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Piped-Water Supplies in Rural Areas of the Mekong Delta, Vietnam: Water Quality and Household Perceptions

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Abstract: In the Mekong Delta (MD) in Vietnam, piped-water supply stations are being intensively built to reach the millennium development goal (MDG) to provide safe and clean drinking water resources to communities. However, studies focusing on the effectiveness of supply stations in reaching these goals are scarce to date. Water samples from 41 water supply stations in the MD were collected between June and October 2012. Water samples were analyzed for general parameters, salinity, nutrients, metal(loid)s and microbial indicator bacteria and compared with World Health Organization (WHO) and Vietnamese drinking water guidelines. In addition, 542 household interviews were conducted to investigate the connection rate to piped-water and people's perceptions regarding piped-water supplies. The results show that water guidelines were exceeded for pH (min. 6.2), turbidity (max. 10 FTU), Cl (max. 1,576 $mg \cdot L^{-1}$), NH_4 (max. 7.92 $mg \cdot L^{-1}$), Fe (431.1 $\mu g \cdot L^{-1}$), Hg (11.9 $\mu g \cdot L^{-1}$), and microbial indicator bacteria (max. total coliform 50,000 CFU 100 mL^{-1}). Moreover, more than half of the interviewed households with access to a piped-water supply did not use this supply as a source of drinking water due to (i) high connection fees; (ii) preference for other water sources; and (iii) perceived poor quality/quantity. Our study shows that the maintenance and distribution of water supply stations should significantly improve in order for piped-water to become a reliable drinking water source. Additionally, alternatives, such as rainwater harvesting and decentralized treatment facilities, should also be considered.

1. Introduction

One of the Millennium Development Goals is that by 2015, the population without sustainable access to safe drinking water and basic sanitation should be halved [1]. The Mekong Delta (MD) in Vietnam is a region where access to and availability of safe drinking water supplies are limited to date. In the region, shallow household groundwater wells are commonly present but are often contaminated with arsenic (As) and other metals [2]. Surface water is also widely available but is intensively polluted by nutrients, agrochemicals and microbial contaminants [3,4]. Rainwater is another popular drinking water source, although most people do not have sufficient storage capacity to supply water-year round [5] and the quality is often deteriorated by a variety of factors including unhygienic post-harvest practices [6]. As a result, Vietnam has a high rate of water-borne diseases. For example, 8.5% of all deaths are caused by diarrhea, which is likely to be partially related to inadequate water quality [7]. Access to safe and clean water is therefore a priority in the region and water supply facilities are considered to be a main solution to this problem, as stated in the National Target Program for Rural Water Supply and Sanitation [8]. This program is sponsored by a variety of countries and its aim is to provide access to safe and clean water for 85% of the rural population in Vietnam by 2015 [9]. In contrast, to date, less than 10% of the rural population in Vietnam is connected to piped-water supply systems [5]. The importance of piped-water supplies in achieving an improvement in the health conditions of the rural population is emphasized in a variety of studies. Esrey *et al.* [10] found a reduction in morbidity for various water-related diseases, such as diarrhea and dracunculiasis, due to improved water supplies and sanitation world-wide. A study in the rural areas of the MD found that people connected to piped-water benefited from better water quality and improved water availability while the risk of diarrhea was reduced in comparison with households that used other water sources [11]. Furthermore, it was found that the development of water supply systems is generally economically beneficial due to time savings (no water collection needed) and reduced illness and mortality [12]. However, other studies mention concerns regarding the role of piped-water supply networks as the only solution to overcome clean water supply problems. Reis and Mollinga [13], for example, found that some households in the rural areas of the MD did not connect to piped-water even when the networks were available, either due to their preference for other water sources or their inability to pay the connection fee or both. According to Carter [14], water supply systems in developing countries are often under-utilized, broken down or abandoned and that time-savings and health impacts remain limited. Furthermore, in Vietnam 40%–80% of water supply systems were found to be broken due to poor construction and natural disasters [5]. Tran *et al.* [15] reported problems regarding piped-water, including low reliability of water supply, high costs, and water quality aspects, such as odor, taste, and turbidity. These concerns are why many households prefer other water sources or store piped-water in jars and tanks prior to usage, leading to an enhanced risk of malaria and dengue due to the increased occurrence of habitats for mosquito larvae.

In this study, piped-water is defined as tap water from the distribution lines of a piped-water supply station. In general, this water source is considered to be a solution to providing safe (drinking) water to people in the rural areas of the MD by (inter)national authorities. However, studies on the quality of the water supplied by these stations are scarce to date. Water supply stations use either groundwater or surface water and apply various treatment techniques including sand and rock filtration, alum coagulation, chlorination and, in some cases, active coal. However, the quality of piped-water cannot *a priori* be assumed to be better than its original sources when treatments are poorly applied or when maintenance of supply stations is limited, which, based on the literature, could be a main concern in the MD. Moreover, it was found that the connection rate of rural people in the MD to piped-water networks is still insufficient to date [13]. Therefore, many people still rely on completely untreated or insufficiently treated water sources for domestic use and drinking water, such as surface water. The objectives of this study were therefore to: (i) investigate the piped-water quality from different sources (surface water and groundwater) for general parameters, Cl, nutrients, metal(loid)s, and microbial indicator bacteria and compare results with (inter)national drinking water guidelines; (ii) assess spatial differences in piped-water quality; (iii) compare piped-water quality with the quality of untreated water sources in order to assess the efficiency of applied treatments; and (iv) assess reasons for the low connection rate to piped-water supplies in rural areas of the MD. In this study, we describe the current status of piped-water supply stations in the MD, which is of interest to decision makers in order to improve management strategies. Furthermore, the findings of this study can be used to inform decision makers on the efficacy of water supply stations for providing the rural populations of the MD with safe drinking water.

2. Materials and Methods

2.1. Study Area

The MD is located in the south of Vietnam. Water samples were taken close to supply stations in the three delta provinces Can Tho, Hau Giang, and Soc Trang (Figure 1).

