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Evaluation of Microbial Contamination of Groundwater under Different Topographic Conditions and Household Water Treatment Systems in Special Region of Yogyakarta Province, Indonesia

Indrastuti, Shinobu Kazama * and Satoshi Takizawa

Department of Urban Engineering, Graduate School of Engineering, The University of Tokyo, Bunkyo-Ku, Tokyo 113-8654, Japan; indrastuti@env.t.u-tokyo.ac.jp (I.); takizawa@env.t.u-tokyo.ac.jp (S.T.)
* Correspondence: kazama@env.t.u-tokyo.ac.jp

Abstract: Since the coverage of piped water is still only 20.1% in Indonesia, many people rely on groundwater for drinking and daily use, although the quality of the groundwater is not well understood. This study evaluated the influence of the topography, well type, groundwater abstraction depth, sanitation facility type, and distance between the well and the sanitation facility on the groundwater quality. In addition, a possible household treatment system was investigated based on microbial removal efficiency and household acceptance. The results showed the groundwater abstraction depth and well type were the most important factors in controlling microbial contamination. The sanitation facility type, except small-scale sewer systems, and the distance from a well were not significantly correlated with *E. coli* concentration. A high microbial concentration was found in a flat area with predominantly shallow wells, latrines, and septic tanks because the topographic conditions determined the commonly used well types and groundwater abstraction depth. The RO + UV system was the only system that assured microbial safety of treated water. The chlorination and microfiltration systems had difficulty with chlorine-dosage adjustment and microbial removal, respectively. Raising public awareness of water quality problems was found to be important to improve acceptance of household treatment systems.

Keywords: groundwater quality; *E. coli*; sanitation facility; groundwater abstraction depth; well type; household acceptance

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Citation: Indrastuti; Kazama, S.; Takizawa, S. Evaluation of Microbial Contamination of Groundwater under Different Topographic Conditions and Household Water Treatment Systems in Special Region of Yogyakarta Province, Indonesia. *Water* **2021**, *13*, 1673. https://doi.org/10.3390/w13121673

Academic Editor: Domenico Cicchella

Received: 29 April 2021
Accepted: 13 June 2021
Published: 16 June 2021

1. Introduction

Although 1.8 billion people around the world gained access to at least basic water services between 2000 and 2017, approximately 2.2 billion people (29% of the global population) still have no access to safely managed drinking water [1]. Approximately 4.2 billion people (55% of the global population) still lack safely managed sanitation services, although 2.1 billion people gained access to at least basic sanitation services [1]. There must be further efforts to achieve Sustainable Development Goal 6, ensuring access to safe and affordable drinking water for all by 2030 [2,3].

Groundwater via boreholes, dug wells, or tube wells is still a preferable source of drinking water in many developing countries because of its reliability and accessibility [1,4], although piped water was a more common source than other improved sources for the global population in 2017 [1]. The use of groundwater could increase access to at least basic water services; however, population growth without adequate environmental protection can lead to a deterioration of groundwater quality [5–7]. In many developing countries, especially in rural areas, pit latrines and septic tanks have been installed as improved sanitation facilities because of the low cost and simple construction, operation, and maintenance [1,8,9]. However, those facilities can potentially contaminate groundwater with enteric pathogen because of improper construction and operation and maintenance.

Rainfall can accelerate infiltration of contaminants into groundwater [10]. In addition, groundwater vulnerability to contamination is attributed to hydrogeological properties such as a shallow depth to groundwater wells and high hydraulic conductivity [11]. The improper installation of improved sanitation facilities could consequently cause diarrheal diseases [12,13]. Frequent diarrhea by chronic exposure to enteric pathogens causes malnutrition, which can lead to stunting [14,15].

To cope with the contamination of drinking water sources, household water treatment systems, such as chlorination and filtration, have been installed as a promising strategy to provide clean water [16,17]. However, improper installation and operation and inadequate maintenance of those systems cause insufficient reduction of contaminants [1,18–20]. The matrix of source water (e.g., microorganism concentration, turbidity, pH, and temperature) also influences the contaminant removal efficiency of those systems [21].

Many people in Indonesia also rely on groundwater for drinking and daily use as in other developing countries since the coverage of piped water is still only 20.1% [22]. Among 34 provinces in Indonesia, Special Region of Yogyakarta (SRY) is the second smallest province. Only 13% of the population have access to piped water, while around 70% of population still rely on private wells [23]. Only 13% of the population have access to improved sanitation facilities [24]. According to a water quality survey in SRY, 89% of drinking water sources were contaminated by *E. coli* [23]. Notably, infectious diarrhea is commonly found in SRY, with 59,638 cases in 2019 (prevalence: 15 cases per 1000 persons) [25]. Two out of the five districts in SRY, Bantul and Kulon Progo, have high stunting rates (23% of the population in each district) [26].

The Indonesian government, since 2018, has promoted the installation of septic tanks as one of the strategies to prevent infectious diarrhea and eventual stunting in the districts [27]. The expectation for the installation includes improving the groundwater quality by increasing access to improved sanitation services, although coverage is still very low in the districts. However, there is no other active promotion strategy to protect groundwater from pollution and improve its quality because there is no coordinated system for monitoring groundwater quality. Although there are several reports on the influence of well type and depth, distance to sanitation facilities, and geological and hydrological characteristics [28–34], it is necessary to monitor groundwater quality and evaluate the condition of wells and sanitation facilities in order to have an effective strategy for protecting the groundwater. Since the level of such influence varies depending on site-specific conditions [35,36], more empirical studies are needed. Although detailed information of the factors affecting the groundwater quality, e.g., geological and hydrological characteristics, is very limited, studies using available information are desired for the understanding groundwater quality not only in SRY, but also other areas of Indonesia and other countries.

