water

Article

Intermittent Water Supply Management, Household Adaptation, and Drinking Water Quality: A Comparative Study in Two Chinese Provinces

Hongxing Li [1,*], Alasdair Cohen [2], Zheng Li [3], Shibo Lv [4], Zuan He [5], Li Wang [1] and Xinyi Zhang [1]

[1] National Center for Rural Water Supply Technical Guidance, Chinese Center for Disease Control and Prevention, Beijing 10050, China; wangli@ncrwstg.chinacdc.cn (L.W.); cdczhangxy@hotmail.com (X.Z.)
[2] Department of Population Health Sciences & the Virginia Tech Public Health Program, Virginia Polytechnic Institute & State University (Virginia Tech), Blacksburg, VA 24061, USA; alasdair.cohen@linacre.oxon.org
[3] National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, Beijing 10050, China; lizheng@nieh.chinacdc.cn
[4] Shandong Center for Disease Control and Prevention, Jinan 250014, China; 18615281861@wo.cn
[5] Hubei Center for Disease Control and Prevention, Wuhan 430079, China; hezuan@126.com
* Correspondence: lihx@ncrwstg.chinacdc.cn

Received: 3 April 2020; Accepted: 8 May 2020; Published: 12 May 2020

Abstract: Intermittent water supply (IWS) is a relatively common phenomenon across the world as well as in rural and peri-urban areas across China, though there has been little IWS-focused research from China published to date. IWS consumers typically adopt a range of strategies to cope with insufficient water supply, poor drinking water quality, and associated inconveniences. In this study, we collected a range of data from small-scale utilities and households in two IWS systems and two continuous water supply (CWS) systems, as well as from comparison groups, in Shandong and Hubei provinces. Data collection included water quality testing, interviews, and surveys on behavioral adaptations, coping strategies, water-related health perceptions, and other metrics of consumer satisfaction. Overall, we found that the IWS coping strategies employed in northern China (Shandong) were associated with generally safe, but inconvenient, water access, whereas adaptation strategies observed in southern China (Hubei) appeared to improve convenience, but not water quality. Compared to the CWS comparison groups, we did not observe significant differences in water- and sanitation-related behaviors in the IWS groups, suggesting interventions to increase adaptive and protective behaviors at the household level might further improve safe water access for households living with IWS. Overall, although the water supply infrastructure in these study areas appeared to be in relatively good condition, in contrast to reported data on IWS systems in other countries, we observed multiple risk factors associated with the water treatment and distribution processes in these IWS systems. Among policy recommendations, our results suggest that the implementation of Water Safety Plans in China would likely improve the management of drinking water treatment and, by extension, safe drinking water supply under conditions of IWS.

Keywords: intermittent water supply; drinking water quality; water and sanitation; household adaptation; China

1. Introduction

Intermittent water supply (IWS)—i.e., piped water supply service delivering water to users for less than 24 h one or more days per week—is prevalent in many countries and is estimated to impact more than 300 million people globally [1]. IWS can be viewed as an adaptive measure to the scarcity of water resources and/or increasing water demand from consumers. IWS is relatively common in rural China where a large proportion of the rural water supply is non-continuous [2–4].

A survey on rural water supply in Shandong province, for example, showed there was only 1 village which had a constant (24 h/day, 7 days/week) water supply among 515 villages before municipal water supply extended to these villages [3]. The discontinuity of water supply has also been cited as a primary source of reported contamination in water distribution networks in China [4]. Although China has substantially improved rural water supply over the past two decades, small-scale centralized water supply facilities are still the norm in many rural areas [5,6]. In much of China, water supply also remains vulnerable to water shortages, increasing water supply–demand from growing populations, and increasing demand due to rapid urbanization [7,8]. Overall, IWS in China can be attributed to water shortages, insufficient local-level funding and technical support, low water consumption demand, and other technical and economic factors [9–12], though the ways in which households may adapt to conditions of IWS, and the associated impacts, are not well understood.

Evidence from other countries indicates that, from a health perspective, the impacts associated with IWS often contribute to water quality degradation—microbiological, chemical, physical, and/or aesthetic [13,14]. Studies also show that the perceived odor and clarity of supplied drinking water are important factors for water consumer satisfaction, especially so under conditions of IWS [15,16]. Water quality degradation may be caused by contaminant backflow and intrusion into the distribution pipes, as well as the release of particulates, or sloughing of biofilms, within pipes [1]. As microbial contamination is the primary factor impacting drinking water safety in much of rural China [17], evidence from other countries suggests IWS would be expected to increase this water quality risk.

IWS is also associated with deleterious coping strategies and other behaviors which tend to result under conditions of insufficient water supply [18]. In rural areas, IWS has been shown to decrease indoor (drinking water) and outdoor (other uses) water consumption overall [19]. Duration of water supply under conditions of IWS had also been shown to significantly impact per capita water consumption, and overall water supply under IWS rarely aligns with water demand [20]. Typical behavior changes observed under conditions of IWS include the use of an alternative water sources, storing water at home, and decreased frequencies of washing, hygiene, and bathing [21]. Other evidence points to negative socioeconomic impacts of IWS [22]. Indeed, inadequate or infrequent water supply typically causes residents to spend additional time and income on activities related to the collection of water and water storage infrastructure and management, compared to those with CWS.

The strategies consumers use in the face of insufficient or unreliable water supply, poor water quality, and the inconveniences associated with daily water use practices, vary depending on the particulars of the IWS system, timing, and setting [23]. In northern China, for example, where groundwater is often used for source water with little or no treatment, rudimentary ground water pump stations are often managed by village user associations, and in many such areas the water is not treated at all prior to distribution [24]. In much of southern China, state-owned utilities and private enterprises more commonly use surface water sources, coupled with basic water treatment processes. Due to the differences in water sources, management approaches, and regional cultural differences, IWS-induced adaptive measures would be expected to vary considerably between norther and southern areas of rural China.

A great deal of IWS research conducted outside of China has focused on the mechanisms of water quality, household consumption, and associated health impacts [9,20,25]. The relatively few China-focused IWS studies [19,26] do little to improve our understanding of IWS in China generally, or our understanding of rural household's adaptive behaviors in the face of IWS. To fill this research and knowledge gap, we studied two relatively typical IWS systems, in Shandong (northern China) and Hubei (southern China) provinces, with the goal of identifying management options and strategies for improving drinking water management and reducing health-related risks in rural IWS systems. Specifically, our primary objectives were to evaluate and better understand the impacts on drinking water quality associated with coping strategies under conditions of IWS, and how various behavioral adaptations to IWS may mitigate or exacerbate drinking water quality at the household level as well as subjective satisfaction with perceived water quality and the quantity of water supplied.

2. Methods

2.1. Field Sites and Setting

This comparative study was conducted in Linzi County in Shandong province (China's north) and Zhongxiang County in Hubei province (China's south). IWS systems which were considered to be relatively typical of IWS in other areas of China were selected for the study. The two counties were selected due to their similar levels of social and economic development, but differing types of IWS. The main source of rural water supply in Linzi County was groundwater, and every village has their own water supply wells. In Zhongxiang County, where water resources are relatively abundant, water treatment systems with primary and secondary treatment processes typify rural water supply in the region.