The region has a tropical climate that is influenced by the southwestern monsoon, which generates dry and wet seasons [16]. The MD is dominated by agricultural activities and is considered as the "rice granary" of Vietnam. Other agricultural activities like fruit orchards, aquaculture and upland crops are also common in the MD [17]. The total population was 17.3 million in 2011 [18]. The MD has a dense network of waterways including rivers, main canals and a variety of lower order canals. Most people in the MD live along these waterways and, thus, most houses are widely dispersed across the region. However, along rivers and intersections of main canals people settle in larger villages and cities. Since surface water is commonly available at most locations, this resource is used for a variety of functions including drinking, especially in rural areas that are not influenced by salinity intrusion. Other sources of water used for drinking in the rural areas include groundwater, especially since the 1990s [19], and harvested rainwater, while in (larger) villages and cities most people are connected to piped-water sources. In rural areas of the MD, piped-water supplies are also available at some locations.

Figure 1. Overview of the MD and the selected water supply stations for water quality analysis. The white dots indicate water supply stations that use surface water sources while the black dots represent supply stations that use groundwater sources.
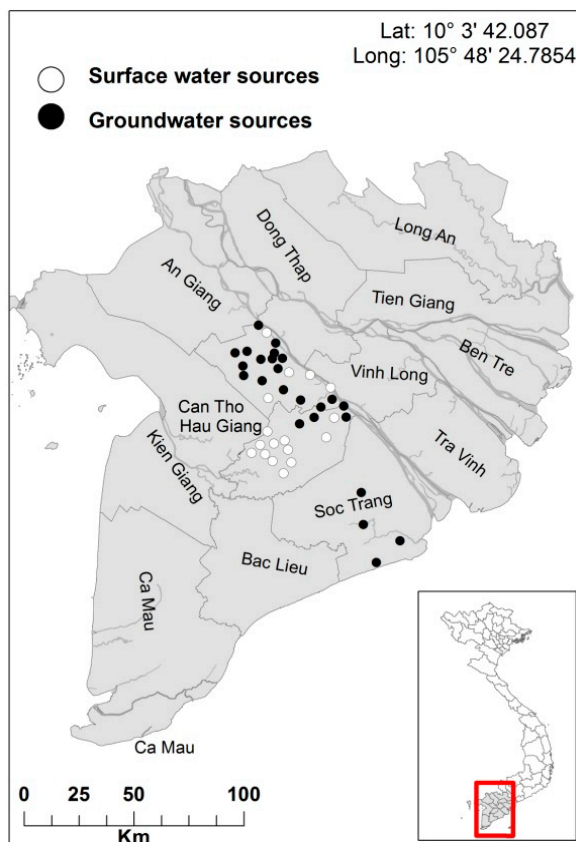
2.2. Water Sampling and Analytical Procedures

Piped-water samples were collected in 2012 in the rainy season from June to October, as part of a larger monitoring program of drinking water sources in the MD. In total, 41 water supply stations were selected in various regions of Can Tho, Hau Giang, and Soc Trang provinces in order to achieve good spatial representation and sufficient coverage for stations with both groundwater and surface water as intake sources. These provinces were selected as representative study areas of the MD based on land-use characteristics (rice, orchards, aquaculture, urbanization/industrialization) and hydrology (inland *versus* coastal areas) since investigating supply stations in the entire MD was too difficult, due to its large surface area (around 39,000 km^2). Initially, a desk-based study allowed for the identification of sampling locations (via satellite images) and these were subsequently localized in the field by GPS (Garmin eTrex, Olathe, KS, USA). Sampling locations were selected with the aim of achieving a representative coverage of the selected provinces. A working water supply station near the predefined location was then selected. However, a water supply station could only be assessed when it was possible to interview the water supply manager and permission was given to enter the water treatment plant. Even with such permission, sampling at the station was still a sensitive issue; thus the samples were taken directly from the tap of the household closest to the station, which was usually a few meters away from the supply station. Prior to sampling, water supply managers were asked to provide information regarding applied treatments and the intake water source. The supply stations

were also visited to assess treatment facilities and the intake point. Four water supply stations were selected in Soc Trang province, whereas 37 locations were selected in Can Tho and Hau Giang provinces (Figure 1). Only four locations in Soc Trang were selected due to relatively long travel times from this area to laboratory facilities in Can Tho City. Samples were analyzed for general parameters (Electrical Conductivity (EC), pH and turbidity), Chemical Oxygen Demand (COD), chloride (Cl), nutrients (ammonium (NH_4), nitrate (NO_3), nitrite (NO_2), ortho-phosphate (o-PO_4)), metal(loid)s (total arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), manganese (Mn), nickel (Ni), zinc (Zn), and magnesium (Mg)) and for microbial indicator bacteria (*E. coli* and total coliforms). Two-hundred-and-fifty-milliliter polyethylene (PE) bottles were used to store water for EC, pH, turbidity, COD, Cl, and nutrient analysis. Fifty-milliliter PE bottles were filled with water samples and acidified with 1% nitric acid (65%, Merck Millipore, Billerica, MA, USA) for metal analysis. Sterilized 100 mL glass bottles were used to store water for microbial analysis. All samples were cooled with ice and stored in the dark during transportation and delivered to the laboratory within 8 h of sampling. Electrical conductivity and pH were measured with a WTW Multi 340i (Weilheim, Germany) probe in the laboratory within 24 h of sampling. For COD, Cl and nutrient analysis, all samples were stored at 5 °C, pre-treated by syringe filters (0.45 μm, Minisart Satorius, Goettingen, Germany) and analyzed within 24 h. COD was analyzed with the reactor digestion method TNTplus^{TM} low range 3–150 mg·L^{-1} (Hach, Loveland, CO, USA), while Cl was measured by Spectroquant$^®$ cell tests with range 2.5–250 mg·L^{-1} (Merck Millipore, Billerica, MA, USA). For the nutrients, NO_3, NO_2 and o-PO_4 were measured using Merck Millipore Spectroquant$^®$ cell tests with the following ranges: NO_3-N: 0.5–18.0 mg·L^{-1}; NO_2-N: 0.002–1.000 mg·L^{-1}: PO_4-P: 0.05–5.00 mg·L^{-1} (Merck Millipore, Billerica, MA, USA). NH_4 was measured with Nitrogen-Ammonia Reagent Set, Test "N tube" with range 0.2–2.5 mg·L^{-1} (Hach, Loveland, CO, USA). Samples for metal analysis were stored in a fridge at 5 °C and analyzed within three months by inductively coupled plasma atomic emission spectroscopy (Thermo iCAP 6000, Thermo Scientific, FL, USA). Samples for microbial analysis were treated within 8 hours of sampling under sterile conditions by plating 1 mL of sample water on 3M™ petrifilm™ coliform count plates (3M, St. Paul, MN, USA) with replication (*n* = 2). *E. coli* and other coliform colonies were counted 24 ± 4 h after incubation at 37 °C. In order to assess water treatment efficiency, the quality of piped-water samples from stations extracting surface water were compared with the quality of 223 untreated surface water samples that were collected in the same region and time-span as the selected piped-water samples [20]. A comparison between piped-water extracted from groundwater and untreated groundwater was not performed, since no untreated groundwater samples from the locations and well depths that were used by the water supply stations (well depths 100–350 m) were available.