Since SRY comprise several types of topography in terms of slope gradient [37], different types of wells and sanitation facilities have been used depending on the topographic and socioeconomic conditions [38]. This study, therefore, was aimed at elucidating the influence of topography, well type, groundwater abstraction depth, sanitation facility type, and distance between the well and the sanitation facility on groundwater quality in SRY. The groundwater quality analysis, focusing on the microbial contamination, was conducted in five villages with different topography in Bantul District. In addition, several types of household treatment systems were installed with the aim to evaluate the efficiency of removing *E. coli* and total coliform (TC) within the village setting and the level of household acceptance. These results of this research would be relevant to the researchers and international audience because people dependent on groundwater resources are also living in areas with different topography in Indonesia and also in other countries. Although there are different types of household treatment systems, their comparison would provide useful information on selection of the suitable household water treatment systems in other areas as well.

2. Materials and Methods

2.1. Study Areas

Special Region of Yogyakarta, in the middle part of Java Island, is the second smallest province in Indonesia after DKI Jakarta Province. The population of SRY as of 2020 was around 3.8 million, and it is predicted to reach 4 million by 2025 [39]. Only 13% of the population have access to piped water, while the rest still rely on private wells (70%), such as dug wells, shallow wells, deep wells, and bottled water (17%) [38]. Only 6% of the population have access to a sewer system, while 7% use septic tanks, 86% use latrines, and 1% still use open defecation [24].

Bantul District, one of five districts in SRY, is located in the southern part of SRY and approximately 20 km from the capital city of the province, Yogyakarta city (Figure 1). This district has a total area of 508.13 km^2 and had a population of 949,325 in 2019 [39]. Figure 1 shows the topography (slope gradient) and distribution of 5 villages in Bantul District. This district has a varied topography (Figure 1): flat area with less than 2% slope (62% of the district area), sloping area ranging from 2.1 to 7% slope (30%), and hilly area with more than 40% slope (8%). The flat area is mainly found in the middle part of the district, the sloping area in the western part, and the hilly area in the eastern part [37]. Five villages—Canden, Patalan, Triwidadi, Jatimulyo, and Terong (Figure 1)—were selected as the study areas considering the variety of topography, well types, and sanitation facilities.

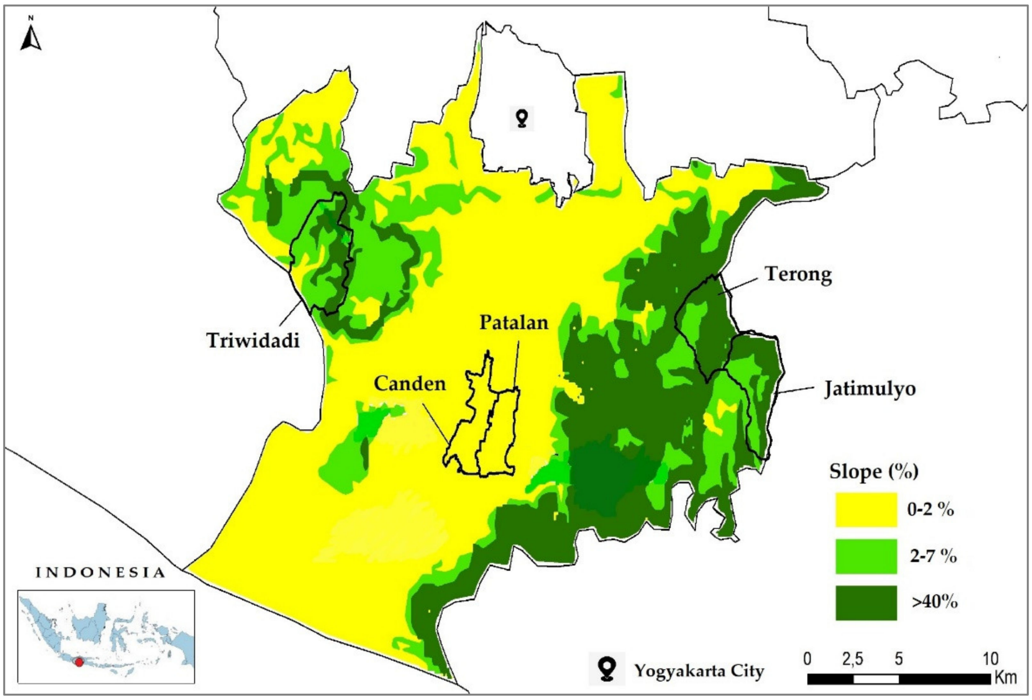


Figure 1. Bantul District with topographic information (slope gradient) and observed villages.

The piped water supply system covers only 11% of the population in Bantul District. The rest depends on private or communal wells (69%) and other sources such as bottled water and rainwater (20%) [38]. Almost all households using wells pump up groundwater to faucets within the house. The types of wells used in the district are unprotected dug wells, shallow wells, and deep wells (Figure 2). The groundwater is only used for domestic purposes since there is no industrial area in the district. All households use a similar type of small pumps with a pumping rate of 10–30 L/min, and abstract 300–600 L/d.