2.2. Study Design and Background Information

In this study, IWS was defined as water supply systems that provide water supply only during pre-scheduled times (usually based on the hours when most households will prepare meals). The criteria for CWS comparison groups were that they have a constant (24 h/day, 7 days/week) water supply derived from a similar source as the IWS groups (surface or groundwater), and that general conditions were, on average, similar to those in the IWS groups (as measured via government data on socioeconomic indicators). Two IWS villages were selected in each county as well as two neighboring villages for the comparison groups. IWS and CWS groups had similar socio-economic characteristics and public water supply facilities. An overview of village-level characteristics and indicators used to inform the selection of study sites is provided in Table 1. The two water systems in Hubei provide water for several villages besides the villages in which this study was conducted.

Table 1. Background information of the study villages.

Characteristics of Water Supply	Shandong		Hubei	
	IWS	CWS	IWS	CWS
Total number of families in the study village	320	380	686	660
Source of water supply	Groundwater	Groundwater	River	River
Water-treatment	Untreated	Untreated	Conventional treatment	Conventional treatment
Water disinfection	No disinfection	No disinfection	Chlorine Dioxide	Chlorine Dioxide
Water supply population	1100	1350	85,000	65,000
Daily water supply capacity (m^3/day)	250,000	30,000	6,000,000	4,000,000
Frequency of daily water supply	1	-	2	-
Water supply period	10:00–14:00	-	5:00–10:00; 17:00–20:00	-
Reason for IWS	To reduce electricity charge	-	To reduce electricity charge	-
Percentage of electricity charges for total water plant operations (%)	80	85	46	30
Water treatment cost (RMB/ m^3)	0.2	1	2.4	1.25
Leakage water ratio (%)	20	30	10	37
Water charging method	No charge	No charge	Metering charge	Metering charge
Water fees (RMB)	-	-/2.5	1.8	2/1.8

2.3. Water Sampling and Analyses

Water quality data were collected based on laboratory testing of samples from this study as well as from historical water quality monitoring records. For source water or finished water, historical water quality data provided by the local Center for Disease Control and Prevention (CDC) were used. Historical water quality data used for compliance assessments were used in this study as an independent variable hypothesized to be associated with drinking water consumer satisfaction. For terminal water (tap water or water in storage facilities), samples from both the IWS and CWS groups were collected and tested in the laboratory. Based on maps of the water distribution networks, tap water sampling points were selected at the farthest, nearest, and mid-point sections of the networks. For IWS areas, tap water samples were collected at different times: the instant the water flow began (first flush); 5 min after the water supply had started; and 30 min after the water supply had started. For CWS, water samples were collected during the daily water supply periods. Water quality parameters including Turbidity, color, pH, Iron, Manganese, disinfectant residual (chlorine dioxide), Total Bacteria (TB), Fecal/Total Coliform (TC), Thermotolerant coliform bacteria (TTC), and *E. coli* were tested. Table A1 lists the methods used to analyze these water quality parameters. For source water, historical data from the last three years were collected; for finished water, three years of historical data plus data from a field analysis were used; for the IWS group, 60 tap water and 10 stored water samples were tested; for the CWS group, 10 tap water samples were tested per site.

2.4. Household Surveys and Sample Size

The household survey was conducted in the four villages, and a random sample of 100 households in each village (total = 400 households) was visited by trained investigators. The surveys included data on basic demographic information, household drinking water and sanitation facilities, hygienic behaviors, knowledge, etc. Water and sanitation facilities data were obtained through direct observation; all other information was collected via self-report. Self-reported water supply satisfaction data was also collected in the surveys. This was the first such study of IWS in China, therefore we did not have reference data from previous studies to use for our initial sample size calculations. We therefore used data and power calculations reported in previous drinking-water-focused studies in other areas of China to inform the determination of our sample size [17,27].

2.5. Data Collection

Data were collected by local CDC staff who had been trained on field survey techniques by the study organizers. A field survey instruction and training manual was also developed and used for administration of the household surveys. Quality control measures, such as double-checking of the questionnaires before data entry, were adopted. Access-based data management software was used for data entry.

2.6. Data Analysis

Boxplots were used to visualize the distribution of water quality data. A Log10 transformation was used for the TB, TC, and TTC data. The normality of the water quality parameter distributions was checked using the Shapiro–Wilk test. Then the Wilcoxon rank-sum test, or a Student's t-test, were used to evaluate water quality differences between IWS and CWS groups (according to the distribution of the water quality variables). For household survey data, Chi-square tests (Fisher's exact test if any expected cell counts were less than 5) were used to compare the categorical variables of the two groups.

Multilevel logistic regression models were employed to evaluate the impact of IWS on self-reported satisfaction with local water supply. The units of analysis were individuals, nested within villages. We controlled for covariates such as gender, age, income, and education level at the household level, and controlled for the method of water supply and socio-economic indicators at the village level. The outcome variable in this analysis was the probability of individuals in the villages being satisfied with the local water supply. Self-reported data from our survey question "are you satisfied with the performance of water supply in your village" was categorized as Yes if the answer was "very satisfied" or "satisfied", and No otherwise (missing data were excluded). An overview of the outcome variable and primary independent variables used in these models is provided in table A2.

Specifically, we used a random-effects model, assuming each village had a different intercept (β_0) and a fixed coefficient. Initially, for comparison we fitted a null model which included no independent variables. We then included village-level independent variables (model 1), using the following structure (Equation (1)):

$$\log\left[\frac{\pi}{1-\pi}\right] = \beta_0 + \beta_1 x_1 + \cdots + \beta_n x_n \quad (1)$$

where π is the probability of being satisfied with the local water supply, β_0 is an estimate of the intercept, β_1 and β_n are estimates of the slope for variables x_1 and x_n.

For the final model (Model 2) we expanded on Model 1 by including individual-level variables, using the following structure (Equation (2)):

$$\log\left[\frac{\pi_{ij}}{1-\pi_{ij}}\right] = \beta_0 + \beta_1 x_{ij} + \beta_2 z_{ji} + u_j \quad (2)$$

where, i and j are household and village-level variables, respectively, x and z are household and village-level influence factors, respectively, and π_{ij} represents the probability of being satisfied with the local water supply for ith household in jth village. β_1 and β_2 are the fixed coefficients, β_0 is the intercept, and u_j is the random effect for jth village.

The significance of the fixed and random parameter variance estimates was assessed using the Wald x^2 test. Intra-class Correlation Coefficient (ICC) was used to examine whether the random effect of the intercept was significant. ICC was calculated using the latent variable method. All multi-level models were estimated using R software (multilevel package and nlm package [28]).

3. Results

3.1. Summary Characteristics of the Study Sites

The household adaptive strategies to IWS in these two study sites were quite different overall, and largely based on the approaches local government used for drinking water supply (Figure 1). In Linzi County (called Shandong mode in this paper): groundwater was piped to households at a set time per day. To cope with the IWS, a combined adaptive strategy was used by the households. To solve the drinking water quality problem, a Reverse Osmosis (RO) water treatment plant was built at the village level by local government to supply households with safe drinking water, which was provided in reusable 19 L plastic bottles. Villagers bought this RO treated water by the bottle and used bottled water dispensers in their homes (top of Figure 1a). For water used for daily cleaning and other household non-drinking water uses, most homes in this area used roof-mounted 189 L water tanks and solar water heaters (bottom of Figure 1a).