2.3. Household Interviews

A total of 542 households were interviewed in the rural areas of Can Tho, Hau Giang, and Soc Trang provinces. Several districts in these provinces were selected in order to cover the entire study region as optimally as possible. Moreover, the selected districts were in the same region as the selected water supply stations. After arrival at the selected districts, rural households were randomly interviewed with the following constraint: the minimum distance between two households was 500 m,

in order to prevent interviewing similar type households (e.g., a cluster of households connected to a piped-water supply station might not be representative for the region). Amongst other purposes, the interviews aimed to assess the availability, usage, and households' perceptions of piped-water supplies. Selected households were asked which water sources (surface-, ground-, rain-, bottled-, and/or piped water) they used for drinking and for domestic purposes, such as washing, cleaning, dishwashing, *etc.* In addition, households were asked (i) whether a connection to a piped-water supply station was available and (ii) whether this source was used for domestic or drinking purposes or both. If piped-water was used, a series of open questions was asked regarding the volume of piped-water used per month and how the quality of the piped-water was perceived. If piped-water was not used, despite being available, questions were asked to clarify the reasons for non-use. The monthly income of households was also assessed.

2.4. Data Analysis

Water quality from selected piped-water supply stations was compared with drinking water guidelines set by the World Health Organization and the Vietnamese Government [21,22]. Statistical tests were carried out with SPSS version 20.0. The differences in piped-water quality from stations using surface- and groundwater sources respectively were statistically assessed by applying the Mann-Whitney-U test. A non-parametric test was applied, due to the unequal amount of samples between datasets, the presence of outliers and the lack of normal distribution, which was verified with the Shapiro-Wilk test. The Mann-Whitney-U test was also applied to assess for significant differences between the quality of piped-water and the quality of untreated surface water, since the datasets were of unequal size and also lacked a normal distribution. Spatial differences in piped-water were assessed visually by plotting the piped-water stations that exceeded guidelines on maps. The results of the household interviews regarding availability and usage of piped-water sources are presented graphically.

3. Results

3.1. Piped-Water Quality

Although piped-water is expected to be a safe drinking water source, some water quality parameters were found to exceed the drinking water guidelines set by the World Health Organization (WHO), the Vietnamese Government (VG) and/or the European Union (EU) [21–24] (Table 1). The quality of piped-water was also found to be dependent on the original source (groundwater or surface water).

Significantly higher EC and pH levels were found in water from supply stations using groundwater compared with those using surface water. WHO and VG water quality guideline values for pH were exceeded in supply systems with both surface and groundwater intakes. Turbidity levels were also found to exceed the guideline values, although no significant difference was observed between supply systems using different water sources. Water quality guidelines for Cl were exceeded in 18% of the water supply stations with groundwater intake, whereas supply stations with surface water intake did not exceed the guidelines set by WHO and VG. For nutrients, the concentrations of NO_2 and NO_3 in all samples were low in piped-water when compared with guideline values. Relatively high concentrations of NH_4 were found for some supply stations with groundwater intake but overall there was no

significant difference in median NH_4 concentrations between the water supply systems with different intake sources. For metals, the concentrations of As, Ba, Cd, Mg, and Zn were significantly different between the two types of supply systems, although WHO and VG drinking water guidelines were not exceeded for any of the samples. In general, most of the piped-water samples investigated showed metal(loid) concentrations close to or below detection limit. However, Fe exceeded WHO and VG drinking water guidelines for 8% of the samples from piped-water with groundwater intake. Hg was detected in some piped-water samples for supply stations with surface- and groundwater intake. Values for Hg exceeded both WHO and VG guideline, VG levels being considerably more stringent than those of the WHO. Microbial indicator bacteria were also detected in some piped-water samples indicating that drinking this water can lead to health-related risks. No significant differences in microbial indicator bacteria cell counts were observed between the two types of supply stations.

3.2. Visualization of the Spatial Distribution of Stations Supplying Contaminated Water

Spatial presentation of the piped-water quality was performed to easily spot water supply stations where piped water quality exceeds drinking water guidelines (Figure 2). For the presentation of guideline exceedance on maps, the WHO drinking water standards were selected as they represent an international standard and can be compared with other regions around the world.