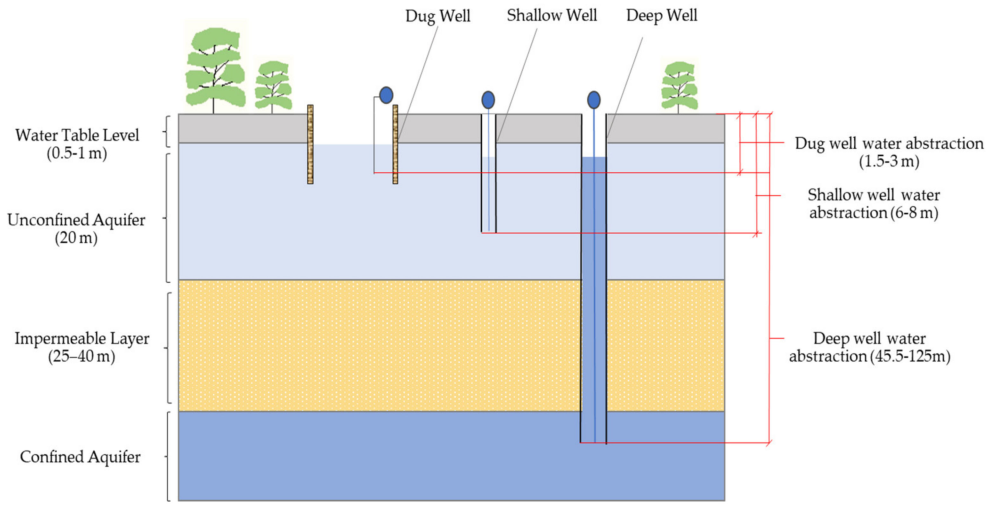


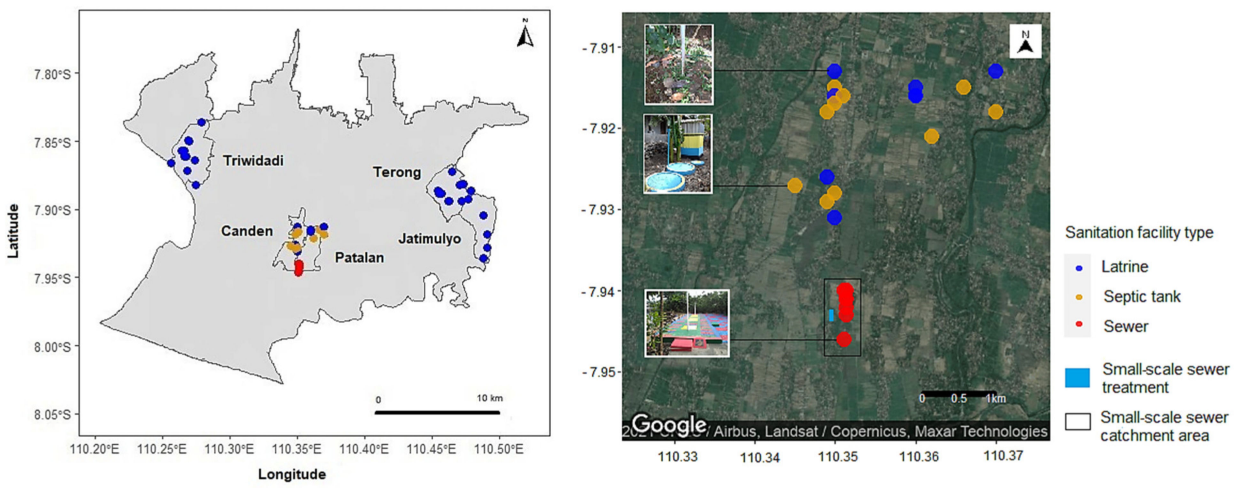
Figure 2. Well types, aquifer depth, and aquifer source in Bantul District.

The dug wells were made to the depth of an unconfined aquifer and lined with stones or concrete. The shallow and deep wells were constructed using iron or polyvinyl chloride (PVC) pipes. The sources of the shallow and deep wells are unconfined and confined aquifers, respectively (Figure 2).

The water table level varies in the district depending on the topography. The water table is about 0.5–1 m deep from the ground in the flat area, more than 14 m deep in the sloping area, and 2.5–20 m deep in the hilly area. The aquifer depths, i.e., the abstraction depths of the wells, in the sloping and hilly areas are deeper than in the flat area, which made it difficult to drill a well in the sloping and hilly areas. Thus, the local government provided some communal deep wells in these areas. The distance between a faucet and a dug well or shallow well is 1–3 m, as those wells are located on the premises. On the other hand, the distance between faucets in houses and deep wells varies from 50 m to 2 km because they are communal wells.

Almost all households have access to a private sanitation facility such as a latrine (78% of the population), a septic tank (14%), or a sewer system (6%), including small scale sewer systems (serving 75–100 households) and a city-wide system [40]. Three types of sanitation facilities namely latrines, septic tanks, and small-scale sewer systems (approximately 75 households within 0.025 km^2 area), are used in only Canden, while latrines or septic tanks were used in other villages (Figure 3, Table 1). The density of latrines and septic tanks can be assumed to be in the range of 2500–3000 facilities per km^2 based on the population and average number of household members (4 people).

Although the information of geological and hydrological characteristics is limited, geologically, alluvium sedimentary soils with sandy, gravel, and clay structures are dominated in the middle part of the district. Sandstone is commonly found in the western area, while the limestone in the eastern area [41]. Based on the previous study [41], the flat topography can be categorized as a high hydraulic conductivity area, while the sloping and hilly areas are in the low area. Hydrologically, since the groundwater flows from the upper western and eastern parts to the middle of the district, the sloping and hilly areas can be categorized as the upgradient area of groundwater flow, while the flat area is in the downgradient [41].



(**a**) (**b**)

Figure 3. (**a**) Sampling locations, (**b**) location of the small-scale sewer system and its catchment area in Canden. The dots represent the households collected water samples.

Table 1. Topography, groundwater source, number of well types, and sanitation facilities in sampling locations of each village.

Condition	Canden	Patalan	Triwidadi	Terong	Jatimulyo	Total
Topography	Flat	Flat	Sloping	Hilly	Hilly	
Slope	<2%	<2%	2.1–7%	40%	40%	
Aquifer source	Unconfined	Unconfined	Unconfined Confined	Unconfined Confined	Unconfined Confined	
Water table level (m)	0.5–1	0.5–1	>14	9–20	2.5–10	
Well type						
Dug well [1]	12	6	9	8	3	38
Shallow well [1]	2	7	-	-	-	9
Deep well [1]	-	-	3	5	1	9
Groundwater abstraction depth (m)						
Dug well	1.5–3	1.5–3	>15	10–20	3–10	
Shallow well	6–8	6–8				
Deep well			>42	>72	>125	
Sanitation facilities						
Small-scale sewer [1]	7	-	-	-	-	7
Septic tank [1]	4	7	-	-	-	11
Pit latrine [1]	3	6	12	13	4	38
Distance (m)	3–1500	2–10	2–10	2–10	2–10	
Total sampling points	14	13	12	13	4	56

[1] Condition of the sampling points.

