporting time to collect water. These measurements were constrained to municipal water supply; supplementary water sources (e.g. borewell water) were excluded. Water consumption data are reported in units of liters per capita per day (LPCD).

5.3.3.1 Metered volumes

Metered water consumption records were available from the first round of data collection (Nov. 2010 - Feb. 2011) for 389 households with IWS that were enrolled in the study (n=1951). For 95 households that could not be matched to utility records, enumerators recorded the volume and charges from the household's most current bill at the time of survey. Billing data were reported in units of kL/con/mon. To convert to units of LPCD, the metered volumes were divided by the average number of days in the month, the number of households sharing the tap, and the number of people living in the household.

5.3.3.2 Storage capacity

Container inventories were conducted at 14% (n=236) of enrolled households during the first round of data collection (Nov. 2010 - Feb. 2011), selected as the first household visit during a day of data collection. Enumerators measured the height, perimeter, and shape (ellipsoid, cylinder, or rectangle) of water storage containers. These dimensions were used to calculate each container's volume. Households reported the volumes of overhead and underground tanks. If multiple households shared these tanks, the total volume was divided evenly between the households. In cases where overhead and underground tank volumes were missing or unknown, the overall mean volume was substituted for the same type of tank material. Households also reported whether the water in underground or overhead tanks was municipal water, borewell water, or mixed; only municipal water volumes were used in our estimates. Calculations of storage capacity assumed that all containers were empty before the supply cycle and were filled completely during the cycle (the implications of this assumption are discussed in the results).

To arrive at measurements in units of LPCD, the total household storage capacity was divided by the reported number of people in the house and the number of days between supply cycles.

5.3.3.3 Consumption during supply

The volume of water households used directly from the taps (without storing) was estimated using a water balance approach, where the total volume of water delivered to a household tap (V_{total}) is the sum of the volume added to storage (V_{stored}) and the volume used directly from the tap during delivery (V_{used}), given by

$$V_{total} = V_{stored} + V_{used} \quad (5.1)$$

An average use factor (UF) was developed for each typology, which estimates V_{used} as the fraction of a household's storage capacity (V_{stored}), given by:

$$V_{total} = V_{stored} + UF * V_{stored} \quad (5.2)$$

The UF is developed through two methods: (1) flow rates (from structured observations) and (2) time spent collecting water (from survey data). An average UF for each type was calculated by averaging the UF of all households in each type.

Observations. Ten structured observations were carried out in June-July 2011 in two or three randomly selected Type 1, 2, and 3 households. The data collected through structured observations were not intended to be statistically representative, however, they do indicate the range of water use behaviors and inform interpretation of the survey data. Shortly before delivery of water to households, container volumes, the volume of stored water remaining in containers, and the conductivity of water in storage containers were measured. Conductivity was used to determine whether the water in a container had come from a borewell, city supply, or a mixed source (the conductivity of surface and groundwater was $<600 \mu\text{S}/\text{cm}$ and $>800 \mu\text{S}/\text{cm}$, respectively) (see Chapter 3). One tap in each selected household was observed for the entire water delivery period, noting how much stored water was used or thrown away, the volume of water stored for future use, and how households used water while it was on. The duration of each activity was recorded (e.g. washing clothes, bathing, filling containers, letting water flow down the drain unused) and the flow rate was measured four times during each supply cycle by measuring the duration of time to fill a container of known volume. These flow rate measurements were used to estimate the volume of water used directly from the tap.

- **Use based on flow rates.** One estimate of use was based on flow rates measured during structured observations. The total volume of water consumed for each observed household ($n=6$) was calculated by multiplying the flow rate (Q) by the observed supply duration (T_{total}). Since flow rates varied throughout the supply cycle, a minimum, average, and maximum value was calculated for each corresponding flow rate.

V_{stored} was measured for each observed household by conducting a container inventory. Therefore, the UF based on these data is:

$$UF = \frac{V_{used}}{V_{stored}} = \frac{Q * T_{total} - V_{stored}}{V_{stored}} \quad (5.3)$$

However, this method is of limited use for households that have an overhead tank (Types 3 and 4). In these households, there are often branching pipes from the main connection; therefore, the observed flow rate at one tap is likely only a fraction of the available water.

- **Use based on time.** V_{total} for each household in the survey (n=1801) was calculated as the duration of time households received water at the tap (T_{total}) divided by the number of households sharing a tap (N) and multiplied by the flow rate (Q). V_{stored} was estimated as the reported duration of time households reported filling their containers (T_{stored}) multiplied by the flow rate (Q). The difference between these volumes is the maximum volume of water a household could use directly from the tap; however, households did not necessarily use water for all of the available time. To account for this, a factor A was used to adjust this time based on the activities households reported engaging in after they finished storing water. Households that reported using all of the available water or passing the tap to a neighbor were assigned a value of $A=1$. Households that reported turning the tap off after they finished storing water likely used a fraction of the available time (the low, medium, and high was estimated as an A of 0, .5, and 1, respectively). This calculation also assumes the average flow rates were similar within a household when storing containers or using water directly; therefore, data on flow rates were not required for calculating the UF using this method. UF was then given by

$$UF = \frac{V_{used}}{V_{stored}} = \frac{(Q * \frac{T_{total}}{N} - Q * T_{stored}) * A}{Q * T_{stored}} = \frac{(\frac{T_{total}}{N} - T_{stored}) * A}{T_{stored}} \quad (5.4)$$

5.3.4 Distribution system losses

Unaccounted-for water (UFW) was calculated using a water balance approach, given by

$$UFW = \frac{V_{supply} - V_{consumption}}{V_{supply}} \quad (5.5)$$

Since bulk meters were installed only at the sources, V_{supply} was estimated as the total bulk supply to residential consumers in Hubli and Dharwad (2,535 ML/month) divided by the population of Hubli-Dharwad (943,857). This resulted in an average V_{supply} of 88 LPCD.

$V_{consumption}$ was estimated using the methods presented previously. Additionally, these estimates were compared with $V_{consumption}$ used by the KUWS&DB. The KUWS&DB estimated household unmetered consumption as a minimum of 15 kL/con/mon for normal

connections, 12 kL/con/mon for customers that use their connection only occasionally, 8 kL/con/mon if a household is in a zone with low pressure, and 25 kL/con/mon for public taps. By multiplying each estimate by the percent of connections in that category in the city and dividing by the average number of households sharing a connection (1.8), the average number of people in a household (6.5), and the number of days in a month. Average consumption estimated in this way was 28 LPCD.

5.3.5 Statistical analysis

Water quantity data were log-normal, therefore geometric means were used as the measure of central tendency and performed statistical tests on their rank values. Graphing and data analysis were carried out using R (R Core Team, 2012). Values were considered significant at the $p < 0.05$ level.

5.4 Results and Discussion

Characteristics of the study site, including supply durations, prevalence of meters, and typologies, are presented first to provide context for the results. Next, the triangulated estimates of per person water consumption are presented and discussed. These estimates are then used to understand water consumption and equity of access between households and to estimate distribution system water losses.

5.4.1 System description

In all eight wards during the first-round study period (Nov. 2010-Feb. 2011), the median supply duration was four hours and median days between supply cycles was six days. The utility supplied limited durations of water to small sections of the network rotationally throughout the cities. Supply durations varied within neighborhoods: households connected to a main line often received water for longer periods while areas with differing elevations received water at different pressures.

The volume of water available to taps depends on the duration, frequency, and pressure supplied by the utility (referred to here as allocation). Additionally, households' water access is affected by the number of households sharing a tap and their storage infrastructure. These factors can lead to inequity of water consumption between wards and between households (Fig. 5.1).

Predominant typologies, which reflect the ability of households to collect and store water, varied between wards (Fig. 5.1). In wards 14, 25, and 38, more than half of households had overhead tanks (Type 3 and 4), reducing their vulnerability to fluctuations in the frequency of supply, while in the remaining wards, only 12%-32% of households had overhead tanks (Table 5.1). Wards 16 and 18 had the highest percentages of households categorized as Type 1, representing the most vulnerable households (Fig. 5.1 and Table 5.1).

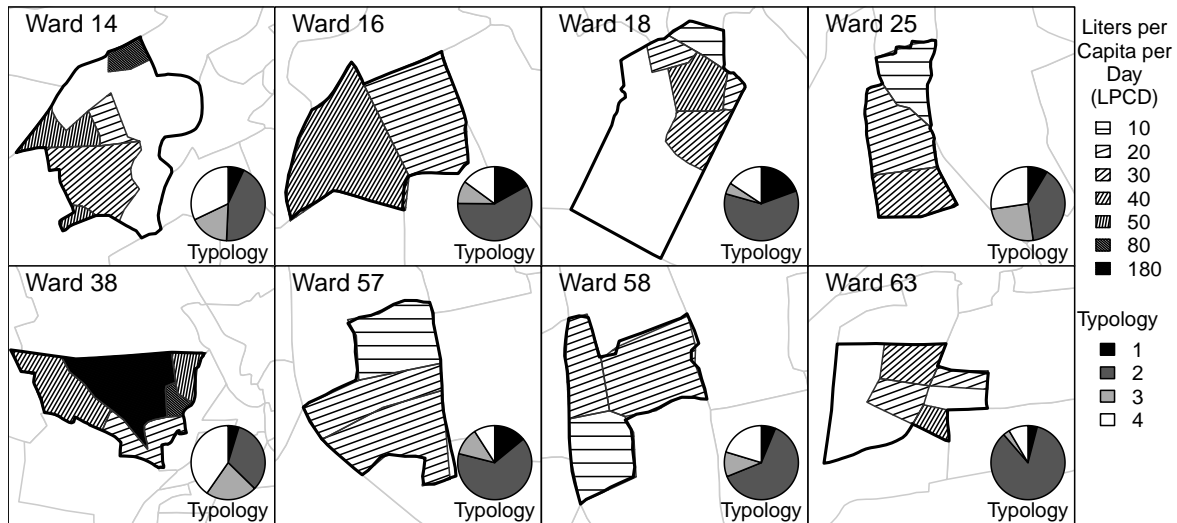


Figure 5.1: Average liters per capita per day (LPCD) based on estimates of storage capacity for each cluster within each ward. Pie charts in the bottom right of each plot show the makeup of each ward based on typology.