The maps show that in coastal regions, piped- water supplies were exclusively taken from groundwater sources. In southern areas of the inland region (Vi Thanh), only surface water was used. In the other regions (between Long Xuyen and Can Tho City) surface- and groundwater were both used for piped-water supplies. For turbidity levels (Figure 2a) and total coliform cell counts (Figure 2f), no spatial relationships were observed between locations and extraction sources, which indicates that the exceedance of drinking water guidelines of turbidity and total coliform concentrations were independent of supply station location and water source. In contrast, concentrations of Cl and NH_4 (Figure 2b,c) mostly exceeded drinking water guidelines at supply stations in the coastal region and only for stations using groundwater. The quality of groundwater that water supply stations use for extraction should be further investigated to assess the causes of elevated Cl and NH_4 concentrations. Two supply stations using groundwater in the inland regions exceeded drinking water guidelines for Fe, although this pattern was not observed for supply stations using surface water (Figure 2d). Two water supply stations in the coastal region exceeded drinking water guidelines for Hg, while this was only the case for one station in inland regions. However, all three supply stations that exceeded the guidelines for Hg used groundwater resources. Three water supply stations had multiple water quality concerns (not shown on the map). One station located east of Can Tho City exceeded guidelines for turbidity, Fe and total coliforms. Two stations in the coastal region exceeded guidelines for Cl, NH_4, Hg and total coliforms.

Table 1. Piped-water quality for 41 water supply stations in three provinces of the Mekong Delta (Can Tho, Hau Giang and Soc Trang). The stations were classified depending on the water source they use for intake. Significant differences in piped-water quality between stations using groundwater and surface water sources are assessed by the Mann-Whitney-U test and visualized by Z-values.

	WHO [a] Guidelines	Vietnam [b] Guidelines	Groundwater source					Surface water source					Statistical difference
			N	Median	Min	Max	%WHO–Vietnam[c]	N	Median	Min	Max	%WHO–Vietnam[c]	Z-value
Phy.chem. Parameters													
EC (dS m^{-1})	-	-	19	1072	110	2190	-	16	158	98	199	-	**−4.54#**
pH (-)	6.5–8.5*	6.5–8.5	22	7.6	6.2	8.3	5–5	9	7.0	6.3	7.3	11–11	**−2.55#**
Turbidity (FTU)	5*	2	24	2.5	0	8	13–54	17	3	0	10	6–71	−0.78
COD (mg L^{-1})	-	-	24	3.2	<3.0	8.3	-	17	<3.0	<3.0	9.2	-	−0.43
Salinity													
Cl (mg L^{-1})	250*	250	22	73	<2.5	1576	18–18	12	18	9	21	0–0	**−3.59#**
Nutrients													
NH$_4$ (mg L^{-1})	0.5 (EU)[d]	-	24	0.07	<0.02	7.92	21–	17	<0.02	<0.02	0.09	0–	−1.29
NO$_3$ (mg L^{-1})	50	50	24	0.6	<0.5	2.0	0–0	17	1.0	0.5	2.9	0–0	**−2.42#**
NO$_2$ (mg L^{-1})	3	3	24	0.004	<0.002	0.078	0–0	17	0.005	<0.002	0.011	0–0	−0.16
o-PO$_4$ (mg L^{-1})	-	-	22	0.15	<0.05	0.32	-	9	0.05	<0.05	0.14	-	**−2.97#**
Metal(loid)s													
As (µg L^{-1})	10	10	24	2.1	<2.0	8.2	0–0	17	<2.0	<2.0	2.3	0–0	**−2.82#**
Ba (µg L^{-1})	700	700	24	112.3	12.2	316.3	0–0	17	17.8	6.9	43.6	0–0	**−4.76#**
Cd (µg L^{-1})	3	3	24	<0.1	<0.1	0.6	0–0	17	<0.1	<0.1	0.3	0–0	**−2.16#**
Cr (µg L^{-1})	50	50	24	<0.4	<0.4	<0.4	0–0	17	<0.4	<0.4	<0.4	0–0	0.00
Cu (µg L^{-1})	2000	1000	24	1.1	<0.3	12.9	0–0	17	2.1	0.3	12.3	0–0	−1.19
Fe (µg L^{-1})	300*	300	24	24.4	3.0	431.1	8–8	17	26.6	7.3	163.8	0–0	−0.29
Hg (µg L^{-1})	6	1	24	1.2	<1.2	11.9	13–42	17	<1.2	<1.2	4.3	0–24	−1.62
Mn (µg L^{-1})	400	300	24	7.1	0.3	193.5	0–0	17	2.9	<0.3	297.3	0–0	−1.03
Ni (µg L^{-1})	70	20	24	<0.4	<0.4	1.4	0–0	17	0.4	<0.4	2.6	0–0	−1.76
Zn (µg L^{-1})	3000*	3000	24	2.9	<0.1	13.2	0–0	17	7.0	<0.1	84.0	0–0	**−2.32#**
Mg (mg L^{-1})	-	-	24	12.0	0.1	48.0	-	17	4.1	1.7	6.3	-	**−3.78#**

Table 1. *Cont.*

	WHO [a] Guidelines	Vietnam [b] Guidelines	Groundwater source					Surface water source					Statistical difference
			N	Median	Min	Max	%WHO–Vietnam[c]	N	Median	Min	Max	%WHO–Vietnam[c]	Z-value
Microbial indicators													
E.coli (CFU 100 mL^{-1})	0	0	24	0	0	100	12–12	17	0	0	0	0–0	−1.50
Total coli. (CFU 100 mL^{-1})	0	0	24	100	0	50,000	54–54	17	0	0	1400	29–29	−1.43

Notes: [a] World Health Organization guideline for drinking-water quality for chemicals of health concern [21]; [b] Drinking water quality guidelines set by the Ministry of Health in Vietnam [22]; [c] Percentages of piped-water samples that exceeds the World Health Organization and Vietnamese drinking water guideline respectively; [d] European Union quality guidelines for water intended for human consumption [23]; * Secondary drinking water guidelines by World Health Organization that are not a direct health-risk [24]; N: Number of samples; -:no guideline value set; [#] Significant different concentrations (p < 0.05); NB: the amount of samples for o-PO4, Cl, pH and EC are lower compared to other investigated parameters due to limited capacity in analysis equipment.