2.2. Groundwater Quality Analysis

Groundwater quality analysis was conducted in November and December 2020 (rainy season). Groundwater samples were collected at 56 houses in the 5 villages. The water samples were taken from faucets after 1 min of flushing. The measurement of *E. coli*, TC, total iron, turbidity, pH, and water temperature was carried out in the field. Detailed information on the sampling locations, including sample number, topography, well type, and sanitation facilities, is shown in Table 1.

E. coli and TC were enumerated using the membrane filtration method (Method 10029, USEPA): 100 mL water samples were filtered through a disposable monitor unit (37 mm monitoring unit, mixed cellulose ester, pore size: 0.45 µm; Advantec, Japan). The culture medium (m-ColiBlue 24 Broth; Hach, Loveland, Colorado, USA) was added to the monitor unit and incubated at 37 °C under aerobic conditions for 24 h [42]. Total iron, and turbidity were measured by a portable colorimeter (DR900, Hach, Tokyo, Japan). The pH and water temperature were measured by a compact pH and conductivity meter (LAQUAtwin, HORIBA, Kyoto, Japan). The measurement of all parameters was carried out following the manufacturer's instructions.

The association of each parameter (the topography, groundwater abstraction depth, sanitation facility type, and distance between the sanitation facility and well) with microbial contamination status was statistically analyzed using R v.3.5.1. Kruskal–Wallis test was used to analyze the difference among more than two sample groups, then Wilcoxon test was used to identify the significant difference between two groups.

2.3. Installation and Operation of Household Water Treatment Systems

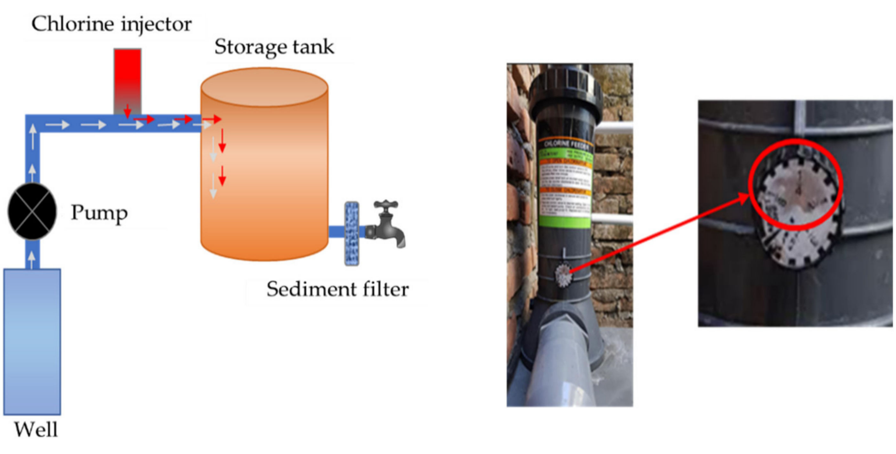
The household water treatment systems were selected by a market survey with the following criteria: (1) able to reduce contaminants (especially bacteria), (2) easily found in the market around the study area, (3) low cost (in the market), and (4) easily installed, operated, and maintained. Three types were selected and installed in 8 voluntary households: chlorination systems (2 households), microfiltration systems (3 households), and reserve osmosis and ultraviolet (RO + UV) systems (3 households).

Water quality parameters (*E. coli*, TC, turbidity, total ion, pH, and water temperature) were analyzed using the methods described above. For the chlorination systems, in addition, total and residual chlorine were measured using a portable colorimeter (DR900, Hach, Tokyo, Japan) following the manufacturer's instruction (Hach Method 8167 and 8021, USEPA DPD Method). The details of system installation and sampling methods are mentioned in Sections 2.3.1–2.3.3.

The performance of each system was evaluated in terms of removal efficiency of *E. coli*, TC, and turbidity at the outlet of the system.

2.3.1. Chlorination System

An automatic chlorine tablet injector (Chlorine Feeder, Penguin) and a 520 L storage tank were installed as the chlorination system. A cartridge with a 254 mm polypropylene (PP) sediment filter (pore size 1 µm; Kolon Industries) was also installed between the tank outlet and the faucet to remove potential precipitation such as iron and manganese that can occur from the oxidation reaction in the tank. The chlorine dose can be controlled by the number of chlorine tablets put in the injector and the injection flow adjusted by the opening position of the valve on the injector (Figure 4).



(**a**) (**b**)

Figure 4. (**a**) Installation of chlorination system; (**b**) chlorine injector and controlling valve.

The water pump was operated using automatic sensors installed at the upper and lower water levels inside the tank. When the water level dropped below the lower sensor, the pump was automatically turned on. The pump was turned off when the water level reached the upper sensor. In this study, the upper and lower water level sensors were installed at 35 cm (108 L) and 20 cm (190 L) from the bottom of the tank, respectively.

A trial was carried out in triplicate to find an appropriate chlorine dosage to both meet the drinking water standard (no more than 5 mg/L; Indonesian Minister of Health regulation 492/2010) and satisfy household acceptance, i.e., no unpleasant chlorine smell. The details of the trial operation, including the initial concentration of residual chlorine and number of tablets, are shown in Table 2.

Table 2. Trial operations of chlorination system.

Trial	Chlorine Dosage Adjustment		Initial Concentration of Total Chlorine (mg/L)	Initial Concentration of Free Residual Chlorine (mg/L)
	Chlorine Tablets	Chlorinator Valve		
1	1	$\frac{1}{4}$	0.6	0.3
2	2	$\frac{1}{2}$	1.2	0.7
3	2	Full	>2.1	>2.1

Based on the setting trials of the chlorination system, all trials seemed to meet the guideline for the chlorine concentration of drinking water (not more than 5 mg/L), but the third trial did not satisfy household acceptance (unpleasant chlorine smell). The performance of the system was evaluated under the second condition using two chlorine tablets and a half-open valve as an appropriate condition. At one of the two households, water sampling was carried out every 2 h for 10 h (6 a.m. to 4 p.m.) because the pump was operated (chlorine injection occurred) twice a day (6 a.m. and 5 p.m.). The measurement of total and free chlorine, *E. coli*, TC, and turbidity in treated water was carried out in each sampling period.