The percent of households with functioning meters varied between and within wards and types (Table 5.1). Few Type 1 households had functioning meters (14%), compared to 20% of Types 2 and 3 households and 43% of Type 4 households. Few households in Ward 57 and 58 had functioning meters, while at least a quarter of households in the remaining study wards had meters (Table 5.1).

Table 5.1: Number of surveyed households of each type within each ward. Characteristics include the percent of households sharing a tap, the percent of households with an overhead tank, and the percent of households with a functioning meter by ward and typology.

Type	Ward										Characteristics		
	14	16	18	25	38	57	58	63	Shared Tap %	OH Tank %	Metered %		
1	15	34	47	21	11	34	15	10	99	0	14		
2	94	117	145	96	76	157	151	209	52	0	20		
3	37	20	12	61	52	29	26	7	100	100	20		
4	69	30	38	67	94	22	49	21	0	100	43		
Characteristics													
Shared Tap (%)	39	55	56	55	41	55	46	61					
OH Tank (%)	50	24	21	52	64	21	32	12					
Metered (%)	44	24	42	46	35	4	1	24					

Allocation in Hubli-Dharwad's supply-restricted distribution system could have affected the quantity of water available to households. The geometric mean duration of supply to a connection reported by Type 1 households was 4.8 hr, the longest duration of any typology. Average durations were similar among connections reported by Types 3 and 4 households (4.6 and 4.4 hr, respectively). The average duration among Type 2 households was significantly lower than the other types (4.0 hr) (Wilcoxon Rank-Sum, $p < 0.05$). However, after dividing the hours of supply by the number of households reportedly sharing the tap, the average duration of supply changed substantially: Type 1 households had an average of 36 minutes of access to the tap, while Type 2 had 2.4 hours, Type 3 had 1.6 hours, and Type 4 had 4.4 hours.

Pressure can also play an important role in water availability. Measured pressure in the distribution system varied between wards from 0-35 psi (see Chapter 4). Households attach pumps directly to taps to draw more water, an action that increases flow to that tap but decreases flow to nearby taps. Few Type 1 or Type 2 households had pumps (8% and 22% of households, respectively), though most reported attaching their pump directly to the tap. More than half of Type 3 and 4 households (62% and 77%, respectively), though only half of those with pumps reported attaching them directly to the tap (pumps are also used for filling overhead tanks from underground sumps).

5.4.2 Household Water Consumption

Fig. 5.2 presents data on per capita consumption by typology compared against two metrics of adequate water use. 50 LPCD, the minimum recommended quantity required for humans to meet the needs of drinking, cooking, and basic hygiene, is used to assess whether consumers have access to a minimum quantity of water (Gleick, 1998) (the standard for the minimum water provision through public standposts in India is 40 LPCD (CPHEEO, 1999)). The Indian government sets a design standard of 135 LPCD for a city with Hubli-Dharwad's infrastructure (partial sewerage), which is useful for comparing with the sizing requirements used for planning the distribution system network (CPHEEO, 1999)

5.4.2.1 Storage capacity and metered volumes

Daily per capita consumption varied between typologies, with increased consumption as restrictions on water access decreased (sharing connections with fewer households, larger storage capacity). Type 3 and 4 households had overhead tanks (median volume 900 L per household), resulting in significantly more storage capacity than Types 1 and 2, which had miscellaneous containers (median volume 480 L per household) (Fig. 5.2). Type 1 and 2 households had very limited storage capacities, with median volumes less than the recommended minimum for meeting daily requirements without supplemental water (50 LPCD), while households in Typologies 3 and 4 appear to have storage volumes greater than 50 LPCD (Fig. 5.2). All types had a median storage capacity less than the design standard of 135 LPCD.

Data from meters were available for only three Type 1 households (which made up 11% of the sample population); the remaining types had median metered consumption volumes greater than 50 LPCD, while few households in the sample met design standards of 135 LPCD.

The two estimation methods (measured containers and metered volumes) did not produce statistically different consumption volumes for Type 3 and 4 households. However, estimates of stored volumes for Type 2 households was significantly less than metered volumes (Wilcoxon Rank-Sum, $p < 0.05$) (Fig. 5.2). Despite their differences in storage capacities, Type 2 and 3 households had similar median metered consumption volumes (Fig. 5.2).

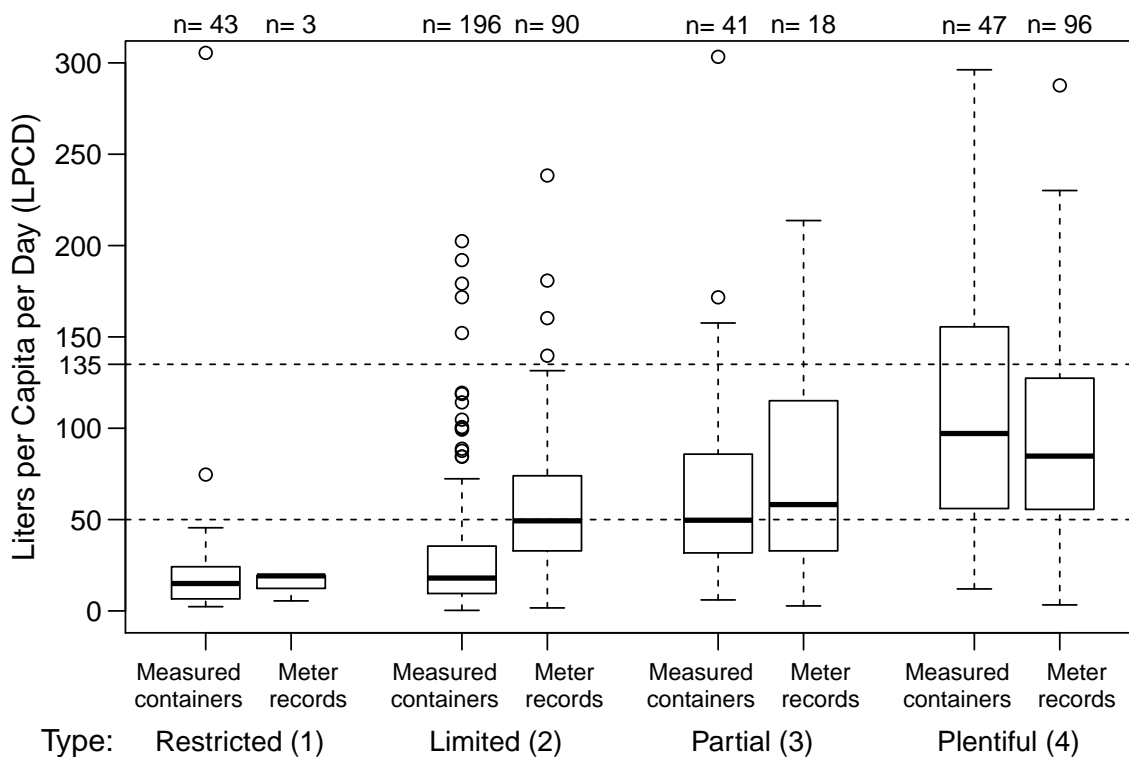


Figure 5.2: Box and whisker plots show the median, lower and upper quartiles, and outliers of liters per capita per day (LPCD), grouped by typology using two measurement methods (storage container measurements and meter records). Horizontal lines at 50 and 135 LPCD, representing guidelines for per capita consumption.

These discrepancies between metered consumption and storage capacity supports our observations that people did water-intensive tasks after filling containers, particularly in households without overhead tanks. This suggests that stored water volumes underestimate total use for households without overhead tanks. To account for these observed patterns of use, stored water estimates were augmented with a use factor (UF), described in the methods section with results presented in the next section.

Table 5.2: Table of water use factors (UF) as a fraction of the total storage capacity using 1) Flow rates and 2) Time at the tap available to households for using water.

Type	1) Flow rate			2) Time at tap		
	low	mean	high	low	med	high
1	-0.8	-0.1	-0.3	0.3	0.4	0.4
2	-0.6	-0.1	0.4	0.4	1.0	1.6
3	-0.9	-0.7	-0.6	0.3	0.7	1.0
4	-0.9	-0.7	-0.6	0.4	1.7	2.9

Some estimates of UF calculated based on flow rate were negative; since flow rates were highly variable and were sampled only several times throughout a supply cycle, the total estimated flow at the tap was sometimes less than the volume added to storage containers. These results also suggest challenges in measuring use in households with overhead tanks (Type 3 and 4) due to several confounding factors identified through structured observations.

Most households with an overhead tank have a branching connection: while the overhead tank fills, another tap is available for use by households. Therefore, flow rates measured at the latter tap can underestimate the total volume of flow. Additionally, since many overhead tanks fill automatically, the duration of time reported by households with overhead tanks for filling storage containers is likely less than the time to fill their total storage capacity, complicating measurements based on time for filling containers.