Figure 2. Spatial representation of water supply stations exceeding drinking water guidelines indicated by black boxes and dots for (**a**) turbidity level; (**b**) chloride; (**c**) ammonium; (**d**) total iron; (**e**) mercury; and (**f**) total coliforms.
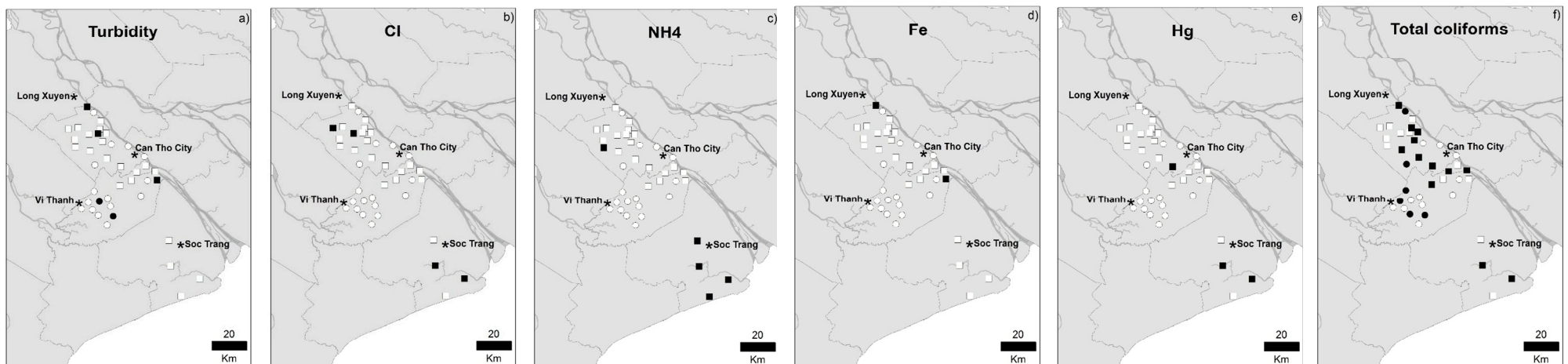
Notes: ○ / ● below / above guideline levels for piped-water supply stations that extract surface water;
□ / ■ below / above guideline levels for piped-water supply stations that extract groundwater.

3.3. Applied Water Treatments

Water supply stations apply various treatment techniques before supplying the water to the local communities. Interviews with water supply managers at the selected stations revealed that water was generally treated by rock and sand filters in combination with disinfection (chlorine), although at one site active coal was used. Water supply companies using surface water additionally apply a chemical treatment step with alum to remove suspended particles. After treatment, the water is usually stored in water towers from where it is distributed to the connected households. The effects of these treatments are clearly visible when the quality of piped-water extracted from surface water is statistically compared with the quality of untreated surface water (Table 2). A comparison of the quality of piped-water from groundwater intake with untreated groundwater was not possible due to a lack of deep groundwater quality data.

For surface water resources, EC and turbidity levels, as well as COD, were significantly lower in piped-water compared with untreated surface water. However, this pattern was not observed for pH values. Treatment was not found to have an effect on Cl levels. Concentrations of NH_4, NO_2 and o-PO_4 were strongly reduced by the water treatment systems while NO_3 concentrations were slightly higher after treatment. Generally, concentrations of metal(loid)s in surface water, especially Cr, Fe, Mn, and Ni, were significantly reduced by treatment at water supply stations. The concentrations of Cu and Zn were not significantly reduced by the treatment steps but concentrations did not exceed drinking water guidelines. Microbial contaminant concentrations were also significantly reduced by treatment, although *E. coli* and total coliform guidelines were still exceeded at some supply stations (Figure 2f).

Further investigation of the influence of separate treatment processes on water quality in order to assess the efficiency of the removal of pollutants in water is recommended.

Table 2. Median levels/concentrations of piped-water and untreated surface water in the selected study areas. Significant differences between the quality of piped-water with untreated surface water sources are visualized by calculated Z-values using the Mann-Whitney-U test.

	Surface water		
	Untreated source[a]	Piped-water surface water[b]	Statistical test (Z-value)
Phy.chem. Parameters			
EC	180	158	**−2.04[#]**
pH (-)	6.8	7.0	−1.43
Turbidity (FTU)	98	3	**−6.87[#]**
COD (mg L^{-1})	22	<3.0	**−6.46[#]**
Salinity			
Cl (mg L^{-1})	18	18	−0.08
Nutrients			
NH_4 (mg L^{-1})	0.7	<0.02	**−6.81[#]**
NO_3 (mg L^{-1})	0.5	1.0	**−4.04[#]**
NO_2 (mg L^{-1})	0.047	0.005	**−6.43[#]**
o-PO4 (mg L^{-1})	0.20	0.05	**−4.55[#]**

Table 2. *Cont.*

	Surface water		
	Untreated source[a]	**Piped-water surface water**[b]	**Statistical test (Z-value)**
Metal(loid)s			
As (μg L^{-1})	2.6	<2.0	**−4.43**[#]
Ba (μg L^{-1})	41.6	17.8	**−4.92**[#]
Cd (μg L^{-1})	0.2	<0.1	**−3.95**[#]
Cr (μg L^{-1})	5.0	<0.4	**−6.57**[#]
Cu (μg L^{-1})	3.4	2.1	−1.74
Fe (μg L^{-1})	2873.9	26.6	**−6.57**[#]
Hg (μg L^{-1})	1.6	<1.2	**−2.50**[#]
Mg (mg L^{-1})	5.5	2.9	**−3.51**[#]
Mn (μg L^{-1})	324.2	0.4	**−5.72**[#]
Ni (μg L^{-1})	3.0	7.0	**−6.18**[#]
Zn (μg L^{-1})	10.8	4.1	−0.96
Microbial indicators			
E.coli (CFU 100 mL^{-1})	3393	0	**−6.87**[#]
Total coli. (CFU 100 mL^{-1})	12272	0	**−6.87**[#]

Notes: [a] Untreated surface water samples collected in same region (results in preparation); n for untreated surface water is 101 for metals and Cl; 223 for other parameters; [b] piped-water quality from stations with surface water intake; n for piped-water with surface water intake is 917 (see Table 1); [#] Significant difference between piped-water and its original source at p < 0.05

3.4. Household Interviews

In total, 39% of households interviewed had potential access to piped-water distribution systems (Figure 3). In contrast, the other households (61%) had no possible access to piped-water, since a water supply station was not present or was not operational.