2.3.2. Microfiltration System

The microfiltration system consisted of a 254 mm polypropylene (PP) sediment filter (pore size 1 μm Nano Filter), a 254 mm carbon filter (pore size 5 μm; Kolon), and 254 mm ceramic filter candle (pore size 0.5 μm; M P Ceramics, Ltd.). At 1 of 3 households, water sampling was carried out once a week for 5 weeks after the installation.

2.3.3. RO + UV System

The RO + UV system (Inviro) consisted of 3 types of filters for pre-treatment, an RO membrane filter (pore size 0.0001 μm), a carbon filter, and a UV lamp (flow capacity 1 GPM). A 254 mm polypropylene (PP) sediment filter (pore size 1 μm), a 254 mm carbon filter (pore size 5 μm), and a 254 mm granular activated carbon filter was installed for the pre-treatment. At 1 of the 3 households, water sampling was carried out once a week for 5 weeks after the installation.

2.4. Household Acceptance

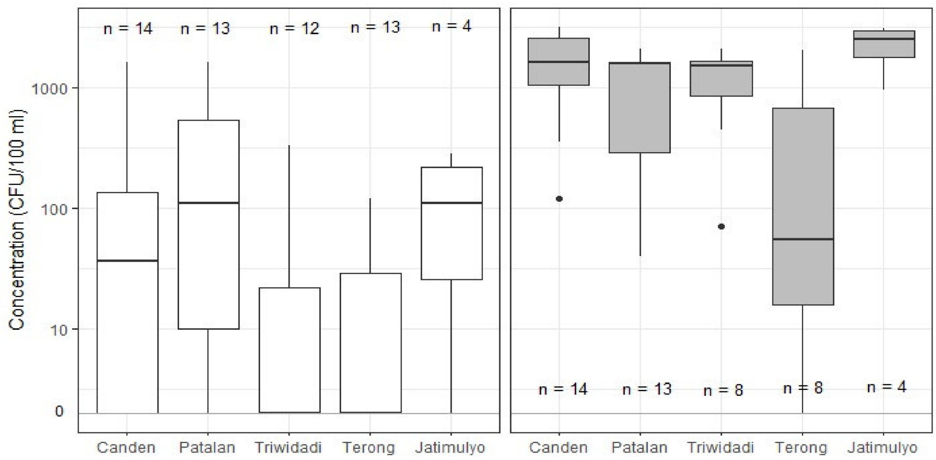
An interview survey was conducted at the 8 voluntary households after operation of each system. Several questions were asked to assess their acceptance of the treatment units, involving (1) system operation and maintenance, (2) operation and maintenance cost, and (3) system investment cost. In addition, the survey also inquired about their understanding of water quality. Regarding system operation and maintenance, the standard operational procedure (SOP) was explained in each household. The SOP of the chlorination system contains instructions to set the chlorinator valve and number of chlorine tablets, add a chlorine tablet after a certain period of use, and clean or replace the sediment filter periodically. The SOPs of the microfiltration and RO + UV systems contain instructions to clean and replace the filters after a certain period of use. The monthly operation and maintenance costs for the chlorination, microfiltration, and RO + UV systems were USD $4.4, $1.4, and $2.4, respectively. The investment costs for the chlorination, microfiltration, and RO+UV systems were USD $36.4, $32.9, and $149.8, respectively.

Approximately 57% of the households in Bantul District were categorized as poor, with monthly expenditure for basic needs below the poverty line [38]. The poverty line of Bantul District is USD 28.3/month [22].

3. Results

3.1. Groundwater Quality in Each Village

E. coli was detected in 34 of 56 groundwater samples (61%) in the five villages. The highest detection rate was observed in Patalan (92%, 12/13), followed by Jatimulyo (75%, 3/4), Canden (64%, 9/14), Terong (53%, 7/13), and Triwidadi (33%, 4/12). Figure 5a shows the distribution of *E. coli* concentration in the water samples in the five villages. The highest median value of *E. coli* concentration was observed in Jatimulyo (130 CFU/100 mL), followed by Patalan, Canden, Triwidadi, and Terong (110, 38, 0, and 0 CFU/100 mL, respectively). The highest concentration of *E. coli* was observed in Patalan and Canden (1600 CFU/100 mL). The *E. coli* concentration in the villages varied, and significant variation was found in Canden and Patalan, ranging from 0 to 1600 CFU/100 mL. Statistical analysis showed a significant difference of *E. coli* concentration in water samples from the five villages (Kruskal–Wallis test, $p < 0.05$). A significant difference in concentration was found between Patalan and Terong, and between Patalan and Triwidadi (Wilcoxon test, $p < 0.05$).



(**a**) (**b**)

Figure 5. Microbial quality of groundwater in each village: (**a**) *E. coli* and (**b**) TC concentration.

Only one sample in Terong was below the detection limit of TC (Figure 4b). The highest concentration of TC (3160 CFU/100 mL) was observed in a water sample in Canden. The highest median value was found in Jatimulyo (2530 CFU/100 mL), followed by Canden, Patalan, Triwidadi, and Terong (1600, 1580, 1520, and 76 CFU/100 mL, respectively). The TC concentration in Terong had a relatively large distribution, ranging from 0 to 2040 CFU/100 mL. Statistical analysis showed a significant difference in TC concentration in water samples from the five villages (Kruskal–Wallis test, $p < 0.05$). A significant difference in concentration was found between Canden and Terong, and between Terong and Jatimulyo (Wilcoxon test, $p < 0.05$). Figure 6a shows the distribution of turbidity in the water samples in the five villages. Out of 47 samples, 39 samples had turbidity less than 5 NTU, which meets the regulation of drinking water in Indonesia (Indonesian Minister of Health regulation 492/2010), while 7 of 13 samples in Patalan had relatively high turbidity, between 6 and 9 NTU.

Total iron was detected in 37 samples at a concentration lower than 0.3 mg/L (Figure 6b), which meets the regulation of drinking water (Indonesian Minister of Health regulation

492/2010). A high concentration of total iron (1 mg/L) was found in four water samples, which were among the samples with high turbidity. The pH ranged from 5.9 to 6.7, and water temperature ranged from 29 to 30 °C.