Calculations based on storage capacity assumed that all tanks were filled completely with each supply cycle. However, since it was observed that large overhead or underground tanks were rarely emptied, storage estimates for overhead and underground tanks may overestimate actual consumption. However, overhead tanks overflowed sometimes for minutes or hours during supply periods, which would result in increased metered consumption but not be accounted for in storage measurements. Additionally, metered data may be inaccurate, as very low flow or low pressure can result in underestimating flow while air bubbles (frequent during the start of supply) can overestimate flow and repeated wetting and drying may damage meters (Criminisi et al., 2009; Totsuka et al., 2004). It appears these confounding factors may cancel out, since metered and storage capacity estimates were statistically similar between Type 3 and Type 4 households (Fig. 5.2). Therefore, given the difficulty of estimating an accurate volume of water used directly from the tap for Type 3 and 4 households and the competing factors affecting estimates of consumption, water consumption was estimated for Type 3 and 4 households using only average storage capacity.

The geometric mean of total average consumption for Type 1 and 2 households is shown in Fig. 5.3. Total consumption was estimated as the sum of the storage capacity and the estimated volume used directly (storage capacity multiplied by the UF). The geometric mean of total consumption for Type 2 households was 24 LPCD (flow method) or 36 LPCD (time method) (Fig. 5.3). Although Type 2 households consume similar volumes of water

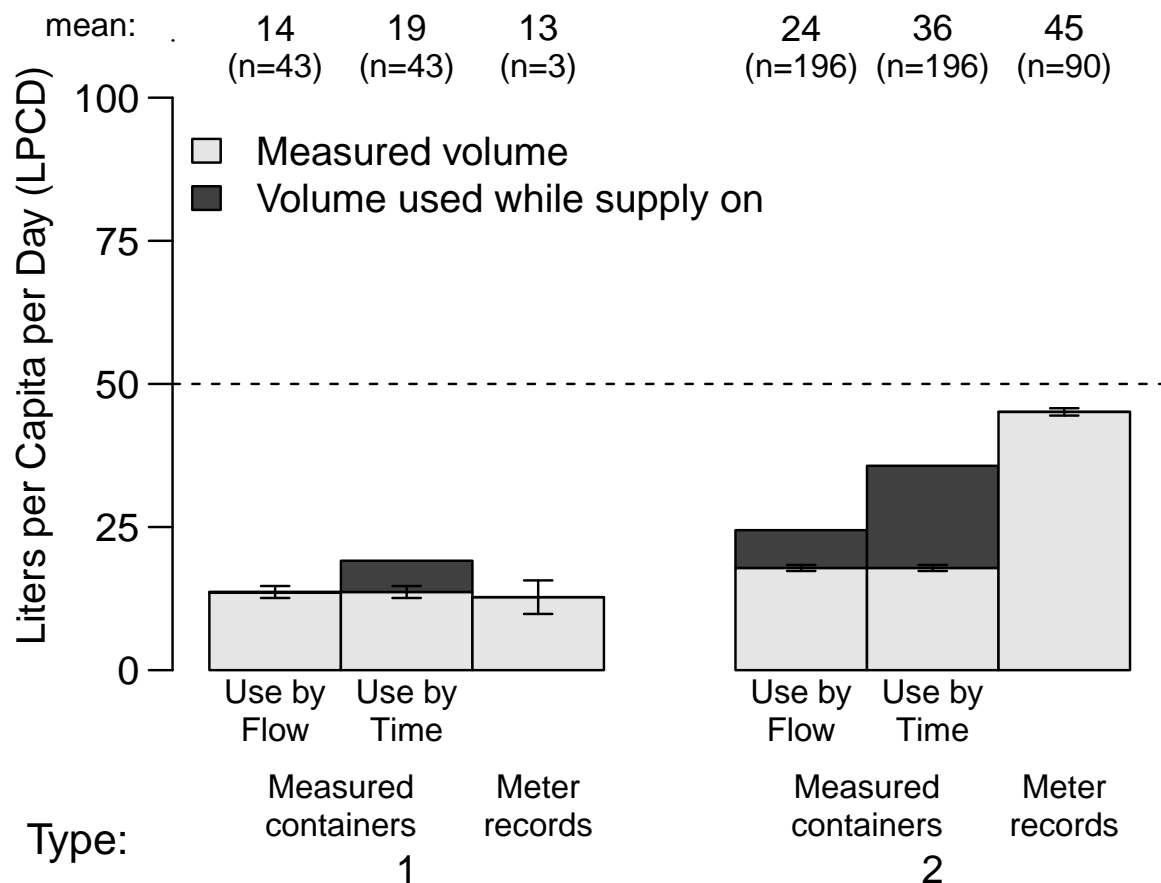


Figure 5.3: The geometric mean of total water consumption for type 2 and 3 households in units of per person per day (LPCD) using two methods of measurements: (1) measured storage volume augmented with an estimate of use while water is on using the mean use by flow rate (Use by Flow) and the medium estimate of use by time (Use by Time) and (2) metered volumes. The geometric mean of consumption volumes and sample sizes are printed above each bar.

as Type 3 households, these results suggest that the timing of that use is different. Lack of an overhead tank imposes coping costs on Type 2 households, which instead must wait until supply periods to wash accumulated clothes and dishes. Type 1 households, which differ from Type 2 households in their access to the tap, have limited ability to use water due to their restricted access, restricting their overall municipal water consumption. Since only three Type 1 households were metered, the storage capacity and use estimates may more accurately reflect consumption, which was 14 LPCD (flow method) or 19 LPCD (time method).

As noted previously, our calculations assume that containers were empty when the supply

cycle began and were re-filled completely during each supply cycle. However, it was observed that some water remains in measured containers, which is then used for non-essential tasks such as flushing out gutters once water is delivered at the tap. Overall, 17% of households reported throwing the remaining water away and 10% of households reported having no extra water, while the remaining households used the water for chores or gardening. Additionally, these estimates omitted containers that reportedly contained water from non-municipal sources. While borewell water is an important supplementary source for many residents of Hubli-Dharwad, they were excluded from this analysis since this focused on access to municipal treated pipe water.

After they finished filling their containers and using the water, 28% of users reported passing their tap on to another household, 16% of households reported using all of the available water from their tap, 56% reported turning the tap off, and only four households reported leaving it on (n=1951). This gives us a sense of how many households were water-limited or sharing-limited, and how many can access all the water they want or need.

5.5 Water losses

5.6 Distribution system losses

The volume of supply per person per day was estimated as 88 LPCD (described in the methods section); while this is likely different for each ward due to varying pressures and durations, detailed data for each ward were not available.

Three methods of estimating consumption are demonstrated here to assess the results they produce in UFW, with three wards selected to demonstrate as examples. These methods include estimates based on metered data, storage capacity combined with the use factor, and the estimates used by the KUWS&DB (described in the methods section).

For methods involving calculations based on typology, the geometric mean of the total water consumption for each person per day uses the storage capacity for total water consumption among Type 3 and 4 households (45.5 and 90.6 LPCD, respectively), while the sum of the storage capacity and the estimated use based on time at the tap were used for Type 1 and 2 households (19.1 and 35.7 LPCD, respectively).

Unaccounted-for-water (UFW) was calculated with these data sources using five models (Table 5.3).

- Model 1 (Typology): Total water consumption estimated using storage capacity and direct use for each type multiplied by the percent of each household type in each ward.
- Model 2 (Metered): Average of only metered data for each ward.
- Model 3 (Utility): 28 LPCD (explained in the methods).

Table 5.3: Monthly consumption (Con) in liters per capita per day (LPCD) in Ward 25, 38, and 57 and unaccounted-for water (UFW) estimates using five models.

Model	Ward 25		Ward 38		Ward 57	
	Con	UFW	Con	UFW	Con	UFW
	LPCD	%	LPCD	%	LPCD	%
1. Typology	52	41	59	33	40	55
2. Metered	51	43	70	20	28	68
3. Utility	28	68	28	68	28	68
4. Metered and Typology	46	48	56	36	37	58
5. Metered and Utility	38	57	43	52	28	68

- Model 4 (Metered and Typology): The sum of the average of the metered data multiplied by the percent of the ward with functioning meters and the consumption using the same method as Model 1 multiplied by the percent of the ward without meters.
- Model 5 (Metered and Utility): The sum of metered data multiplied by the percent of the ward with functioning meters and the 28 LPCD multiplied by the percent of the ward without meters.

An estimated 46%, 35%, and 4% of connections were metered in Wards 25, 38, and 57, respectively. Estimated losses in Ward 25, where nearly half of connections were metered, ranged from 41-68%. In Ward 38, which had fewer meters, losses were lower (20-68%). In Ward 57, which has few meters, estimated losses ranged from 55-68%.

These results suggest that our estimates based on measured storage capacity and direct use were similar to estimates for unmetered use by connection used by the KUWS&DB. They also suggest that there may be higher losses in Wards 57 and 25 than in Ward 38; ward-level data on losses could help the utility target loss reduction strategies within the cities. However, there are several sources of uncertainty in this calculation. In particular, the estimate of the volume of supply likely varies between wards. Improving the accuracy of data on supply to sub-sections by measuring flow rate or installing meters could improve estimates of water loss per ward and help the utility target and prioritize loss reduction strategies.

The UFW in the distribution system estimated using any of the methods is high. In industrialized countries, average physical losses are 12%, compared to estimates of non-revenue water in developing country cities of 35%, with an estimated 60% of these as physical losses (Kingdom et al., 2006). The average unaccounted-for water in the three studied wards was more than 50% of water input to the distribution system.