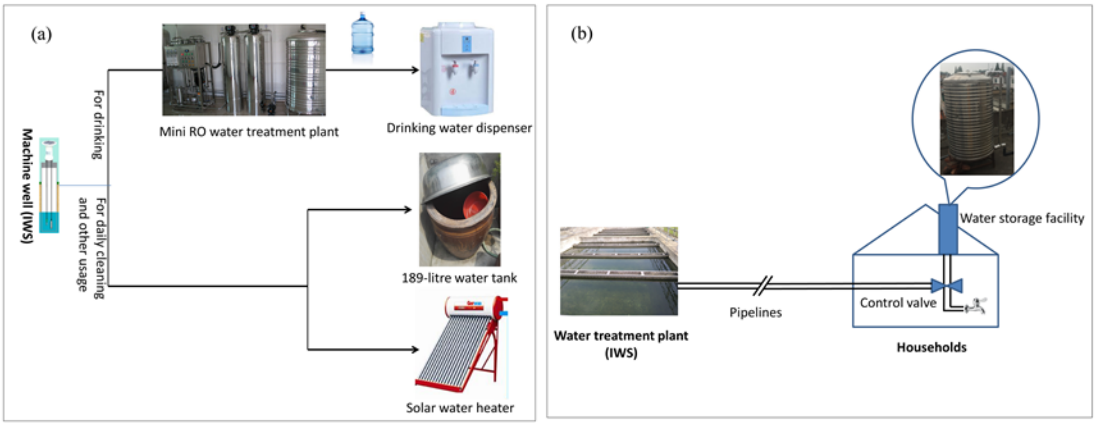

Figure 1. Household adaptive strategies under conditions of intermittent water supply (IWS) in Shandong and Hubei provinces: (**a**) Shandong (Shandong Mode) adaptive strategy centered on RO-treated drinking water and roof-mounted water tanks and solar water heaters; (**b**) Hubei (Hubei Mode) adaptive strategy centered on automated, roof-mounted, water storage tanks.

In Zhongxiang County (called Hubei mode in this paper), the local utility used surface water (from the local river) and a treatment processes consisting of coagulation-flocculation, filtration, and disinfection. To reduce electricity expenditures (from the water pumps), the water treatment plant opted to supply this treated water only intermittently. Village adaptation measures to IWS in Hubei appeared to be relatively uniform, in that all households had installed roof-mounted water tanks which filled automatically when there was available water supply (Figure 1b). When the water supply was unavailable, these roof water storage tanks were used for both drinking and domestic-use water.

Data on water and sanitation related infrastructure are summarized in Table 2. There were significant differences observed between the two groups with regard to the proportion of households which used drinking water dispensers (bottled water dispensing equipment, usually with built-in heating elements), household water storage containers, water flushing toilets, and shower facilities.

Table 2. Household water and sanitation infrastructure.

Household Water and Sanitation Facilities	Shandong			Hubei		
	IWS (%) n = 100	CWS (%) n = 100	p-value[1]	IWS (%) n = 100	CWS (%) n = 100	p-value[1]
Using household water dispenser	96.0	65.0	<0.001	70.0	65.0	0.45
Having household water storing facilities	100	65.0	<0.001	94.0	17.0	<0.001
Having household showering facility	95	79	0.001	50	66	0.022
Using household water-flushing toilet	88	55	<0.001	73	90	0.002
Household wastewater collection pipelines	31	36	0.454	0	0	-
Kiosk and retail bottled water use[2]	100	50	<0.001	93	58	<0.001

Notes: [1] *p*-value based on the chi-square test or Fisher's exact test (for an expected value lower than 5); [2] For the Shandong IWS group, bottled water refers to utility-supplied, Reverse Osmosis (RO)-treated, water provided in reusable 19L bottled (i.e., Kiosk Bottled Water), whereas in for the Shandong continuous water supply (CWS) group, and all groups in Hubei, bottled water refers to the purchase of retail (branded) bottled water.

With regard to bottled water use for the CWS groups, there was a similar rate of retail bottled water use (i.e., not government-supplied) in Shandong (50%, 95% CI = 40.2 − 59.8) and Hubei (58%, 95% CI = 32.3 − 51.6). The proportion of households using bottled water in the IWS group was significantly higher than that in CWS group ($p < 0.001$) in both Shandong and Hubei. However, in the IWS group in Shandong, the use of "bottled water" was primarily that of the utility-supplied, RO-treated water described above, which residents purchases in reusable 19 L bottles (at prices significantly lower than that of retail 19 L bottles). In Hubei, where only retail bottled water was available, rates of bottled water use were significantly higher ($p < 0.001$) in the IWS group (93.0%, 95% CI = 87.9 − 90.0) than in the CWS group (58%, 95% CI = 32.3 − 51.6), indicating that bottled water use may be an adaptation to conditions of IWS (see Table 2).

3.2. Water Quality

3.2.1. Tap Water Quality

Tap water quality data from the two groups is summarized in Figure 2. There were significant differences between the IWS and CWS groups for TB and TTC both for Shandong mode and Hubei mode (Shapiro–Wilk test, $p = 0.034$), which the microbial index for the CWS group was better than that of IWS group. There were no statistical differences observed for the water quality indexes, including color, turbidity, iron, and manganese (Student's t-test, $p > 0.05$).