Figure 3. Availability and connection rate to piped-water in the rural areas of the selected sites in the MD (Potential access means that a functional piped-water tube is present in front of the house).
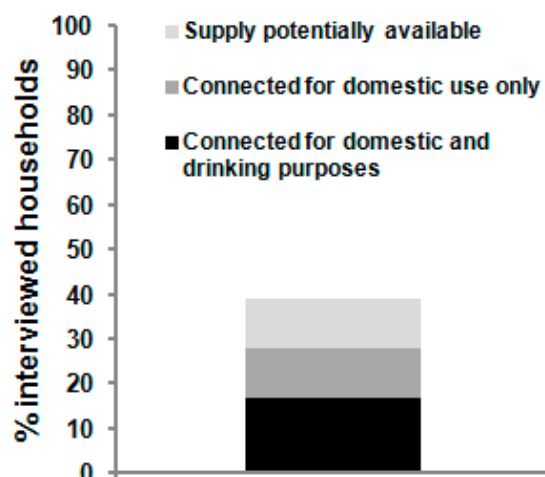
Of the households with possible access to a piped-water supply station, 27% preferred not to connect to the water supply station and used other water sources, such as groundwater for daily purposes. 30% of those with access were connected to the supply station but only used the water for domestic purposes like washing and cleaning rather than for drinking. The remaining residents (43%) with possible access to piped-water indicated that they drank piped-water and were generally satisfied with the quality of this water source, although these households also mentioned concerns regarding irregular water supply. Overall, less than 50% of all households with a potential access to the water supply system used this source for drinking purposes.

4. Discussion

4.1. Pollution of Piped-Water Supplies

This section discusses the potential causes of pollution of piped-water supplies and the reasons for communities to reject this water source for drinking. It should, however, be noted that the presented results are based on data collected from a selected area in the MD. Time and resource availability limited data collection to a subset of the rural population in the MD. Thus, piped-water quality outside the selected stations could be different than that presented in this study.

4.1.1. Salinity

Salinity, which is represented in this study by the concentration of Cl, was found to be unaffected by the treatment systems of water supply stations in the MD. Thus, when intake sources have high Cl concentrations this may lead to exceedance of the drinking water guideline in piped-water. Water supply stations with surface water intake did not show Cl concentrations above guideline values because: (i) water supply companies do not use the saline surface waters in coastal regions and (ii) inland surface waters are not affected by sea water intrusion [25]. On the other hand, saline groundwater bodies in the MD can be found in both coastal and inland regions. This finding is supported by Nuber *et al.* [26] who found Cl concentrations in groundwater ranging from 150 to 1200 mg·L^{-1} in inland provinces (two areas of Can Tho and Hau Giang). Our own groundwater samples in household wells with depths between 30 and 130 m in the region [20] also show elevated Cl concentrations at various locations in Can Tho, Hau Giang and Soc Trang provinces. The occurrence of saline groundwater bodies is likely to be the reason for the high Cl concentrations in piped-water from groundwater intake that was observed in 18% of the samples. As a consequence of increasing groundwater extraction and seawater intrusion, an increasing number of water supply stations using groundwater could be threatened by high salinity levels in the near future. Reis and Mollinga [13] reported that groundwater levels in the MD are decreasing at a rate of 0.5–0.7 m per year. This continuous decrease, which is mainly caused by overexploitation by supply stations, industry and domestic wells, might lead to the intrusion of more saline water from the coast into groundwater resources in the near future [19]. Furthermore, predicted sea level rise is likely to lead to further salinization of ground- and surface water resources. A possible solution for water supply stations affected by saline groundwater is to increase the use of surface water resources, which are less saline, especially in the inland provinces (Can Tho and Hau Giang), due to the continuous fresh water input from the Mekong River. However, surface water may contain

potentially hazardous chemicals like pesticides [4] and should therefore always be monitored for these substances. In the coastal region (Soc Trang province), surface waters already contain high loads of total salts due to sea water intrusions, with concentrations between 3 and 6 $g \cdot L^{-1}$ [27], which makes this source unsuitable for drinking. Therefore, groundwater is the main source for piped-water supplies in these regions. Moreover, suitable fresh groundwater resources in coastal areas are used intensively for irrigation purposes, e.g., for rice and onion cultivation. Given this high degree of reliance on groundwater, this resource should be wisely used, especially in coastal regions, to prevent further depletion of this valuable fresh water source in the near future. Moreover, desalinization techniques to make saline waters potable may still be too expensive for this developing region. A study by Wade [28], for example, revealed that desalinization costs by reversed osmosis are between 0.70 and 0.90 $US \cdot \$/m^3$. In contrast, the current water price in the MD is 0.25–0.85 $US \cdot \$/m^3$ [5], without desalinization treatments.