5.7 Conclusions and Policy Implications

This chapter presented new methods of estimating water consumption in unmetered households with IWS by measuring storage containers and estimating direct use during supply through unstructured observations and survey data. The resulting estimates of per capita water consumption were similar to data obtained through meters within typologies stratified along a water scarcity gradient. Therefore, if metered data exist for some households, it may be reasonable to extrapolate to other households within typologies. Alternatively, if no metered data are available, the methods presented here may provide insight into water access, consumption, and losses.

Increased understanding of how much water is being used can illuminate inequities embedded in existing urban water infrastructure and support utilities in crafting policies that increase equity in water access. Overall, per capita water availability was low and there were substantial disparities in the quantity of water households accessed. In particular, households who shared a tap with many others and had limited storage capacity (Type 1) used very little water (< 50 LPCD), while hardly any households are using the design value of 135 LPCD. Households with overhead tanks are, on average, using less water than the design value.

Additionally, the quantity of water used directly from the tap without storage varied between typologies. Type 2 households, which lacked an overhead tank but had more access to a tap, used the most water during supply; therefore, households that received very limited amounts of water (Type 1) were not necessarily limited because of unequal supply duration by the utility but rather by access to time at the tap and storage capacity. Strategies to improve equity in access to water could include reducing the number of households sharing a tap, providing longer durations of supply to geographic areas that are particularly constrained, or increase households' storage capacity. To accomplish this, it may be possible to approximate the methods presented in this chapter to better understand equity of access in a system and adjust supply durations that improve access to all households.

The relative importance of losses at different scales (utility vs. household) is often debated (McIntosh, 2003). More than half of water was lost in the distribution system in Hubli-Dharwad and that most households were consuming - and therefore wasting - very little water. Reducing losses in the distribution system could significantly increase available water.

Chapter 6

Conclusions

The previous chapters examined how intermittently supplied piped water impacted the quality and quantity of water delivered to residential taps in Hubli-Dharwad, India. This thesis showed that the intermittent supply was frequently subject to contamination in the distribution system and that households with intermittent supply consumed limited quantities of water. While this thesis also demonstrated that converting to a continuous water supply can improve water quality when compared to intermittent supply, this conversion may not be possible in the near future for resource-constrained towns and cities. Therefore, expanding knowledge of the mechanisms causing contamination and constricting water access can inform strategies that improve the current intermittent systems. The major contributions of this research are:

- Compared microbial water quality between an intermittent and a continuous distribution system.
 - Detected more contamination by indicator bacteria at taps provided intermittently compared to those provided with continuous supply, providing evidence that continuous supply does provide the expected benefits to water quality.
 - Improved understanding of water quality deterioration along the distribution system from the water treatment plant to consumer taps and identified seasonal and geographic differences.
 - Identified sub-sections of the intermittent distribution system that provided water of similar quality to that in the continuous system. This suggests that there may be opportunities to improve water quality in the intermittent system.
 - Quantified the negative impact of household storage on water quality in both the intermittent and continuous systems.
- Improved understanding and found evidence of the mechanisms affecting microbial water quality in intermittently supplied piped water distribution systems.

- Critically reviewed the existing knowledge of mechanisms affecting water quality in IWS systems.
 - Documented water quality in an IWS throughout the supply cycle to track temporal variation, particularly the effect of flushing when supply was first turned on.
 - Quantified the relationship between pressure, chlorine, and indicator bacteria in an intermittent supply to provide insight into minimum pressures required for preventing intrusion or backflow during supply.
 - Detected evidence of contamination in an IWS system and identified mechanisms that may have caused the observed contamination.
- Developed methods of measuring water consumption in unmetered households with intermittent supply and used these estimates to understand equity of water access and distribution system losses.
 - Triangulated estimates of household water consumption by measuring both volumes stored and volumes used directly during supply. These estimates were compared with data from meters.
 - Estimated the volume of water available to households and compared these with recommended standards, finding that some households received far less than minimum recommendations.
 - Compared the scale of losses in distribution system to that in households to demonstrate the utility of these new methods and contributed evidence to the debate over whether water loss in intermittent systems occurs in distribution networks or at households.

While this research does not recommend IWS as a mode of operation, these systems currently provide water to hundreds of millions of people. This thesis expanded knowledge of the mechanisms through which IWS affects the quality and quantity of water available to residents. The site studied in this thesis represents an example of severe intermittency, which was useful for demonstrating the most extreme effects of IWS.

The results discussed the previous chapters suggest that it is possible to develop strategies that incrementally improve the safety and sufficiency of intermittently delivered water. For example, introducing programs that flush pipes after supply is first turned on, targeted increases in pressure to areas in networks with persistent low pressure, and maintaining chlorine residual throughout the network would be expected to improve tap water quality, though additional research is required to design such interventions. There is a clear need to improve data collection within the studied system and in other intermittent systems, as there is little data currently available. In particular, water quality and quantity data from systems with less extreme intermittency (more frequent and longer supply durations) could help explain mechanisms affecting water quality that were not possible to identify in this

study site (e.g. causes of periodic contamination) and investigate whether increased supply frequency or duration could improve water quality or equity. An additional challenge that was not studied in this thesis is how reliability and predictability of water delivery can affect water quality and quantity.

Scale-up of continuous water supply can be improved in Hubli-Dharwad and in other Indian cities considering the conversion. Future implementations should include strategies that eliminate household water storage. Identifying the causes of the observed periodic contamination in the continuous supply network can also help ensure that this conversion achieves the maximum possible benefits. While the site examined in this thesis achieved continuous supply by replacing the distribution network and converting directly to continuous supply, there may be alternative paths, such as continuous supply without improvements in infrastructure or increment increases in supply durations.

Intermittent piped water supply is currently a common and important service providing water to people throughout low- and middle-income countries, underscoring the need to study how systems currently function and develop effective and efficient strategies that improve their service to residents. Expanding knowledge of how these systems function and the mechanisms through which they affect water at residential taps can help to ensure that people with piped water receive water that is reliable, safe, and sufficient.

Bibliography

- Abu Amr, S. S. and M. M. Yassin (2008). “Microbial contamination of the drinking water distribution system and its impact on human health in Khan Yunis Governorate, Gaza Strip: Seven years of monitoring (2000-2006)”. *Public Health* 122.11, pp. 1275–1283.
- Ainsworth, R. (2004). *Safe piped water: Managing microbial water quality in piped distribution systems*. World Health Organization.
- Al-Ghamdi, A. S. and S. A. Gutub (2002). “Estimation of leakage in the water distribution network of the Holy City of Makkah”. *Journal of Water Supply Research and Technology-Aqua* 51.6, pp. 343–349.
- Alegre, H., W. Hirner, J. Baptista, and R. Parena (July 2000). *Performance Indicators for Water Supply Services*. IWA Manual of Best Practice. International Water Association.
- Anderson, M. and C. T. Braak (2003). “Permutation tests for multi-factorial analysis of variance”. *Journal of Statistical Computation and Simulation* 73.2, pp. 85–113.
- Andey, S. P. and P. S. Kelkar (2009). “Influence of Intermittent and Continuous Modes of Water Supply on Domestic Water Consumption”. *Water Resources Management* 23.12, pp. 2555–2566.
- Andey, S. and P. Kelkar (2007). “Performance of water distribution systems during intermittent versus continuous water supply”. *Journal American Water Works Association* 99.8, pp. 99–106.
- Annuk, H. and A. P. Moran (2010). “Chapter 39 - Microbial biofilm-related polysaccharides in biofouling and corrosion”. *Microbial Glycobiology*. Ed. by O. Holst, P. J. Brennan, P. J. B. Mark von Itzstein, A. Otto Holst, and M. von Itzstein. San Diego: Academic Press, pp. 781–801.
- Antoun, E. N., J. E. Dyksen, and D. J. Hildebrand (1999). “Unidirectional flushing: a powerful tool”. *Journal American Water Works Association* 91.7, pp. 62–71.
- AWWA (2003). *Water Transmission and Distribution*. Denver, CO: American Water Works Association.
- AWWA (2011). *Internal Corrosion Control in Water Distribution Systems*. en. American Water Works Association.
- Banerjee, S. G. and E. Morella (2011). *Africa's Water and Sanitation Infrastructure: Access, Affordability, and Alternatives*. Tech. rep. Washington, D.C.: World Bank.