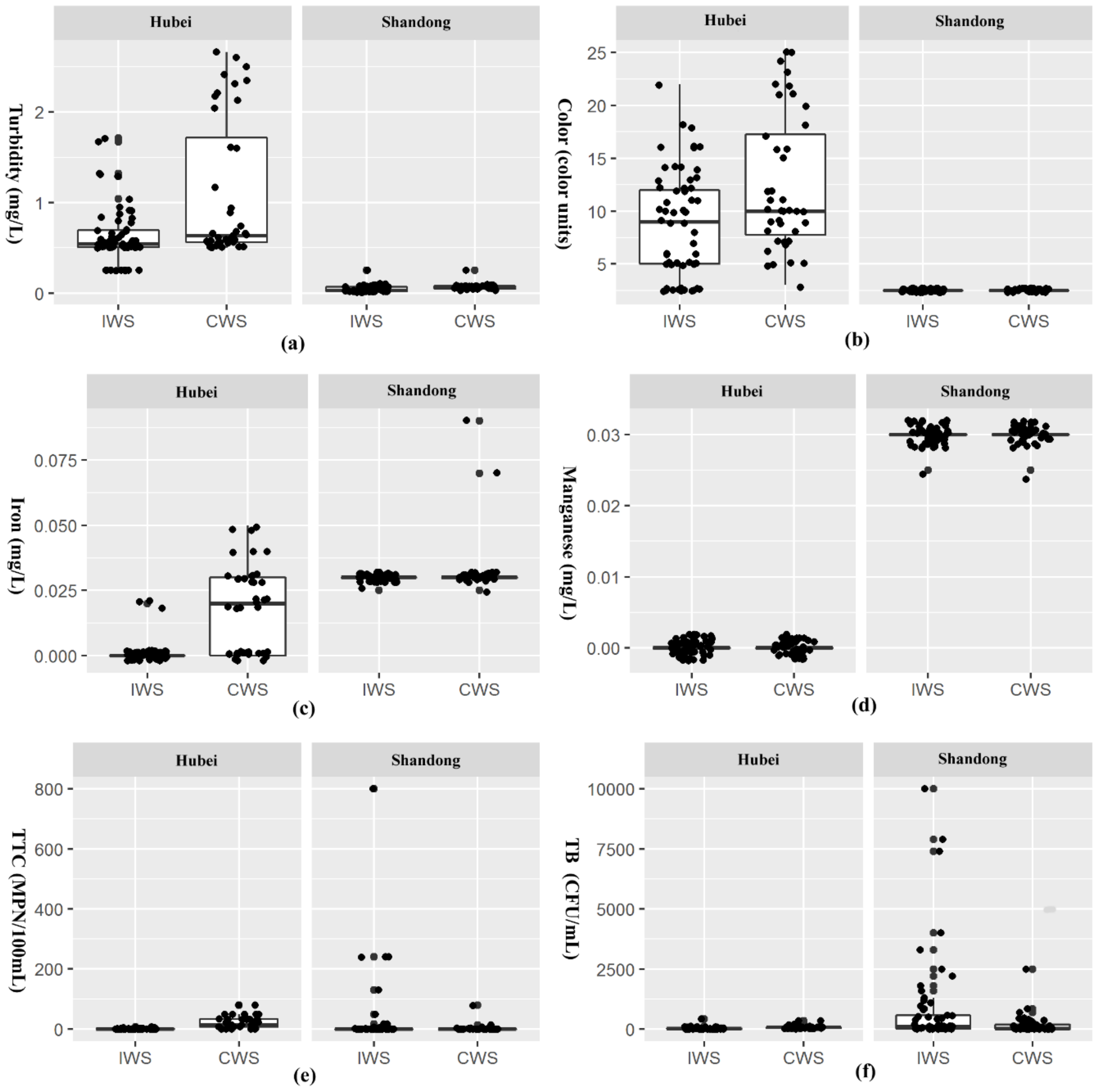

Figure 2. Tap water quality parameters for households using IWS and CWS in Shandong & Hubei (Data source: This study): (**a**) Turbidity; (**b**) Color; (**c**) Iron; (**d**) Manganese; (**e**) Thermotolerant Coliforms; (**f**) Total Bacteria.

3.2.2. Stored Water Quality

As observed in other countries, households living under conditions of IWS typically store their water, a practice which can introduce additional health risks. Figure 3 shows that there was high degree of variation observed for turbidity, color, and iron in the stored drinking water samples from Hubei, while there was more variation for the microbiological indexes observed in Shandong.

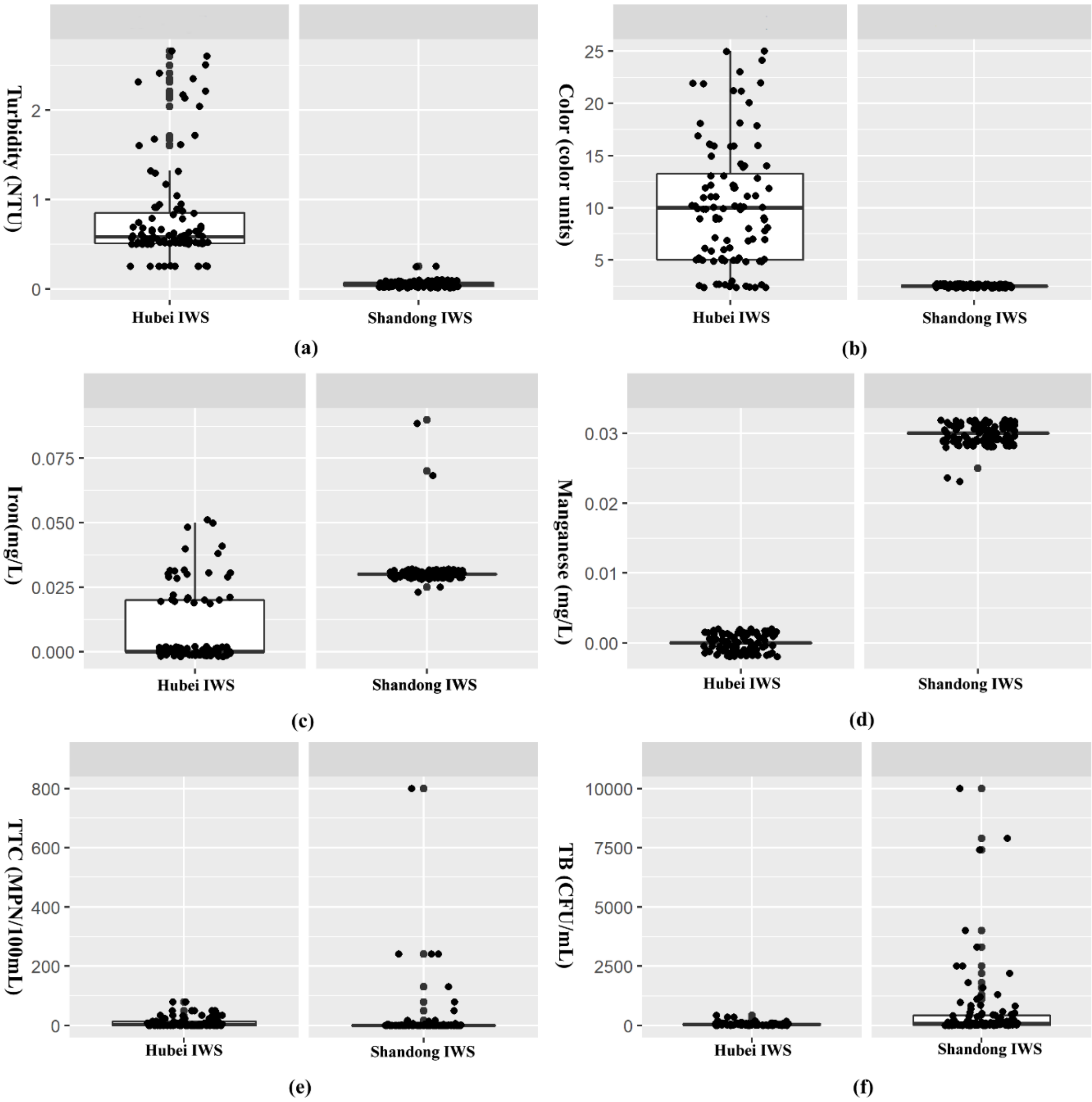

Figure 3. Quality of stored water for households using IWS and CWS in Shandong & Hubei (Data source: This study): (**a**) Turbidity; (**b**) Color; (**c**) Iron; (**d**) Manganese; (**e**) Thermotolerant Coliforms; (**f**) Total Bacteria.