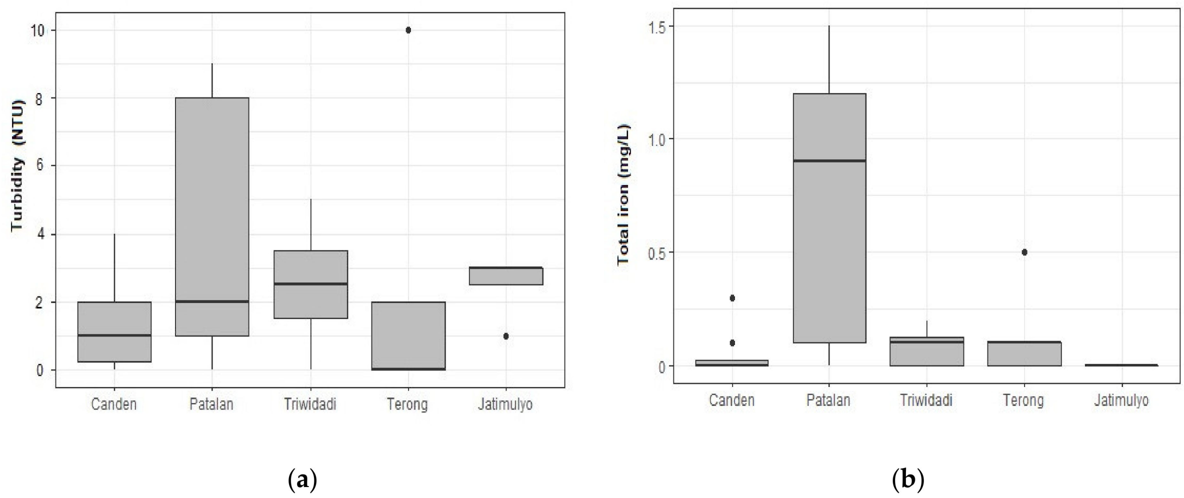


Figure 6. Groundwater quality in each village: (**a**) turbidity and (**b**) total iron concentration.

3.2. Water Quality in Different Topographies

The distribution of *E. coli* concentration in water samples for each topographical condition (flat, sloping, and hilly areas) is shown in Figure 7a. The median value of *E. coli* in flat, sloping, and hilly areas was 60, 0, and 2 CFU/100 mL, respectively. Statistical analysis showed a significant difference in *E. coli* concentration in water samples from the three types of topography (Kruskal–Wallis test, $p < 0.05$). A significant difference in *E. coli* concentration was found between the flat area and the other two areas (Wilcoxon test, $p < 0.05$). The median value of TC concentration in flat, sloping, and hilly areas was 1600, 1520, and 760 CFU/100 mL, respectively (Figure 7b). Statistical analysis found no significant difference in concentration between areas (Kruskal–Wallis test, $p > 0.05$). The TC concentration in the hilly area was found to have a large distribution, ranging from 0 CFU to 3100 CFU/100 mL. The median value of turbidity in the flat, sloping, and hilly areas was 2, 3, and 2 NTU, respectively. Statistical analysis found no significant difference in turbidity between the areas (Kruskal–Wallis test, $p > 0.05$). The median value of total iron in the flat, sloping, and hilly areas was 0.1, 0.1, and 0 mg/L, respectively. Statistical analysis found no significant difference in total iron between the areas (Kruskal–Wallis test, $p > 0.05$).

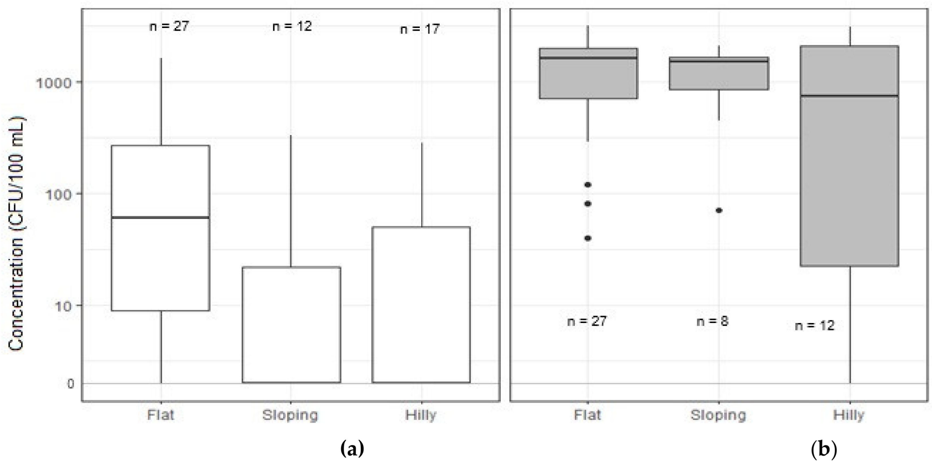
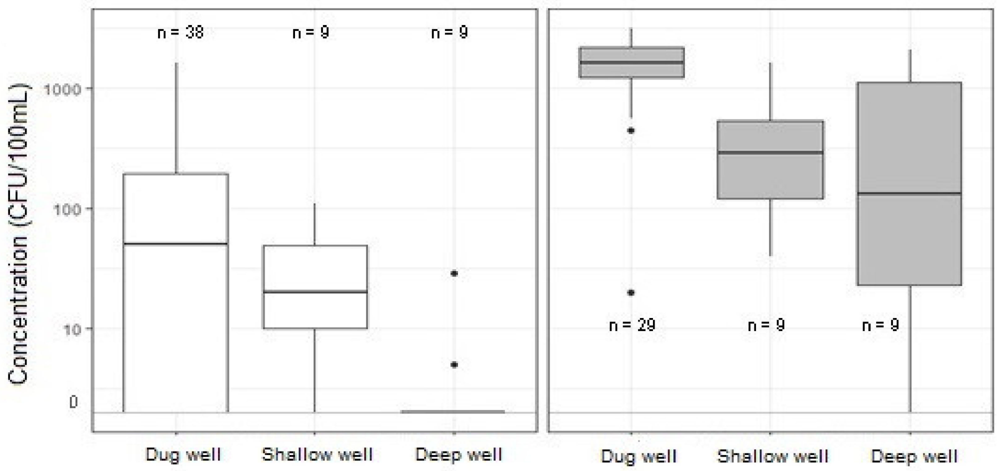


Figure 7. (**a**) *E. coli* and (**b**) TC in flat, hilly, and sloping areas.