- Barbeau, B., V. Gauthier, K. Julienne, and A. Carriere (2005). "Dead-end flushing of a distribution system: Short and long-term effects on water quality". *Journal of Water Supply Research and Technology-Aqua* 54.6, pp. 371–383.
- Barwick, R. S., A. Uzicanin, S. Lareau, N. Malakmadze, P. Imnadze, M. Iosava, N. Ninashvili, M. Wilson, A. W. Hightower, S. Johnston, H. Bishop, W. A. Petri, and D. D. Juranek (2002). "Outbreak of amebiasis in Tbilisi, Republic of Georgia, 1998". *American Journal of Tropical Medicine and Hygiene* 67.6, pp. 623–631.
- Basualdo, J., B. Pezzani, M. De Luca, A. Cordoba, and M. Apezteguia (2000). "Screening of the municipal water system of La Plata, Argentina, for human intestinal parasites". *International Journal of Hygiene and Environmental Health* 203.2, pp. 177–182.
- Batish, R. (2003). "A New Approach to the Design of Intermittent Water Supply Networks". *World Water and Environmental Resources Congress 2003*. Philadelphia, PA, USA: ASCE, pp. 1–11.
- Benjamin, B. (1967). "Gravity currents and related phenomena". *Journal of Fluid Mechanics* 31.2, pp. 209–248.
- Besner, M. C., J. Lavoie, C. Morissette, P. Payment, and M. Prevost (2008). "Effect of water main repairs on water quality". *Journal American Water Works Association* 100.7, pp. 95–109.
- Besner, M.-C., M. Prevost, and S. Regli (2011). "Assessing the public health risk of microbial intrusion events in distribution systems: Conceptual model, available data, and challenges". *Water Research* 45.3, pp. 961–979.
- Besner, M.-C., P. Servais, and M. Prevost (2008). "Efficacy of Disinfectant Residual on Microbial Intrusion: A Review of Experiments". *Journal American Water Works Association* 100.10, pp. 116–130.
- Besner, M.-C., R. Broseus, J. Lavoie, G. D. Giovanni, P. Payment, and M. Prevost (2009). "Pressure Monitoring and Characterization of External Sources of Contamination at the Site of the Payment Drinking Water Epidemiological Studies". *Environmental Science & Technology* 44.1, pp. 269–277.
- Besner, M., G. Ebacher, B. Jung, B. Karney, J. Lavoie, P. Payment, and M. Prvost (2010). "Negative pressures in full-scale distribution system: field investigation, modelling, estimation of intrusion volumes and risk for public health". *Drinking Water Engineering and Science* 3, pp. 101–106.
- Betanzo, E. W., R. Hofmann, Z. F. Hu, H. Baribeau, and Z. Alam (2008). "Modeling the impact of microbial intrusion on secondary disinfection in a drinking water distribution system". *Journal of Environmental Engineering-ASCE* 134.4, pp. 231–237.
- BIS (2004). *Drinking Water Standards IS 10500*. Tech. rep. Bureau of Indian Standards.
- Boulos, P. F., W. M. Grayman, R. W. Bowcock, J. W. Clapp, L. A. Rossman, R. M. Clark, R. A. Deininger, and A. K. Dhingra (1996). "Hydraulic mixing and free chlorine residual in reservoirs". *Journal American Water Works Association* 88.7, pp. 48–59.
- Boulos, P. F., B. W. Karney, D. J. Wood, and S. Lingireddy (2005). "Hydraulic transient guidelines for protecting water distribution systems". *Journal American Water Works Association* 97.5, pp. 111–124.

- Boxall, J. and A. Saul (2005). "Modeling Discoloration in Potable Water Distribution Systems". *Journal of Environmental Engineering* 131.5, pp. 716–725.
- Boyd, G. R., H. Wang, M. D. Britton, D. C. Howie, D. J. Wood, J. E. Funk, and M. J. Friedman (2004). "Intrusion within a simulated water distribution system due to hydraulic transients. I: Description of test rig and chemical tracer method". *Journal of Environmental Engineering-Asce* 130.7, pp. 774–777.
- Carpenter, A. (1875). "The Fever at Croydon: And Intermittent Water-Supply as a Cause of Typhoid". *British Medical Journal* 2.777, pp. 632–635.
- Cartier, C., M. C. Besner, B. Barbeau, J. Lavoie, R. Desjardins, and M. Prevost (2009). "Evaluating aerobic endospores as indicators of intrusion in distribution systems". *Journal American Water Works Association* 101.7, pp. 46–58.
- Cerrato, J. M. (2005). "Impact of Piping Materials on Water Quality in Tegucigalpa, Honduras". PhD thesis. Virginia Polytechnic Institute and State University.
- Cerrato, J. M., L. P. Reyes, C. N. Alvarado, and A. M. Dietrich (2006). "Effect of PVC and iron materials on Mn(II) deposition in drinking water distribution systems". *Water Research* 40.14, pp. 2720–2726.
- CGWB (2008). *Groundwater Information Booklet: Dharwad District, Karnataka*. Tech. rep. Bangalore: Government of India Ministry of Water Resources Central Groundwater Board.
- Chadderton, R. A., G. L. Christensen, and P. Henryunrath (1993). "Planning a Distribution-System Flushing Program". *Journal American Water Works Association* 85.7, pp. 89–94.
- Choe, K., R. Varley, and H. Bilani (1996). *Coping with Intermittent Water Supply: Problems and Prospects, Environmental Health Project*. Tech. rep. Washington, DC: USAID.
- Choi, Y and E E (2003). "Monitoring biofilm detachment under dynamic changes in shear stress using laser-based particle size analysis and mass fractionation". *Water Science & Technology* 47.5, pp. 69–76.
- Christodoulou, S. and A. Agathokleous (2012). "A study on the effects of intermittent water supply on the vulnerability of urban water distribution networks". *Water Science & Technology: Water Supply* 12.4, p. 523.
- Clark, R. and W. Grayman (1998). *Modeling Water Quality in Drinking Water Distribution Systems*. Denver: American Water Works Association.
- CMDR (2006). *Socio Economic Survey of Hubli Dharwad City*. Tech. rep. Dharwad: Center for Multi-Disciplinary Development Research.
- Codony, F., J. Morat, and J. Mas (2005). "Role of discontinuous chlorination on microbial production by drinking water biofilms". *Water Research* 39.9, pp. 1896–1906.
- Coelho, S., S. James, N. Sunna, A. A. Jaish, and J. Chatila (2003). "Controlling water quality in intermittent supply systems". *Water Science and Technology: Water Supply* 3.1-2, pp. 119–125.
- Cordoba, M. A., V. F. D. Coco, M. C. Minvielle, and J. A. Basualdo (2010). "Influencing factors in the occurrence of injured coliforms in the drinking water distribution system in the city of La Plata, Argentina". *Journal of Water and Health* 08.2.

- CPHEEO (1999). *Manual on Water Supply and Treatment*. Tech. rep. New Delhi: Ministry of Urban Development, Government of India.
- Craun, G. F., N. Nwachuku, R. L. Calderon, and M. F. Craun (2002). “Outbreaks in drinking-water systems, 1991-1998”. *Journal of Environmental Health* 65.1, pp. 16–23.
- Craun, G. F., J. M. Brunkard, J. S. Yoder, V. A. Roberts, J. Carpenter, T. Wade, R. L. Calderon, J. M. Roberts, M. J. Beach, and S. L. Roy (2010). “Causes of Outbreaks Associated with Drinking Water in the United States from 1971 to 2006”. *Clinical Microbiology Reviews* 23.3, pp. 507–528.
- 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 Science & Technology* 60.9, p. 2373.
- CSE (2012). *The waste-water portrait: Karnataka: Hubli-Dharwad*. Delhi, India: Center for Science and Environment.
- Dasgupta, P. and R. Dasgupta (2004). “Economic value of safe water for the infrastructurally disadvantaged urban household: A case study in Delhi, India”. *Water Resources Research* 40.
- De Marchis, M., C. M. Fontanazza, G. Freni, G. La Loggia, E. Napoli, and V. Notaro (2010). “A model of the filling process of an intermittent distribution network”. *Urban Water Journal* 7.6, pp. 321–333.
- Derlon, N., A. Mass, R. Escudi, N. Bernet, and E. Paul (Apr. 2008). “Stratification in the cohesion of biofilms grown under various environmental conditions”. *Water Research* 42.89, pp. 2102–2110.
- Desai, S., A. Dubey, B. Joshi, M. Sen, A. Shariff, and R. Vanneman (2007). *India Human Development Survey (IHDS)*. ICPSR22626-v2.
- DOH (2009). *Water System Design Manual*. Tech. rep. Olympia, WA: Washington State Department of Health.
- Douterelo, I., R. Sharpe, and J. Boxall (2013). “Influence of hydraulic regimes on bacterial community structure and composition in an experimental drinking water distribution system”. *Water Research* 47.2, pp. 503–516.
- Dutta, V., S. Chander, and L. Srivastava (2005). “Public support for water supply improvements: empirical evidence from unplanned settlements of Delhi, India”. *Journal of Environment & Development* 14.4, pp. 439–462.
- Ebacher, G., M. Besner, B. Clment, and M. Prvost (Sept. 2012). “Sensitivity analysis of some critical factors affecting simulated intrusion volumes during a low pressure transient event in a full-scale water distribution system”. *Water Research* 46.13, pp. 4017–4030.
- Edwards, J. and J. Maher (2008). “Water quality considerations for distribution system storage facilities”. *Journal American Water Works Association* 100.7.
- Egorov, A., T. Ford, A. Tereschenko, N. Drizhd, I. Segedevich, and V. Fourman (2002). “Deterioration of drinking water quality in the distribution system and gastrointestinal morbidity in a Russian city”. *International Journal of Environmental Health Research* 12.3, pp. 221–233.