3.3. Hygiene Behaviors

3.3.1. Household Hygiene-Related Behaviors

Differences in household hygiene-related behavior between the two groups are presented in Table 3. Information on the hygienic status of the home yard/courtyard, toilet and kitchen was collected via direct-observation, and the other data presented in the table was self-reported. In the Shandong mode, more households in the IWS group used electric kettles (57%) to boil their water (for drinking, not for tea or coffee) than other types of household water treatment. In terms of kitchen, toilet, and indoor sanitation, the hygienic status of the CWS group was better than that of the IWS group in Shandong. In the Hubei mode, there was no significant difference for most health behaviors between the IWS group and the CWS comparison group. These results suggest that the two household-level adaptation strategies observed serve to significantly reduce the impacts, and associated risks, of IWS for household drinking water and hygiene.

Table 3. Families' hygiene behaviors in Shandong and Hubei mode.

Household Hygiene	Shandong			Hubei		
	IWS % n = 100	CWS % n = 100	*p*-value[1]	IWS % n = 100	CWS % n = 100	*p*-value[1]
Household drinking water treatment						
Boil: Pot or kettle	6	0		11	15	
Boil: Electric kettle	57	46		76	70	
Household Water Treatment Machine	1	3	0.008	1	4	0.459
No treatment	35	51		12	11	
Urinating or defecating around the house						
Very often	1	1		0	1	
Occasionally	53	49	0.834	0	6	0.014
No	46	50		100	93	
Under what situations do you wash your hands:						
Before having a meal	99	99		100	100	
Before cooking	100	99		100	100	
Before feeding the baby	44	27	-	37	45	-
After defecation	100	100		100	100	
After disposing of children's feces	44	27		33	42	
Soap or hand wash were used in the family:						
No	2	4		2	5	0.534
Having, but using occasionally	45	65	0.004	25	22	
Using frequently	53	31		73	73	
How often do you bathe in summer:						
Every day	100	99	-	82	83	0.769
Not every day	0	1		18	17	
Indoor cleaning status						
Very clean	23	36		38	42	
Clean	77	63	0.083	59	54	0.756
Not clean	0	1		3	4	
Yard cleaning status						
Very clean	4	33		35	41	
Clean	96	66	<0.001	62	55	0.655
Not clean	0	1		3	4	
Household toilet cleaning status						
Very clean	3	29		27	26	
Clean	95	58	<0.001	60	70	0.062
Not clean	2	13		13	4	
Household kitchen cleaning status						
Very clean	5	27		28	25	
Clean	95	68	<0.001	63	69	0.594
Not clean	0	5		9	6	

Note: [1] *p*-value based on the chi-square test or Fisher's exact test (for an expected value lower than 5).

3.3.2. Household Water Storage Behavior

Household water storage remains a relatively common practice in much of rural China [29]. In this study, household water storage data was collected in both the IWS and the CWS groups. Data on storage container material/type, management, and maintenance are provided in Table A3. Statistical differences were not observed for most indexes between the two groups, although differences were observed for water storage facility materials and water collection methods. These differences were attributed largely to differences in local conditions, such that households in the same villages tend to purchase the same types of water storage equipment, and tend to use similar methods to collect water from the storage facilities. Our study also described the related risks from household water storage, such as using unsafe water storage infrastructure, insufficient water storage cleaning/disinfection, and prolonged water storage durations.

3.4. Satisfaction with Local Water Supply

Table A4 describes key attitude-related factors for those households living under conditions of IWS in Shandong and Hubei villages. When comparing the two adaptation modes, more households in Shandong reported that their daily lives were substantially affected by IWS than in Hubei. However, residents in Hubei expressed a stronger desire to change from IWS to CWS, as compared to Shandong. Moreover, more residents in Hubei were willing to actually pay for this transition from IWS to CWS—an observation we believe to be largely explained by the higher relative household incomes in Hubei province. According to the data from our household survey, the average reported household income in the Hubei province study area was 46,900 RMB/year, while in the Shandong study area it was 34,300 RMB/ year.

Data on the satisfaction rates with local water supply in the two adaptive modes are summarized in Table A5. No statistical differences were observed between the IWS and CWS groups in Hubei or Shandong provinces. This result suggests both approaches may result in sufficient adaptation to IWS. However, because water supply satisfaction is influenced by a range of factors, such as income, education, and culture, we used a logistic regression (model 1) and multilevel logistic regression (model 2) to examine the potential impact of such factors.

Model 1 was used to examine factors at the village level, while model 2 was applied for examining influencing factors at both village and individual levels. Results from model 1 (Table 4) suggest that, at the village level, water quality was associated with residents' reported satisfaction, while IWS appeared to have no significant impact on satisfaction. For the results of model 2, after we controlled education levels, health-related knowledge level, and the local water quality, living under conditions of IWS still did not appear to significantly predict resident satisfaction.

Table 4. Multilevel logistic regression of individual and village level factors on satisfaction with self-reported water supply.

Individual and Village Level Characteristics	Model 1	Model 2
	OR (95% CI)	OR (95% CI)
Level 1 (Village)		
IWS (CWS for reference)	1.26 (0.38–2.14)	0.25(0.22–2.28)
Water quality meets the national standard (Yes for reference)	0.36(0.23–0.49)	0.36(0.17–0.55)
Water and health education organized in the village (No for reference)	2.86(0.29–5.43)	3.59(0.37–6.81)
Free tap water supply in the village (No for reference)	6.77(0.66–12.88)	7.27(0.18–14.36)
Level 2 (Individual)		
Gender (Male for reference)		10.03(0.03–20.03)
Education: Primary school and below (reference)		-
Junior high school and above		0.07(0.02–0.12)
Health knowledge score (Medium for reference):		
High grade		0.53(0.48–0.58)
Low grade		2.01(1.17–2.85)
Household member being in city for work (No for reference)		
Yes (reference = no)		(0.02–12.29)
The intuitive feeling of your tap water		
Bad (references = bad)		(0.01–0.05)
Intra class correlation	0.35	0.38
Log-likelihood	824.11	810.76

4. Discussion

4.1. Characters of the Observed Adaptive Strategies to IWS

In this study, two typical adaptive strategies to IWS in northern and southern China were observed and investigated. IWS remains relatively widespread in China because it allows for flexible utility management, low water supply costs, and the optimizable allocation of water resources in regions with limited supply. There are two primary reasons why utilities use IWS in rural China: to decrease water supply operational costs, or as a response to inadequate water production. The primary reason for utility use of IWS in our study was to reduce electricity expenditures associated with water pumping (i.e., with water supply), which also represent the primary expenditure for water treatment plants in elsewhere in the study regions. Indeed, reducing water supply operational costs is a commonly cited motivation for why water system managers may deliberately transition from CWS to IWS. Inadequate water production capacity was the other primary reason cited for IWS in the two study areas. In our study, areas under IWS were provided water 1–2 times per day. Water supply hours were decided according to population densities and water use data. Hence, periods such as morning, evening, or meal preparation times were often selected to accommodate basic water consumption demands.