4.1.2. Nutrients

The concentrations of NO_2 and NO_3 in piped-water were low when compared to guideline values, which corresponds with the low concentrations of these nutrients in untreated water in the MD. In groundwater, reducing conditions lead to low NO_2 and NO_3 concentrations. Surface water also contains low concentrations of NO_2 and NO_3 since dissolved oxygen concentrations are low due to high water temperatures and high organic pollutant concentrations. Therefore, nitrification processes are expected to be minimal in these waters. In contrast, NH_4 was found in higher concentrations in piped-water compared with other nutrients, especially at stations in the coastal region. This could be explained by naturally high concentrations of NH_4 in groundwater at those locations which was not effectively removed during treatment. The inclusion of additional aeration techniques could further enhance nitrification processes which is likely to lead to a decrease in NH_4 levels in piped-water at those locations. Further reduction of NH_4 in drinking water is required since concentrations >0.5 $mg \cdot L^{-1}$ could severely affect disinfection efficiency by chloride. Phosphate concentrations in piped-water were significantly lower than concentrations in its untreated sources. This is likely to be the result of the applied sand filtrations. This result is in line with Berg *et al.* [29] who found that household sand filters in the Red River Delta in Vietnam reduced phosphate concentrations by 90%.

4.1.3. Metals

The concentrations of metal(loid)s did not exceed drinking water guidelines, except for Hg and Fe. The observed concentrations of Hg in piped-water were higher than the background levels in surface water and groundwater of 0.5 $\mu g \cdot L^{-1}$ [30]. The sources of Hg in piped-water could be explained by its natural presence in soils or could also be the result of external pollution by antiseptics, fungicides and other reagents containing mercury. Actual sources of Hg should be further assessed. The guideline exceedance for Fe in piped-water from groundwater sources could be caused by high natural concentrations in groundwater that were not completely removed by the treatment systems. Improved aeration techniques could further decrease Fe in piped-water supplies. Nevertheless, the quality of piped-water in the MD with respect to metals is in fact better when compared with other studies of metal contamination in piped-water sources. Berg *et al.* [31] detected As concentrations of between 25 and 91 $\mu g \cdot L^{-1}$ in water supplies after treatment in Hanoi, Vietnam, whereas As concentrations in

our study reached a maximum of 8.2 μg L^{-1}. In Karachi, Pakistan, elevated concentrations of Ni and lead (Pb) exceeding WHO drinking water guidelines, were detected in piped-water supplies [32]. Ni was only found in traces in our study and Pb was not investigated. The generally low metal concentrations in our study could be explained by the common usage of sand and rock filters. Those filtering techniques sufficiently remove metals like Fe and Mn [29] but might also remove other metals from water. The addition of alum to remove suspended solids from surface water in order to reduce turbidity levels and organic pollutants, could also contribute to reducing the concentration of metals in water, since many metals tend to adsorb to suspended materials. However, low metal concentrations in untreated surface- and groundwater resources could also account for the generally low concentrations in piped-water in our study sites.

4.1.4. Microbial Pollution

The observed amounts of coliform bacteria in piped-water were significantly lower than in untreated surface water (Table 2). It is likely that the removal of bacteria was mainly achieved by the application of alum, a flocculating agent which results in the settlement of suspended matter, typically containing high loads of pathogens. Nevertheless, *E. coli* and total coliform were commonly detected in piped-water samples (for both intake sources). Possible reasons for the presence of microbial indicator bacteria in treated piped-water may include failures of treatment processes as well as contamination in the pipe system. Firstly, the chlorination process might not be optimally managed. In one case, it was observed that the chlorine tank was completely empty while piped-water was still being processed. Secondly, it was observed during the field work that some storage basins for treated water were not covered, which could lead to external pollution by air-borne dust and bird droppings. A third possible reason for microbial contamination in piped-water could be decreased chlorination efficiency due to unfavorable water characteristics such as turbidity and high concentrations of NH$_4$. Turbidity levels higher than 5 FTU have been reported to negatively affect the efficiency of chlorination [33]. This threshold level was exceeded in 6% and 13% of studied piped-water samples from surface water and groundwater intake respectively. Duong *et al.* [34] found that chlorination efficiency is negatively affected by NH$_4$ concentrations >0.1 mg·L^{-1}. Especially in the coastal region, piped-water samples were found with NH$_4$ concentrations much higher than 0.1 mg·L^{-1}. A fourth reason for microbial contamination in piped-water supplies could be leakage in the distribution network between the supply station and the sampling point (our samples were collected at the closest household to the supply station which was typically within 25 meters of the supply station). In general, the maintenance and adequate operating of water supply stations is still a major challenge for rural water supply stations in the MD. However this situation is not unique to the MD but also occurs in other developing regions. In South Africa, for example, it was concluded that water quality from rural water supply stations did not meet water quality standards, including for pathogens, due to limited technical understanding of treatment processes by operators. As a result, coagulants and disinfectants were applied in low or high amounts, causing water quality problems [35]. Possible measures to reduce microbial pollution within piped-water supplies are (i) the inclusion of aeration techniques to improve nitrification processes for water sources with elevated NH$_4$ concentrations; (ii) reduction of the interaction between treated stored water and the open air to reduce external

pollution by airborne dust and bird droppings; (iii) improved management of water treatment plants and education of water supply operators in order to optimally supply coagulants and chlorine to piped-water; and (iv) prevention and repair of leaks in the distribution system.

4.2. Perceptions of Rural Communities of Piped-Water Quality

Although piped-water supplies are developed to provide safe and clean water to rural communities, only 43% of potentially connected households were actually using the water for drinking. Some households did not connect to piped-water at all, although there was a possible connection. Other households choose to connect, but indicated to use this water source for washing, cleaning and cooking only.

4.2.1. Reasons of Households Not to Connect to Piped-Water

Financial reasons were found to be a main reason for the low connection rate. Household interviews showed the initial connection fee in the rural areas to be around 1,000,000 VND (*ca.* 45 US$ in 2013), including the costs for the pipes and the installation of the connection. Many people perceived this cost as high. In comparison, interviewed households in the rural areas reported monthly earnings of 500,000–5,000,000 VND. Therefore, the connection fee can be regarded as high, especially for poor households in the rural areas of the MD. Another reason for rejecting piped-water supplies is the preference for other water sources for domestic services and drinking. Some households reported having a groundwater well or harvesting rainwater for daily purposes including drinking and therefore did not require a connection to piped-water. People with a groundwater well for example, had already made major investments to gain access to this water source and this could explain why these households do not desire a connection to piped-water. Other households were found to invest in large storage basins for rainwater storage, such as large tanks, and do not, therefore, require piped-water.