- Elala, D., P. Labhassetwar, and S. F. Tyrrel (2011). "Deterioration in water quality from supply chain to household and appropriate storage in the context of intermittent water supplies". *Water Science & Technology: Water Supply* 11.4, p. 400.
- EPA (2002a). *Health Risks from Microbial Growth and Biofilms in Drinking Water Distribution Systems*. Tech. rep. EPA Office of Ground Water and Drinking Water.
- EPA (2002b). *Potential Contamination Due to Cross-Connections and Backflow and the Associated Health Risks*. Tech. rep. EPA's Office of Ground Water and Drinking Water.
- EPA (2003). *Cross-Connection Control Manual*. Tech. rep. Office of Water Office of Ground Water and Drinking Water.
- EPA (2005). *Finished Water Storage Facilities*. Tech. rep. Washington, D.C.: EPA Office of Water.
- Eshcol, J., P. Mahapatra, and S. Keshapagu (2009). "Is fecal contamination of drinking water after collection associated with household water handling and hygiene practices? A study of urban slum households in Hyderabad, India". *Journal of Water and Health* 7.1, pp. 145–154.
- Francisque, A., M. J. Rodriguez, L. F. Miranda-Moreno, R. Sadiq, and F. Proulx (2009). "Modeling of heterotrophic bacteria counts in a water distribution system". *Water Research* 43.4, pp. 1075–1087.
- Gadgil, A. (1998). "Drinking water in developing countries". *Annual Review of Energy and the Environment* 23, pp. 253–286.
- Gauthier, V., B. Grard, J.-M. Portal, J.-C. Block, and D. Gatel (1999). "Organic matter as loose deposits in a drinking water distribution system". *Water Research* 33.4, pp. 1014–1026.
- Geldreich, E. (1996). *Microbial Quality of Water Supply in Distribution Systems*. Boca Raton: CRC Lewis Publishers.
- Gibbs, S. G., M. C. Meckes, and P. V. Scarpino (2003). "The effect of long-term wastewater cross-connection on the biofilm of a simulated water distribution system". *Journal of Environmental Engineering and Science* 2.2, pp. 85–98.
- Gleick, P. (1998). "The human right to water". *Water Policy* 1.5, pp. 487–503.
- Grayman, W. M., L. A. Rossman, R. A. Deininger, C. D. Smith, C. N. Arnold, and J. F. Smith (2004). "Mixing and aging of water in distribution system storage facilities". *Journal American Water Works Association* 96.9.
- Greyvenstein, B. and J. E. van Zyl (2007). "An experimental investigation into the pressure-leakage relationship of some failed water pipes". *Journal of Water Supply Research and Technology-Aqua* 56.2, pp. 117–124.
- Gullick, R. W., M. Lechevallier, R. Svindland, and M. Friedman (2004). "Occurrence of transient low and negative pressures in distribution systems". *Journal American Water Works Association* 96.11, pp. 52–66.
- Gullick, R. W., M. W. LeChevallier, J. Case, D. J. Wood, J. E. Funk, and M. J. Friedman (2005). "Application of pressure monitoring and modelling to detect and minimize low pressure events in distribution systems". *Journal of Water Supply Research and Technology-Aqua* 54.2, pp. 65–81.

- Hallam, N., J. West, C. Forster, and J Simms (2001). "The potential for biofilm growth in water distribution systems". *Water Research* 35.17, pp. 4063–4071.
- Hayes, C. (2012). *Internal Corrosion Control of Water Supply Systems: Code of Practice*. IWA Publishing.
- He, X. Q., L. Cheng, D. Y. Zhang, W. Li, X. M. Xie, M. Ma, and Z. J. Wang (2009). "First Molecular Detection of Group A Rotaviruses in Drinking Water Sources in Beijing, China". *Bulletin of Environmental Contamination and Toxicology* 83.1, pp. 120–124.
- Herson, D. S., B. McGonigle, M. A. Payer, and K. H. Baker (1987). "Attachment as a factor in the protection of *Enterobacter cloacae* from chlorination." en. *Applied and Environmental Microbiology* 53.5, pp. 1178–1180.
- Hooper, S. M., C. L. Moe, J. G. Uber, and K. A. Nilsson (2006). "Assessment of microbiological water quality after low pressure events in a distribution system". *Proceedings of the 8th Annual Water Distribution Systems Analysis Symposium*. Cincinnati, OH.
- Hunter, P. R., R. M. Chalmers, S. Hughes, and Q. Syed (2005). "Self-reported diarrhea in a control group: a strong association with reporting of low-pressure events in tap water". *Clinical Infectious Diseases* 40, pp. 32–34.
- Husband, P. and J. Boxall (2011). "Asset deterioration and discolouration in water distribution systems". *Water Research* 45.1, pp. 113–124.
- Husband, P., J. Boxall, and A. Saul (2008). "Laboratory studies investigating the processes leading to discolouration in water distribution networks". *Water Research* 42.16, pp. 4309–4318.
- Husband, S. and J. B. Boxall (2010). "Field Studies of Discoloration in Water Distribution Systems: Model Verification and Practical Implications". *Journal of Environmental Engineering* 136.1, pp. 86–94.
- IMD. *District Rainfall (mm.) for Last Five Years*. Tech. rep. India Meteorological Department Hydromet Division. URL: www.imd.gov.in/section/hydro/distrainfall/webra/in/karnataka/dharwad.txt (visited on 01/14/2013).
- India, R. G. of (2011). *Census of India 2011: Karnataka: Dharwad District*. Tech. rep. New Delhi: Registrar General of India. URL: <http://censusindia.gov.in>.
- Ingeduld, P., A. Pradhan, Z. Svitak, and A. Terrai (2006). "Modeling Intermittant Water Supply Systems with EPANET". *8th Annual Water Distribution Systems Analysis Symposium*. Cincinnati, Ohio: August 27-30, 2006.
- Ismail, Z. and W. Puad (2007). "Non-Revenue Water Losses: A Case Study". *Asian Journal of Water, Environment and Pollution* 4.2, pp. 113–117.
- Jacobs, H. E., J. L. Strijdom, et al. (2009). "Evaluation of minimum residual pressure as design criterion for South African water distribution systems". *Water SA* 35.2, pp. 183–191.
- Jagals, P, T. Bokako, and W. Grabow (1999). "Changing consumer water-use patterns and their effect on microbiological water quality as a result of an engineering intervention". *Water SA* 25.3, pp. 297–300.

- Jakopanec, I., K. Borgen, L. Vold, H. Lund, T. Forseth, R. Hannula, and K. Nygard (2008). "A large waterborne outbreak of campylobacteriosis in Norway: The need to focus on distribution system safety". *BMC Infectious Diseases* 8.128.
- Jeffcoate, P. and A. Saravanapavan (1987). *The Reduction and Control of Unaccounted-for Water*. Tech. rep. Washington, DC: World Bank.
- Kandra, H. S., R. K. Johri, and A. Kapur (2004). "Water auditing tracking unaccounted-for water in Delhi, India". *Waterlines* 22.3, pp. 19–21.
- Karim, M. R., M. Abbaszadegan, and M. Lechevallier (2003). "Potential for pathogen intrusion during pressure transients". *Journal American Water Works Association* 95.5, pp. 134–146.
- Karney, B. W. and Y. R. Filion (2003). "Energy Dissipation Mechanisms in Water Distribution Systems". ASME, pp. 2771–2778.
- Kelkar, P. S., S. P. Andey, S. K. Pathak, and K. G. Nimbalkar (2002). "Evaluation of water distribution system for water consumption, flow pattern and pressure survey during intermittent vis-a-vis continuous water supply in Panaji City". *Journal of Indian Water Works Association* 34.1, pp. 27–36.
- Kerneis, A., F. Nakache, A. Deguin, and M. Feinberg (1995). "The effects of water residence time on the biological quality in a distribution network". *Water Research* 29.7, pp. 1719–1727.
- Kim, M., S. H. Yoon, P. A. Domanski, and W. Vance Payne (2008). "Design of a steady-state detector for fault detection and diagnosis of a residential air conditioner". *International Journal of Refrigeration* 31.5, pp. 790–799.
- Kingdom, B., R. Liemberger, and P. Marin (2006). *The Challenge of Reducing Non-Revenue Water (NRW) in Developing Countries*. Tech. rep. World Bank.
- Kirmeyer, G. J., M. Friedman, K. Martel, D. Howie, M. LeChevallier, M. Abbaszadegan, M. Karim, J. Funk, and J. Harbour (2001a). *Pathogen Intrusion into the Distribution System*. Tech. rep. Denver, CO: AWWARF.
- Kirmeyer, G. J., M. Friedman, K. D. Martel, P. F. Noran, and D. Smith (2001b). "Practical guidelines for maintaining distribution system water quality". *Journal American Water Works Association* 93.7, pp. 62–73.
- Kjellen, M. (2006). "From Public Pipes to Private Hands : Water Access and Distribution in Dar es Salaam, Tanzania". PhD thesis. Stockholm University.
- Korfali, S. I. and M. Jurdi (2007). "Assessment of domestic water quality: case study, Beirut, Lebanon". *Environmental Monitoring and Assessment* 135.1-3, pp. 241–251.
- Kudat, A., M. Bell, J. Boland, F. Humplick, S. Madanat, and N. Mukherjee (1993). *Reliability of Urban Water Supply in Developing Countries: The Emperor Has No Clothes*. Tech. rep. Washington, DC: The World Bank.
- Lambertini, E., M. A. Borchardt, B. A. Kieke, S. K. Spencer, and F. J. Loge (2012). "Risk of Viral Acute Gastrointestinal Illness from Nondisinfected Drinking Water Distribution Systems". *Environmental Science & Technology* 46.17, pp. 9299–307.