The two IWS-associated strategies we observed have their own relative advantages and disadvantages. From the perspective of changing from IWS to CWS, such a transition would be easier for Hubei. If the water treatment plant could secure sufficient external support to afford 24-hour water supply, the only required adjustment from households would be to shut down the valves on their roof water tanks. Indeed, at present, for the households in Hubei, if the water supply lasts long enough between supply intervals, and the storage capacity of the roof water tank is sufficient, for all intents and purposes many such residents may feel they have CWS. However, even for such households we observed water quality-related risks from substandard tank materials, excessive storage durations, infrequent tank cleaning, and incorrectly installed water flow systems.

In Shandong where the day-to-day situation was less convenient, households reported higher rates of dissatisfaction with IWS. Surveyed residents in Shandong and Hubei both wished to change from IWS to CWS, but the percentage of people willing to pay for such a transition was higher in Hubei, which may be related to the higher incomes in Hubei (as discussed above).

The primary health risk for both regions was unsafe household water storage [30,31]. This is due to a number of factors. In areas where the water supply contains a residual chlorine disinfectant, over time it will gradually decrease, thus increasing the risk of microbial growth. A study in Mali, for example, showed that households which stored water overnight had inadequate free residual chlorine detected the following day, and Coliforms were detected in 48% of stored household water samples [32]. In addition to long storage durations, we observed sources of pollution around the water storage containers, uncovered water tanks, and infrequent tank disinfection—factors associated with secondary contamination in other studies [33]. In addition, more than 40% of the water storage tanks used by study households did not have government-required hygienic certification.

4.2. Impacts of Different Adaptation Strategies to IWS

IWS is often classified as predictable, irregular, or unreliable intermittency, based on the characteristics of the water supply [9]. The two IWS systems described in this paper were both predictably intermittent, meaning water the was usually supplied within a predictable period, and with relatively constant water pressure during each supply period. Although IWS often results in insufficient water quantity, which has been reported in many studies, this was not observed in either of our study locations. This might be attributed to the regular water supply cycle, duration of water supply, as well as household ability to purchase and install water storage infrastructure.

Previous IWS-focused research suggests that IWS results in a series of water and sanitation-related behavioral changes at the household level, including increased water storage, reduced overall domestic water consumption, and reduced face and/or handwashing [19]. Our study also revealed indoor water consumption behaviors associated with IWS. Contrasted with the CWS group, a higher proportion of families with IWS used drinking water dispensers, with both utility-supplied and retail bottled water. In both study areas, this use of bottled water dispensers as the household's primary source of drinking water was higher in the IWS groups compared to the CWS groups, suggesting higher reliance on bottled water for those living under conditions of IWS, though this difference was only statistically significant in Shandong (96% vs. 65%, $p < 0.001$).

Our study also found differences in hand washing between the two groups, in which IWS households often use containers such as washbasins to wash their hands, while CWS households mostly used tap water to wash their hands. These findings mirror those of Fan et al [19]. As hand washing is one of the key protective measures associated with reductions in diarrhea and some intestinal infectious diseases [34], reduction of personal hand washing frequency under IWS would be expected to increase health risks for individuals. In addition, household-cleaning behaviors in the IWS group were also observed to be less frequent than those in CWS, and study investigators observed poorer sanitary conditions in the homes, yards, kitchens, and toilet facilities of IWS households—a phenomenon likely related to insufficient water availability in IWS regions.

For residents in our study areas, IWS did not appear to be associated with adverse socio-economic impacts, except for the relatively low rate of water supply satisfaction. However, anecdotal evidence from our study suggests that many of those living under conditions of IWS believe that their lack of access to CWS may reflect larger socio-economic inequities, since they are aware that many similar communities in China do have CWS. At the same time, IWS can actually increase utility economic losses. In the short and medium term, IWS decrease the power expenses (the largest part of the cost of most water treatment plant operations), however, in the long run, higher water losses and pipe network damage brought about by IWS serve to increase the costs for water treatment plants, and the would-be savings in electricity costs would not be sufficient to cover these longer term repair and water loss related expenses.

4.3. Recommendations to Improve Rural IWS Management

Considering the water quality risks from IWS and unsafe household water storage, the management of rural IWS should be strengthened further. At the village level, water storage facilities or advanced treatment equipment could be installed and maintained by the village committees, and then more clean and continuous water could be supplied to villagers. In situations in which adaptive measures at the village level are not feasible, improved household water-storage could be promoted. To achieve these—and other water safety related goals—we advocate the use of drinking Water Safety Plans (WSP) for water quality management of intermittent water supply [35,36]. WSP is a systematic risk management tool for rural supply systems, though its application in China remains limited to date [37]. The overall aim of WSPs is to ensure the consistent provision of safe drinking-water supply. In the case of IWS, as it presents greater risks for the entry of contaminants in the distribution network (due primarily to low pressures and back-flows into broken pipes), the key objective is to maintain the integrity and safety of the distribution system. Guidance on how to implement WSPs in distribution systems, especially under conditions of IWS, has been provided by WHO [38]. With respect to IWS in China, the following water quality factors and risks should to be assessed and addressed when implementing WSP: (1) Microbial pollution in IWS networks; (2) at the initial stages of water supply, aesthetic parameters (including turbidity, iron, manganese) may be abnormal; and (3) risks of drinking water quality caused from inadequate or improper household water storage.

To strengthen water quality management under IWS, we propose the following: (1) Setting reasonable water supply frequencies and periods for IWS, avoidance of extended water storage in water treatment plants (which reduces residual disinfectant), and reducing the continuous negative pressure in pipe networks (since it will increase the risk of wastewater intrusion); (2) promoting the use of appropriate water storage facilities, especially safe domestic water storage or water supply equipment. More broadly, while increasing reliance on retail bottled water in many rural areas is problematic in a number of respects [39], in areas of rural China where safe CWS is not feasible, local government should be encouraged and supported to provide drinking water treatment kiosks which local residents can use to fill up reusable 19L water bottles at minimal costs (i.e., much lower than the costs for retail bottled water). (3) Health and hygiene education programs on how to use tap water under conditions of IWS should also be emphasized.

5. Conclusions

Due to the limited availability of water resources and increasing populations and demand, it was inevitable that utilities in some areas in rural China would opt to use IWS. From a water quality and health perspectives, as well as that of adequate water availability/quantity, the two IWS systems observed in this study do appear to be meeting basic water safety and supply requirements. Overall, we found that (1) adaptation strategies to IWS in northern China tended to yield safe but inconvenient drinking water, while adaptation strategies in southern China tended to yield convenient but unsafe drinking water; (2) no water and sanitation-related behavior changes were observed in either IWS groups (compared to comparison groups), indicating that households did have sufficient water supply in both areas; and (3) although we observed many sources of potential risk in the water treatment and distribution processes, the water supply infrastructure was in relatively good condition overall. Although IWS in these study areas did not appear to measurably impact consumers' satisfaction with their local water supply, more attention should be paid to the water quality management of IWS in order to safeguard public health, as well as water supply infrastructure. We therefore recommend the use of Water Safety Plans to improve drinking water supply management better ensure safe drinking water supply under conditions of IWS.

Author Contributions: Conceptualization, H.L.; methodology, H.L. and A.C.; software, H.L. and X.Z.; validation, Z.L. and Z.Z.; investigation, S.L. and H.Z.; resources, H.L., S.L., and H.Z.; writing—original draft preparation, H.L.; writing—review and editing, A.C.; visualization, H.L.; project administration, H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Operation Project of Public Health Emergency Response Mechanism, China CDC.