3.3. Water Quality Based on Well Type

The distribution of *E. coli* concentration in water samples from each well type is shown in Figure 8a. The median value of *E. coli* concentration from dug wells, shallow wells, and deep wells was 50, 20, and 0 CFU/100 mL, respectively. Statistical analysis showed a significant difference in *E. coli* concentration in water samples among the three well types (Kruskal–Wallis test, $p < 0.05$). The *E. coli* concentration in the dug wells was significantly higher than in the shallow and deep wells (Wilcoxon test, $p < 0.05$, respectively), and there was no significant difference in *E. coli* concentration between dug wells and shallow wells (Wilcoxon test, $p > 0.05$). The median TC value in the dug wells, shallow wells, and deep wells was 1600, 293, and 130 CFU/100mL, respectively. Statistical analysis showed a significant difference in TC concentration in water samples among the three well types (Kruskal–Wallis test, $p < 0.05$). The TC concentration in water samples from dug wells was also significantly higher than in the other well types (Wilcoxon test, $p < 0.05$) (Figure 8b). The median values of turbidity in water samples from dug wells, shallow wells, and deep wells were 2, 3, and 3 NTU, respectively. Statistical analysis showed no significant difference in turbidity among the three well types (Kruskal–Wallis test, $p > 0.05$). The median value of total iron in water samples from dug wells, shallow wells, and deep wells was 0, 1.1, and 0.1 mg/L, respectively. Statistical analysis showed a significant difference in total iron among the three well types (Kruskal–Wallis test, $p < 0.05$). The total iron in water samples from shallow wells was significantly higher than that in the other well types (Wilcoxon test, $p < 0.05$).



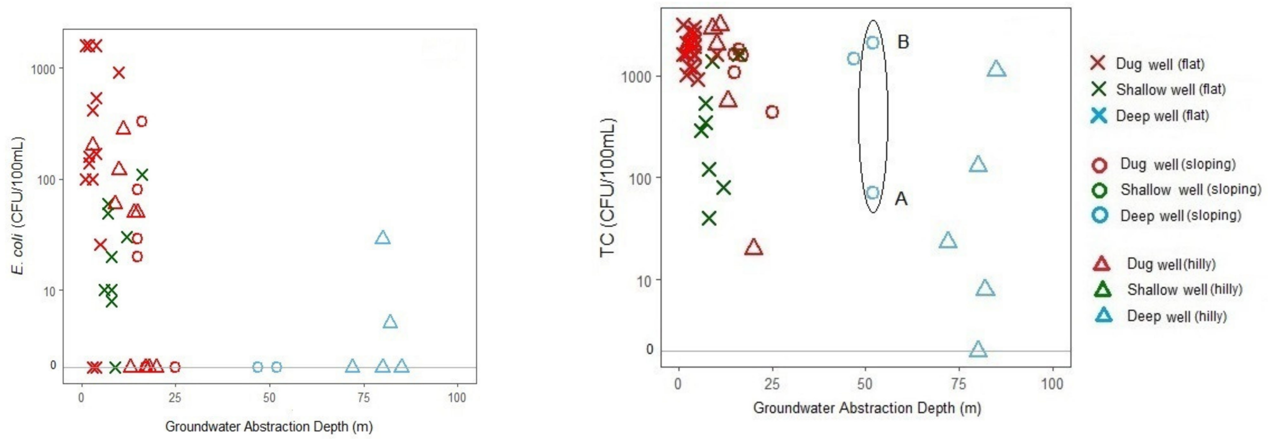
(**a**) (**b**)

Figure 8. Distribution of (**a**) *E. coli* and (**b**) TC concentration in different well types.

3.4. Water Quality Based on Groundwater Abstraction Depth and Well Type

Figure 9 shows the *E. coli* and TC concentration in water samples with different groundwater abstraction depths and well types. Higher concentrations of *E. coli* and TC were observed in water samples from dug wells with a depth of less than 5 m. Their concentrations in shallow wells were lower than in dug wells even though the wells have similar depths. In addition, *E. coli* was not detected in 15 water samples of dug wells (well depth less than 25 m) and one shallow well with an abstraction depth of 7 m. In the deep wells, *E. coli* was detected in only two of the nine water samples in the range of 2–29 CFU/100 mL, and TC was detected in eight of the nine samples in the range of 0–2080 CFU/100 mL. The TC concentration in the water samples labeled A (70 CFU/100 mL) and B (2080 CFU/100 mL) in Figure 9b had a large difference, even though they were taken from the same deep well. Turbidity in water samples from the shallow wells with the groundwater abstraction depth more than 5 m was more than

5 NTU, while those from the dug wells and deep wells were less than 5 NTU. The turbidity might have been caused by iron concentration which is more than 1 mg/L in water samples from shallow wells.