- Lautenschlager, K., N. Boon, Y. Wang, T. Egli, and F. Hammes (2010). "Overnight stagnation of drinking water in household taps induces microbial growth and changes in community composition". *Water Research* 44.17, pp. 4868–4877.
- LeChevallier, M., M. Karim, R. Aboytes, R. W. Gullick, J. Weihe, B. Earnhardt, J. Mohr, J. Starceovich, J. Case, J. Rosen, J. Sobrinho, J. L. Clancy, R. McCuin, J. Funk, and D. J. Wood (2004). *Profiling Water Quality Parameters: From Source Water to the Household Tap*. Denver, CO: AWWA.
- LeChevallier, M., R. Gullick, M. Karim, M. Friedman, and J. Funk (2003). "The potential for health risks from intrusion of contaminants into the distribution system from pressure transients". *Journal of Water and Health* 1.1, pp. 3–14.
- LeChevallier, M., N. Welch, and D. Smith (1996). "Full-scale studies of factors related to coliform regrowth in drinking water". *Appl. Environ. Microbiol.* 62.7, pp. 2201–2211.
- Lee, D. G., S. J. Kim, and S. J. Park (2006). "Effect of reservoirs on microbiological water qualities in a drinking water distribution system". *Journal of Microbiology and Biotechnology* 16.7, pp. 1060–1067.
- Lee, E. J. and K. J. Schwab (2005). "Deficiencies in drinking water distribution systems in developing countries". *Journal of Water and Health* 3.2, pp. 109–127.
- Lehtola, M. J., T. K. Nissinen, I. T. Miettinen, P. J. Martikainen, and T. Vartiainen (2004). "Removal of soft deposits from the distribution system improves the drinking water quality". *Water Research* 38.3, pp. 601–610.
- Lehtola, M. J., M. Laxander, I. T. Miettinen, A. Hirvonen, T. Vartiainen, and P. J. Martikainen (2006). "The effects of changing water flow velocity on the formation of biofilms and water quality in pilot distribution system consisting of copper or polyethylene pipes". *Water Research* 40.11, pp. 2151–2160.
- Levy, K., K. L. Nelson, A. Hubbard, and J. N. S. Eisenberg (2008). "Following the Water: A Controlled Study of Drinking Water Storage in Northern Coastal Ecuador". *Environmental Health Perspectives* 116.11, pp. 1533–1540.
- Lindley, T. R. and S. G. Buchberger (2002). "Assessing intrusion susceptibility in distribution systems". *Journal American Water Works Association* 94.6.
- Manuel, C., O. Nunes, and L. Melo (2007). "Dynamics of drinking water biofilm in flow/non-flow conditions". *Water Research* 41.3, pp. 551–562.
- Mays, L. (2000). *Water Distribution Systems Handbook*. New York: McGraw-Hill.
- McDonald, R. I., P. Green, D. Balk, B. M. Fekete, C. Revenga, M. Todd, and M. Montgomery (2011). "Urban growth, climate change, and freshwater availability". *Proceedings of the National Academy of Sciences* 108.15, pp. 6312–6317.
- McIntosh, A. C. (2003). *Asian Water Supplies: Reaching the Urban Poor*. Tech. rep. Asian Development Bank.
- McIntosh, A. C. and C. E. Yiguez (1997). *Second Water Utilities Data Book: Asian and Pacific Region*. Tech. rep. Manila, Philippines: Asian Development Bank.
- McKenzie, D. and I. Ray (2005). *Household Water Delivery Options in Urban and Rural India*. Tech. rep. Stanford, CA: Stanford Center for International Development.

- McKenzie, D. and I. Ray (2009). "Urban water supply in India: status, reform options and possible lessons". *Water Policy* 11.4, pp. 442–460.
- Mermin, J. H., R. Villar, J. Carpenter, L. Roberts, A. Samariddin, L. Gasanova, S. Lomakina, C. Bopp, L. Hutwagner, P. Mead, B. Ross, and E. D. Mintz (1999). "A massive epidemic of multidrug-resistant typhoid fever in Tajikistan associated with consumption of municipal water". *The Journal of Infectious Diseases* 179.6, pp. 1416–1422.
- Misra, K. and G. Malhotra (2012). "Water management: the obscurity of demand and supply in Delhi, India". *Management of Environmental Quality: An International Journal* 23.1, pp. 23–35.
- Mitra, S. G. (2008). "Power and policy processes in drinking water supply in Karnataka, India". *Development (London)* 51.1, pp. 96–101.
- Mohanty, J. C., T. E. Ford, J. J. Harrington, and V. Lakshmipathy (2002). "A cross-sectional study of enteric disease risks associated with water quality and sanitation in Hyderabad City". *Journal of Water Supply Research and Technology-Aqua* 51.5, pp. 239–251.
- Murray, R., T. Haxton, S. A. McKenna, D. B. Hart, K. Klise, M. Koch, E. D. Vugrin, S. Martin, M. Wilson, V. Cruz, and L. Cutler (2010). *Water Quality Event Detection System for Drinking Water Contamination Warning Systems: Development, Testing, and Application of CANARY*. Tech. rep. Cincinnati, OH: National Homeland Security Research Center Office of Research and Development.
- Mustonen, S. M., S. Tissari, L. Huikko, M. Kolehmainen, M. J. Lehtola, and A. Hirvonen (2008). "Evaluating online data of water quality changes in a pilot drinking water distribution system with multivariate data exploration methods". *Water Research* 42.10-11, pp. 2421–2430.
- National Fire Protection Association (2007). *NFPA 1142: Standard on Water Supplies for Suburban and Rural Fire Fighting*.
- Nawrocki, J., U. Raczky-Stanisawiak, J. wietlik, A. Olejnik, and M. J. Sroka (2010). "Corrosion in a distribution system: Steady water and its composition". *Water Research* 44.6, pp. 1863–1872.
- Nygaard, K., E. Wahl, T. Krogh, O. A. Tveit, E. Bohleng, A. Tverdal, and P. Aavitsland (2007). "Breaks and maintenance work in the water distribution systems and gastrointestinal illness: a cohort study". *International Journal of Epidemiology* 36.4, pp. 873–880.
- Onda, K., J. LoBuglio, and J. Bartram (2012). "Global Access to Safe Water: Accounting for Water Quality and the Resulting Impact on MDG Progress". *International Journal of Environmental Research and Public Health* 9.3, pp. 880–894.
- Ostfeld, A. and E. Salomons (2005). "Securing water distribution systems using online contamination monitoring". *Journal of Water Resources Planning and Management-ASCE* 131.5, pp. 402–405.
- Paul, E., J. C. Ochoa, Y. Pechaud, Y. Liu, and A. Lin (2012). "Effect of shear stress and growth conditions on detachment and physical properties of biofilms". *Water Research* 46.17, pp. 5499–5508.

- Payment, P. (1999). "Poor Efficacy of Residual Chlorine Disinfectant in drinking water to inactivate waterborne pathogens in distribution systems". *Canadian Journal of Microbiology* 45.8, pp. 709–715.
- Payment, P., J. Siemiatycki, L. Richardson, G. Renaud, E. Franco, and M. Prevost (1997). "A prospective epidemiological study of gastrointestinal health effects due to the consumption of drinking water". *International Journal of Environmental Health Research* 7.1, pp. 5–31.
- Percival, S. L. and J. T. Walker (1999). "Potable water and biofilms: A review of the public health implications". *Biofouling* 14.2, pp. 99–115.
- Pilcher, R., A. Dizdar, S. Toprak, E. D. Angelis, A. C. Koc, C. Dilsiz, K. D. Angelis, F. Dikbas, M. Firat, and U. G. Bacanli (2008). *PROWAT: The Basic Water Loss Book*. Turkey: Leonardo da Vinci project.
- Pothof, I. and B. Karney (2012). "Chapter 1: Guidelines for Transient Analysis in Water Transmission and Distribution Systems". *Water Supply System Analysis - Selected Topics*. Ed. by A. Ostfeld. URL: <http://www.intechopen.com/books/water-supply-system-analysis-selected-topics/guidelines-for-transient-analysis-in-water-transmission-and-distribution-systems>.
- Power, K. N. and L. A. Nagy (1999). "Relationship between bacterial regrowth and some physical and chemical parameters within Sydney's drinking water distribution system". *Water Research* 33.3, pp. 741–750.
- Prevost, M., A. Rompre, H. Baribeau, J. Coallier, and P. Lafrance (1997). "Service lines: Their effect on microbiological quality". *Journal American Water Works Association* 89.7, pp. 78–91.
- Propato, M. and J. G. Uber (2004). "Vulnerability of Water Distribution Systems to Pathogen Intrusion: How Effective Is a Disinfectant Residual?" *Environmental Science & Technology* 38.13, pp. 3713–3722.
- R Core Team (2012). *R: A Language and Environment for Statistical Computing*. Vienna, Austria. URL: <http://www.R-project.org/>.
- Rahman, A., H. K. Lee, and M. A. Khan (1997). "Domestic water contamination in rapidly growing megacities of Asia: Case of Karachi, Pakistan". *Environmental Monitoring and Assessment* 44.1-3, pp. 339–360.
- Raman, V., N. Parhad, A. Deshpande, and S. Pathak (1978). "Assessment and Control of Water Quality in a Town Distribution System with Reference to the Incidence of Gastrointestinal Diseases". *Prog. Wat. Tech.* 11.1/2, pp. 65–71.
- Ridgway, H. F. and B. H. Olson (1982). "Chlorine resistance patterns of bacteria from two drinking water distribution systems." *Applied and Environmental Microbiology* 44.4, pp. 972–987.
- Rochex, A., J.-J. Godon, N. Bernet, and R. Escudi (2008). "Role of shear stress on composition, diversity and dynamics of biofilm bacterial communities". *Water Research* 42.20, pp. 4915–4922.