Acknowledgments: The authors thank John M. Jr Colford, Isha Ray, Ayse Ercumen, and other colleagues at the University of California, Berkeley, for their advice on study design. The authors also extend thanks to staff at the Zhongxiang CDC and Zibo CDC for their support with, and collaboration on, the data collection and field work for this research.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Methods for water quality parameter.

Parameter	Method[1]
Color	Eye-measurement colorimetry of platinum-cobalt color-code
Turbidity	Scattering method (Formazine standard)
Odor	Smell method
pH	Glass electrode method
Total hardness	EDTA titration method
Iron	Atomic Absorption Spectrophotometry
Manganese	Atomic Absorption Spectrophotometry
Chlorine dioxide	DPD ammonium ferrous sulfate titration
Total Bacteria (TB)	Standard plate-count
Total coliform bacteria (TC)	Plate counting method
Thermotolerant coliform bacteria (TTC)	Multi-tube Fermentation Method

Note: [1] Water quality testing was conducted in accordance with China's Standard Examination Methods for Drinking Water (GB/T 5750-2006).

Table A2. Multilevel logistic model outcome and independent variables.

Variables or Variable Description	Categorization/Coding
Outcome variable	
Are you satisfied with the performance of water supply in your village?	Very satisfied or satisfied = 1; Unsatisfied = 0
Independent variables	
Level 1 (Village)	
Water quality could meet the national standard in the historical monitoring in the villages	Yes = 0; No = 1
Whether health education on water and health has been organized in the village	Yes = 1; No = 0
Is the tap water free for the households in the village?	Yes = 1; No = 0
Level 2 (Individual)	
Sex	Male = 1; Female = 0
Education	Junior high school and above = 1; Primary school and below = 0
Health knowledge score	High grade (8~10) = 2; Medium grade (4~7) = 0; Low grade (0~3) = 1
Is there anyone in the family working outside the village?	Yes = 1; No = 0
Subjective assessment of drinking water quality	Bad = 1; Good = 0

Table A3. Household water storage behavior differences in IWS and CWS groups

Household Water Storage Behavior	IWS (%) n = 200	IWS (%) n = 200	*p*-value¹
The material of the water storage facility			
Stainless steel	5.5	1	<0.001
Iron	2.5	0.5	
Wood	0	0	
Ceramics	26.5	6.5	
Plastics	22.5	14	
Others	2	16	
Is the water storage facility sealed or covered with a lid?			
Yes	46	25.50%	0.07
No	13	13	
Is the water storage facility with an approval document?			
Yes	34.5	18	0.109
No	24.5	20.5	
Is the water storage facility clean?			
Very clean	17.5	17	0.104
Clean	37.5	20	
Not clean	4	1.5	
How often do you have a routine cleaning on the water storage facility?			
Never	3.5	2	0.766
Daily	4	2.5	
At least once a week	28.5	19	
At least once a month	17.5	9	
Once a month	6	6	
How do you take water from the storage facility?			
Spoon with handle	45.5	35	-
Spoon without handle	0	0.5	
Pouring water directly	0.5	0	
The material of the roof water tank			
Stainless steel container	37	2	0.145
Irony container	3	0.5	
Aluminum alloy container	1	1	
Plastic container	6.5	0	
Other	8.5	0	
The way you purchase the roof water stank?			
Private provider	10	1	0.519
Stores	27.5	1.5	
Online shopping	10	0	
Other	18.5	0	
How long it will take water in the water storage container to be completely renewed?			
<24 h	35	44	0.223
1–2 days	2.5	1	
2–3 days	1	1.5	
>3 days	61.5	53.5	
Do you use disinfectant when cleaning the water storage facilities			
Yes	0.5	0	-
No	56	2.5	

How to disinfect the water storage after washing			
No disinfection	84.5	37	0.151
Direct-sun exposure	10	2	
Disinfectant	0.5	1	
Other ways	0.5	2	
Is there stagnant water in the storage facility			
Yes	11	17	0.042
No	84.5	32	
Usage of the stored water			
Drinking	44.5	12	<0.001
Cooking	81	31.5	
Washing	86.5	22.5	
Watering the plants or flowers	38.5	6.5	
Showering	58.5	8.5	
Toilet flushing	43	2	
Other	2	20	

Note: [1] *p*-value based on the chi-square test or Fisher's exact test (for an expected value lower than 5).

Table A4. Residents' attitudes to IWS in Shandong and Hubei mode

Questions	Shandong (%)	Hubei (%)	x^2	*p*-value[1]
Is your life affected by intermittent water supply?				
Yes	86.0	63.0	12.74	0.0003
No	14.0	37.0		
Do you think it is necessary to change IWS to CWS?				
Yes	80.0	91.0	4.03	0.04
No	20.0	9.0		
Are you willing to pay for changing IWS to CWS?				
Yes	54.0	80.0	14.13	0.0001
No	46.0	20.0		

Note: [1] *p*-value based on the chi-square test or Fisher's exact test (for an expected value lower than 5).

Table A5. Residents' satisfaction to local water supply in Shandong and Hubei mode

Questions	Shandong			Hubei		
	IWS (%)	CWS (%)	*p*-value[1]	IWS (%)	CWS (%)	*p*-value[1]
Are you concerned about drinking water quality?						
Yes	68.0	60.0	0.24	91.0	86.0	0.27
No	32.0	40.0		9.0	14.0	
Are you satisfied with your drinking water quality?						
Yes	84.0	87.0	0.54	75.0	77.0	0.42
No	16.0	13.0		25.0	33.0	

Note: [1] p-value is based on the chi-square test.

References

1. Kumpel, E.; Nelson, K.L. Intermittent Water Supply: Prevalence, Practice, and Microbial Water Quality. *Environ. Sci. Technol.* **2016**, *50*, 542–553, doi:10.1021/acs.est.5b03973.