These findings are in line with Reis and Mollinga [13], who also found low connection rates to piped-water supplies in local communities in the MD due to financial reasons and preference of other water sources.

4.2.2. Reasons for Rejecting Piped-Water

An observed reason for rejecting piped-water supplies for drinking is the perceived poor quality of piped-water. In the MD, people judge the quality of drinking water mainly based on taste, smell and color [36]. In our study, some piped-water samples had elevated turbidity levels and Cl and Fe concentrations which affect color and taste, respectively. This may have contributed to the perception that piped-water would be unsafe and to its rejection as drinking water source and could explain the number of households that use piped-water for domestic purposes only. The reliability of supplied piped-water was another concern in some of the studied areas, which led to the fact that households used more reliable sources like groundwater and even surface water.

4.3. Alternative Water Supply Facilities

The observed water quality issues of piped-water may pose a severe threat to human health. Moreover, water quality and quantity concerns associated with piped-water lead to high rejection rates of this water source. Therefore piped-water cannot be regarded as the only solution for safe water supplies in rural areas of the MD. Other measures should be considered to provide safe and clean water to rural communities in the MD, such as harvested rainwater and surface and groundwater. Harvested rainwater, for example, could be a good alternative, especially for low-income families since, when properly stored, the quality is generally good when compared with groundwater and surface water [6]. However, the quantity of this water source could be insufficient in the dry season. Therefore, Point-of-Use (POU) treatment systems should also be encouraged to generate home-made safe water supplies from groundwater and surface water sources. Household treatment systems such as sand and/or iron filters were found to effectively remove contaminants including arsenic [29,37]. Another alternative is the development of decentralized water provision units (DWPU) that supply drinking water to remote communities by using the abundantly present surface- and/or groundwater resources. DWPU's can be equipped with low-tech, cheap and effective treatment measures to provide safe water to remote communities. Noubactep *et al.* [38], for example, propose the use of zerovalent iron between two layers of sand in order to effectively remove chemicals, arsenic, nitrate and viruses. Zerovalent iron based filters are affordable, appropriate and effective and thus a decent water treatment technique for remote communities [39]. Furthermore, the use of small, transportable and easy to use gravity-driven dead end membrane filtration units could be an effective way of supplying drinking water to remote communities [40]. In general, the combination of the use of harvested rainwater and decentralized water treatment plants in remote areas in the MD could significantly increase the quality of drinking water for communities, and will most likely reduce the prevalence of various water-related diseases.

5. Conclusions and Recommendations

Although piped-water is considered to be a safe and clean water source by the national government, WHO and Vietnamese drinking water guidelines are exceeded at water supply stations in the selected study sites of the Mekong Delta in Vietnam for pH, turbidity, Cl, NH_4, Fe, Hg, *E. coli*, and total coliforms (among the investigated parameters in this study). Furthermore, the quality of piped-water varies depending on location and intake source. Some piped-water supply stations that use groundwater resources were found to exceed drinking water guidelines for Cl, although this was not observed for supply stations using surface water. Due to overexploitation of groundwater resources in the MD for drinking, domestic and irrigation purposes, groundwater levels continue to drop which increases saline intrusion. Therefore, piped-water stations that use groundwater have a risk of becoming unsuitable, since desalinization techniques are too expensive for this developing region. The highest NH_4 concentrations in piped-water were detected at coastal supply stations and were due to high natural concentrations of this nutrient in groundwater which were not effectively removed by current treatment processes. In contrast, piped-water with surface water intake did not exceed WHO and Vietnamese drinking water guidelines at all for NH_4. Mercury (Hg) concentrations in piped-water

exceeded WHO guidelines for two out of four coastal supply stations, whereas this was only the case for one supply station in the inland provinces. Moreover, highest Hg concentrations in water were found at supply stations with groundwater intake. The reasons for elevated Hg concentrations in "piped-water should be further assessed. In addition to several quality issues associated with piped-water, the connectivity rate of rural communities to piped-water supply stations is also concerning. In the generally poor rural areas of the MD, many people cannot financially afford connection charges or do not switch to piped-water due to the presence of other easily accessible sources or the perceived poor quality and reliability of piped-water. Therefore, less than 50% of the rural community with a potential connection to piped-water actually uses this source for drinking.

In order to improve the quality of piped-water by further decreasing concentrations of NH_4 and metals like Fe, installation of aeration processes in supply stations is recommended. Water supply stations should also improve the management of their treatment system and prevent post-treatment pollution in order to prevent the occurrence of pathogens in piped-water supplies. It is also urgently recommended that management strategies be developed for a sustainable use of groundwater resources to maintain drinking water supplies for future generations. One such strategy in coastal areas could be the transition from crops with low salinity tolerance to agricultural systems which are more tolerant to high salinity levels in order to reduce the pressure on valuable groundwater resources. When supply stations are better maintained and are more reliable in terms of delivered quantity, the use of piped-water to communities may increase. However, in remote areas with scattered settlements, focusing on alternatives like proper rainwater harvesting techniques and decentralized (low-tech) water supply systems that can also provide safe water for these generally low-income households is recommended.

Author Contributions

The original research concept was developed by Fabrice G. Renaud and Zita Sebesvari. The sampling strategy, collection and physical/chemical and microbial analysis of the water samples was performed by Gert-Jan Wilbers. The development of the questionnaire was developed by Gert-Jan Wilbers, Zita Sebesvari and Fabrice G. Renaud. Gert-Jan Wilbers conducted all household interviews. Data analysis, interpretation and the writing of the paper was conducted by Gert-Jan Wilbers, Zita Sebesvari and Fabrice G. Renaud.

Conflicts of Interest

The authors declare no conflict of interest.

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