- Rosenberg, D., S. Talazi, and J. Lund (2008). “Intermittent Water Supplies: Challenges and Opportunities for Residential Water Users in Jordan”. *Water International* 33.4, pp. 488–504.
- Rosenberg, D. E., T. Tarawneh, R. Abdel-Khaleq, and J. R. Lund (2007). “Modeling integrated water user decisions in intermittent supply systems”. *Water Resources Research* 43.7.
- Rossmann, L. and W. Grayman (1999). “Scale-Model Studies of Mixing in Drinking Water Storage Tanks”. *Journal of Environmental Engineering* 125.8, pp. 755–761.
- Sangameswaran, P., R. Madhav, and C. D’Rozario (2008). “24/7, ‘Privatisation’ and water reform: insights from Hubli-Dharwad”. *Economic and Political Weekly* 43.14, pp. 60–67.
- Sarin, P., V. Snoeyink, J. Bebee, K. Jim, M. Beckett, W. Kriven, and J. Clement (2004). “Iron release from corroded iron pipes in drinking water distribution systems: effect of dissolved oxygen”. *Water Research* 38.5, pp. 1259–1269.
- Sashikumar, N., M. S. Mohankumar, and K. Sridharan (2003). “Modelling an Intermittent Water Supply”. *World Water and Environmental Resources Congress 2003*. Ed. by B. Paul and D. Paul. Vol. 118. Philadelphia, PA, USA: ASCE, p. 261.
- Schouten, M. and R. Halim (2010). “Resolving strategy paradoxes of water loss reduction: A synthesis in Jakarta”. *Resources, Conservation and Recycling* 54.12, pp. 1322–1330.
- Seetharam, K. E. and G. Bridges (2005). *Helping India Achieve 24x7 Water Supply Service by 2010*. Tech. rep.
- Sekhon, J. S. and R. Grieve (2008). *A Nonparametric Matching Method for Covariate Adjustment with Application to Economic Evaluation*. Tech. rep.
- Semenza, J. C., L. Roberts, A. Henderson, J. Bogan, and C. H. Rubin (1998). “Water distribution system and diarrheal disease transmission: A case study in Uzbekistan”. *American Journal of Tropical Medicine and Hygiene* 59.6, pp. 941–946.
- Simpson, G. L. (2012). *permute: Functions for generating restricted permutations of data*. Tech. rep. R package version 0.7-0. URL: <http://CRAN.R-project.org/package=permute>.
- Skadsen, J., R. Janke, W. Grayman, W. Samuels, M. TenBroek, B. Steglitz, and S. Bahl (2008). “Distribution system on-line monitoring for detecting contamination and water quality changes”. *Journal American Water Works Association* 100.7.
- Snead, M. C., V. P. Olivieri, K. Kawata, and C. W. Kruse (1980). “The effectiveness of chlorine residuals in inactivation of bacteria and viruses introduced by post-treatment contamination”. *Water Research* 14, pp. 403–408.
- Spencer, C. (2012). “Water quality in the distribution system: a review”. *Journal American Water Works Association* 104.7.
- Storey, M. V., B. van der Gaag, and B. P. Burns (Jan. 2011). “Advances in on-line drinking water quality monitoring and early warning systems”. *Water Research* 45.2, pp. 741–747.
- Swerdlow, D. L., E. D. Mintz, M. Rodriguez, E. Tejada, C. Ocampo, L. Espejo, K. D. Greene, W. Saldana, L. Seminario, R. V. Tauxe, J. G. Wells, N. H. Bean, A. A. Ries, M. Pollack, B. Vertiz, and P. A. Blake (1992). “Waterborne Transmission of Epidemic Cholera in Trujillo, Peru - Lessons for a Continent at Risk”. *Lancet* 340.8810, pp. 28–32.

- Telgmann, U., H. Horn, and E. Morgenroth (2004). "Influence of growth history on sloughing and erosion from biofilms". *Water Research* 38.17, pp. 3671–3684.
- Teunis, P. F. M., M Xu, K. K. Fleming, J Yang, C. L. Moe, and M. W. Lechevallier (2010). "Enteric virus infection risk from intrusion of sewage into a drinking water distribution network". *Environmental Science & Technology* 44.22, pp. 8561–8566.
- Thompson, J., I. T. Porras, J. K. Tumwine, M. R. Mujwahuzi, M. Katui-Katua, N. Johnstone, and L. Wood (2001). *Drawers of Water II: 30 years of change in domestic water use and environmental health in east Africa*. Tech. rep. International Institute for Environment and Development.
- Tokajian, S. and F. Hashwa (2003). "Water quality problems associated with intermittent water supply". *Water Science and Technology* 47.3, pp. 229–234.
- Tokajian, S. and F. Hashwa (2004). "Phenotypic and genotypic identification of *Aeromonas* spp. isolated from a chlorinated intermittent water distribution system in Lebanon". *Journal of Water and Health* 2.2, pp. 115–122.
- Totsuka, N., N. Trifunovic, and K. Vairavamoorthy (2004). "Intermittent urban water supply under water starving situations". *30th WEDC International Conference*. Vientiane, Lao PDR: Water, Engineering and Development Centre.
- Vairavamoorthy, K., S. D. Gorantiwar, and S. Mohan (2007). "Intermittent water supply under water scarcity situations". *Water International* 32.1, pp. 121–132.
- Vairavamoorthy, K., S. D. Gorantiwar, and A. Pathirana (2008). "Managing urban water supplies in developing countries - Climate change and water scarcity scenarios". *Physics and Chemistry of the Earth* 33.5, pp. 330–339.
- Vairavamoorthy, K., J. M. Yan, H. M. Galgale, and S. D. Gorantiwar (2007). "IRA-WDS: A GIS-based risk analysis tool for water distribution systems". *Environmental Modelling & Software* 22.7, pp. 951–965.
- 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*. Washington, DC: World Bank.
- van der Wende, E, W. Characklis, and D. Smith (1989). "Biofilms and bacterial drinking water quality". *Water Research* 23.10, pp. 1313–1322.
- Vasconcelos, J. G. and S. J. Wright (2008). "Rapid flow startup in filled horizontal pipelines". *Journal of Hydraulic Engineering-ASCE* 134.7, pp. 984–992.
- Volk, C., E. Dundore, J. Schiermann, and M. Lechevallier (2000). "Practical evaluation of iron corrosion control in a drinking water distribution system". *Water Research* 34.6, pp. 1967–1974.
- Vreeburg, I. J. and D. J. Boxall (2007). "Discolouration in potable water distribution systems: A review". *Water Research* 41.3, pp. 519–529.
- Walter, R. K., P.-H. Lin, M. Edwards, and R. E. Richardson (2011). "Investigation of factors affecting the accumulation of vinyl chloride in polyvinyl chloride piping used in drinking water distribution systems". *Water Research* 45.8, pp. 2607–2615.
- Wang, K.-H., Q. Shen, and B. Zhang (2003). "Modeling propagation of pressure surges with the formation of an air pocket in pipelines". *Computers & Fluids* 32.9, 11791194.

- WHO (1997). *Guidelines for Drinking Water Quality: Surveillance and Control of Community Supplies*. 2nd ed. Vol. 3. Geneva: World Health Organization.
- WHO and UNICEF (2000). “Annex A: Methodology”. *Global Water Supply and Sanitation Assessment 2000 Report*. Geneva: WHO/UNICEF, pp. 77–79.
- WHO and UNICEF (2006). *Meeting the MDG Drinking Water and Sanitation Target: The Urban and Rural Challenge of the Decade*. Tech. rep. Geneva: WHO/UNICEF.
- WHO and UNICEF (2010). *Progress on Sanitation and Drinking Water: 2010 Update*. Tech. rep. Geneva: WHO/UNICEF.
- WHO and UNICEF (2012). *Progress on Drinking Water and Sanitation*. Tech. rep. Geneva: WHO/UNICEF.
- Wilbur Smith Associates Private Limited (Oct. 2009). *Tranche II Sub-Projects in Hubli-Dharwad Municipal Corporation: Initial Environmental Examination*. Tech. rep. Project Number: 38254. Karnataka Urban Infrastructure Development Finance Corporation.
- Wilkinson, D. L. (1982). “Motion of air cavities in long horizontal ducts”. *Journal of Fluid Mechanics* 118, pp. 109–122.
- World Bank (2003). *Nagari: 24-hour Water Supply: Is this Goal Achievable?* Tech. rep. Hyderabad, India: World Bank - Water and Sanitation Program.
- 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*. Tech. rep. Report No: 27180-IN. The World Bank.
- World Bank (2010). *The Karnataka Urban Water Sector Improvement Project: 24x7 Water Supply is Achievable*. Tech. rep. World Bank - Water and Sanitation Program.
- Wright, J., S. Gundry, and R. Conroy (2004). “Household drinking water in developing countries: a systematic review of microbiological contamination between source and point-of-use”. *Tropical Medicine & International Health* 9.1, pp. 106–117.
- Yang, J., M. W. LeChevallier, P. F. M. Teunis, and M. Xu (June 2011). “Managing risks from virus intrusion into water distribution systems due to pressure transients”. *Journal of Water and Health* 9.2, pp. 291–305.
- Yassin, M. M., S. S. Abu Amr, and H. M. Al-Najar (2006). “Assessment of microbiological water quality and its relation to human health in Gaza Governorate, Gaza Strip”. *Public Health* 120.12, pp. 1177–1187.
- Zacheus, O. M., M. J. Lehtola, L. K. Korhonen, and P. J. Martikainen (2001). “Soft deposits, the key site for microbial growth in drinking water distribution networks”. *Water Research* 35.7, pp. 1757–1765.
- Zerah, M. H. (1998). “How to assess the quality dimension of urban infrastructure: The case of water supply in Delhi”. *Cities* 15.4, pp. 285–290.
- Zhang, Y. and K. Vairavamorthy (2006). “Application of Method-of-Lines to Charging-Up Process in Pipelines with Entrapped Air”. *Tsinghua Science & Technology* 11.3, pp. 324–331.