2. Ping, L.; Fangyi, L.; Dianping, Z.; Jianzhen, L.; Chao, M. Survey on Hygienic Quality of Rural Drinking Water in Zibo City, 2008–2011. *Prev. Med. Trib.* **2012**, *18*, 443–445.
3. Dianping, Z.; Qiguang, Z.; Ping, L.; Fangyi, L.; Pengfei, D. Impact of Urbanization Management on the Quality of Rural Drinking Water Supply in Gaoqing. *J. Environ. Hyg.* **2012**, *12*, 17–20.
4. Ze, C.; Yong, Q.; Fuli, S.; Wenjun, M.; Chunhui, G.; Baoyuan, Z. Analysis on emergencies by contamination of drinking water in recent 10 years in Beijing. *Chin. J. Public Health Manag.* **2008**, *24*, 31–33.
5. Yu, X.; Geng, Y.; Heck, P.; Xue, B. A Review of China's Rural Water Management. *Sustainability* **2015**, *7*, 5773–5792.
6. Li, H.; Zhang, Q.; Li, W.; Luo, Q.; Liu, K.; Tao, Y. Spatial analysis of rural drinking water supply in China. *Water Policy* **2014**, *17*, 441–453.
7. Jiang, Y. China's water scarcity. *J. Environ. Manag.* **2009**, *90*, 3185–3196.
8. Wu, P.; Tan, M. Challenges for sustainable urbanization: A case study of water shortage and water environment changes in Shandong, China. *Procedia Environ. Sci.* **2012**, *13*, 919–927.
9. Galaitsi, S.; Russell, R.; Bishara, A.; Durant, J.L.; Bogle, J.; Huber-Lee, A. Intermittent domestic water supply: A critical review and analysis of causal-consequential pathways. *Water* **2016**, *8*, 274.
10. Klingel, P. Technical causes and impacts of intermittent water distribution. *Water Sci. Technol. Water Supply* **2012**, *12*, 504–512.
11. Simukonda, K.; Farmani, R.; Butler, D. Causes of intermittent water supply in Lusaka City, Zambia. *Water Pract. Technol.* **2018**, *13*, 335–345.
12. Simukonda, K.; Farmani, R.; Butler, D. Intermittent water supply systems: Causal factors, problems and solution options. *Urban Water J.* **2018**, *15*, 488–500.
13. Tokajian, S.; Hashwa, F. Water quality problems associated with intermittent water supply. *Water Sci. Technol.* **2003**, *47*, 229–234.
14. Ayoub, G.M.; Malaeb, L. Impact of intermittent water supply on water quality in Lebanon. *Int. J. Environ. Pollut.* **2006**, *26*, 379–397.
15. Ellawala, K.; Priyankara, D. Consumer satisfaction on quantity and quality of water supply: A study in Matara, Southern Sri Lanka. *Water Pract. Technol.* **2016**, *11*, 678–689.
16. Jayaramu, K.; Kumar, B.M.; Prasanna, R. Customer satisfaction with domestic water supply in India–A study in Hubli city. *J. Environ. Earth Sci.* **2014**, *4*, 105–116.
17. Rong, Z.; Hongxing, L.; Xianfeng, W.; Fucheng, F.; Boyin, S.; Zhanshe, W.; QI, Z.; Yong, T. Current Situation Analysis on China Rural Drinking Water Quality. *J. Environ. Health* **2009**, *26*, 6–8.
18. Bivins, A.W.; Sumner, T.; Kumpel, E.; Howard, G.; Cumming, O.; Ross, I.; Nelson, K.; Brown, J. Estimating infection risks and the global burden of diarrheal disease attributable to intermittent water supply using QMRA. *Environ. Sci. Technol.* **2017**, *51*, 7542–7551.
19. Fan, L.; Liu, G.; Wang, F.; Ritsema, C.J.; Geissen, V. Domestic water consumption under intermittent and continuous modes of water supply. *Water Resour. Manag.* **2014**, *28*, 853–865.
20. Andey, S.P.; Kelkar, P.S. Influence of intermittent and continuous modes of water supply on domestic water consumption. *Water Resour. Manag.* **2009**, *23*, 2555–2566.
21. Muta'aHellandendu, J. Health implications of water scarcity in Nigeria. *Eur. Sci. J.* **2012**, *8*.
22. Aiga, H.; Umenai, T. Impact of improvement of water supply on household economy in a squatter area of Manila. *Soc. Sci. Med.* **2002**, *55*, 627–641.
23. Zérah, M.-H. Household strategies for coping with unreliable water supplies: The case of Delhi. *Habitat Int.* **2000**, *24*, 295–307.
24. Bei, E.; Wu, X.; Qiu, Y.; Chen, C.; Zhang, X. A Tale of Two Water Supplies in China: Finding Practical Solutions to Urban and Rural Water Supply Problems. *Acc. Chem. Res.* **2019**, *52*, 867–875, doi:10.1021/acs.accounts.8b00605.
25. Elala, D.; Labhasetwar, P.; Tyrrel, S.F. Deterioration in water quality from supply chain to household and appropriate storage in the context of intermittent water supplies. *Water Sci. Technol. Water Supply* **2011**, *11*, 400–408.
26. Fan, L.; Liu, G.; Wang, F.; Geissen, V.; Ritsema, C.J. Factors affecting domestic water consumption in rural households upon access to improved water supply: Insights from the Wei River Basin, China. *PLoS ONE* **2013**, *8*.

27. Cohen, A.; Tao, Y.; Luo, Q.; Zhong, G.; Romm, J.; Colford, J.M., Jr.; Ray, I. Microbiological Evaluation of Household Drinking Water Treatment in Rural China Shows Benefits of Electric Kettles: A Cross-Sectional Study. *PLoS ONE* **2015**, *10*, e0138451.
28. Finch, W.H.; Bolin, J.E.; Kelley, K. *Multilevel modeling using R*; CRC Press: New York, USA, 2019.
29. Rong, Z.; Hongxing, L.; Yong, T. Sanitary risk assessment on rural water Supply facility in China. *Chises J. Public Health* **2008**, *24*, 560–561.
30. Günther, I.; Schipper, Y. Pumps, germs and storage: The impact of improved water containers on water quality and health. *Health Econ.* **2013**, *22*, 757–774.
31. Oswald, W.E.; Lescano, A.G.; Bern, C.; Calderon, M.M.; Cabrera, L.; Gilman, R.H. Fecal contamination of drinking water within peri-urban households, Lima, Peru. *Am. J. Trop. Med. Hyg.* **2007**, *77*, 699–704.
32. Baker, K.K.; Sow, S.O.; Kotloff, K.L.; Nataro, J.P.; Farag, T.H.; Tamboura, B.; Doumbia, M.; Sanogo, D.; Diarra, D.; O'Reilly, C.E. Quality of piped and stored water in households with children under five years of age enrolled in the Mali site of the Global Enteric Multi-Center Study (GEMS). *Am. J. Trop. Med. Hyg.* **2013**, *89*, 214–222.
33. Jensen, P.K.; Ensink, J.H.; Jayasinghe, G.; Van Der Hoek, W.; Cairncross, S.; Dalsgaard, A. Domestic transmission routes of pathogens: The problem of in-house contamination of drinking water during storage in developing countries. *Trop. Med. Int. Health* **2002**, *7*, 604–609.
34. Zwane, A.P.; Kremer, M. What works in fighting diarrheal diseases in developing countries? A critical review. *World Bank Res. Obs.* **2007**, *22*, 1–24.
35. WHO. *Guidelines for Drinking-Water Quality*, 3rd ed.; World Health Organization: Geneva, Switzerland, 2004; pp. 48–73.
36. WHO. *Guidelines for Drinking-Water Quality*, 4th ed.; World Health Organization: Geneva, Switzerland, 2011; pp. 45–76.
37. Li, H.; Smith, C.D.; Cohen, A.; Wang, L.; Li, Z.; Zhang, X.; Zhong, G.; Zhang, R. Implementation of water safety plans in China: 2004–2018. *Int. J. Hyg. Environ. Health* **2020**, *223*, 106–115.
38. WHO. *Water Safety In Distrubution Systmes*; World Health Organization: Geneva, Switzerland, 2014; pp. 24–44.
39. Cohen, A.; Ray, I. The global risks of increasing reliance on bottled water. *Nat. Sustain.* **2018**, *1*, 327–329.