(**a**) (**b**)

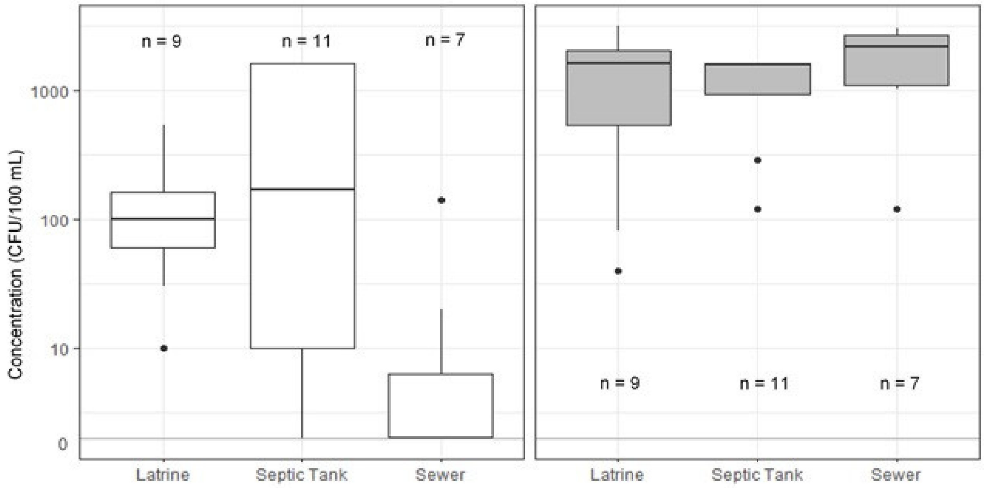
Figure 9. (**a**) *E. coli* and (**b**) TC concentration in water samples with different groundwater abstraction depths and well types. Water samples represented as A and B were collected from the same deep well but different households.

3.5. Water Quality Based on Sanitation Facility and Well Type

Figure 10 shows the distributions of *E. coli* and TC concentrations in water samples from households using different types of sanitation facilities in Patalan and Canden, which are located in the flat area and have all three types: latrines, septic tanks, and small-scale sewer systems. The median value of *E. coli* from households connected to a latrine, septic tank, or small-scale sewer system was 100, 170, and 2 CFU/100 mL, respectively (Figure 10a). Statistical analysis showed a significant difference in *E. coli* concentration in water samples between the three types of sanitation facility (Kruskal–Wallis test, $p < 0.05$). The concentration of *E. coli* in the water samples from households using a small-scale sewer system was significantly lower than that for those using a septic tank or a latrine (Wilcoxon test, $p < 0.05$). The median values of turbidity in water samples from households using latrines, septic tanks, and a small-scale sewer system were 3, 1, and 0 NTU, respectively. Statistical analysis showed no significant difference in turbidity in water samples among the three types of sanitation facility (Kruskal–Wallis test, $p > 0.05$). The median values of total iron in water samples from households using latrines, septic tanks, and small-scale sewer system were 0.1, 1.3, and 0 mg/L, respectively. Statistical analysis showed no significant difference in total iron among the three types of sanitation facility (Kruskal–Wallis test, $p > 0.05$).

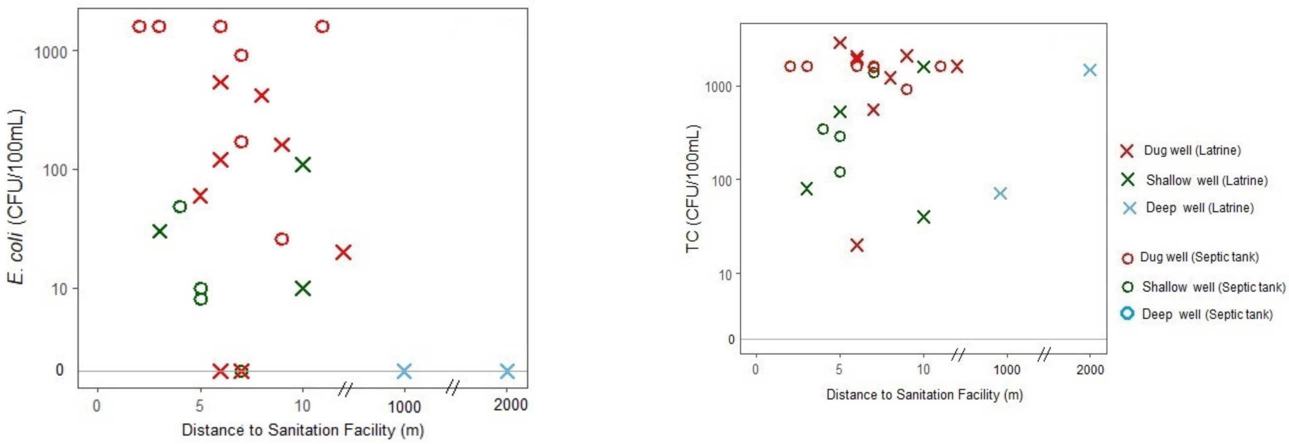
The median value of TC concentration in well water from households connected to a latrine, septic tank, or small-scale sewer system were 1600, 1580, and 2200 CFU/100 mL, respectively (Figure 10b). Statistical analysis found no significant difference in TC between the three types (Kruskal–Wallis test, $p > 0.05$).

Since there was no significant difference in the *E. coli* and TC concentrations in the water samples from households connected to latrines or septic tanks, their concentrations were examined based on the distance between the well and a sanitation facility (Figure 10) and both well and sanitation facility type. *E. coli* was not detected in deep wells situated a long distance (more than 1 km) from a latrine, while TC was detected at a concentration comparable to that in other well types (Figure 11). Comparing dug wells and shallow wells located less than 12 m from a sanitation facility, the *E. coli* and TC concentrations from both wells varied and had no significant correlation with the distance to the sanitation facility ($p > 0.05$, $R^2 = 0.04$ and 0.03, respectively).



(**a**) (**b**)

Figure 10. Distribution of (**a**) *E. coli* and (**b**) TC concentration in water samples at households using different types of sanitation facilities.



(**a**) (**b**)

Figure 11. (**a**) *E. coli* and (**b**) TC concentration in water samples at different distances to a latrine/septic tank.

Meanwhile, the concentrations of *E. coli* and TC were higher in water samples from dug wells than in those from shallow wells (Figure 12). Although the number of water samples is small, especially a sample from household using a shallow well and the small-scale sewer system (n = 1), these results indicate that the sanitation type (latrine or septic tank) was not an influencing factor in the difference in *E. coli* and TC concentrations in this study area, but well type was. It must be noted that the concentration of *E. coli* was lower in water samples from households connected to a small-scale sewer system, even though the households were using dug wells.

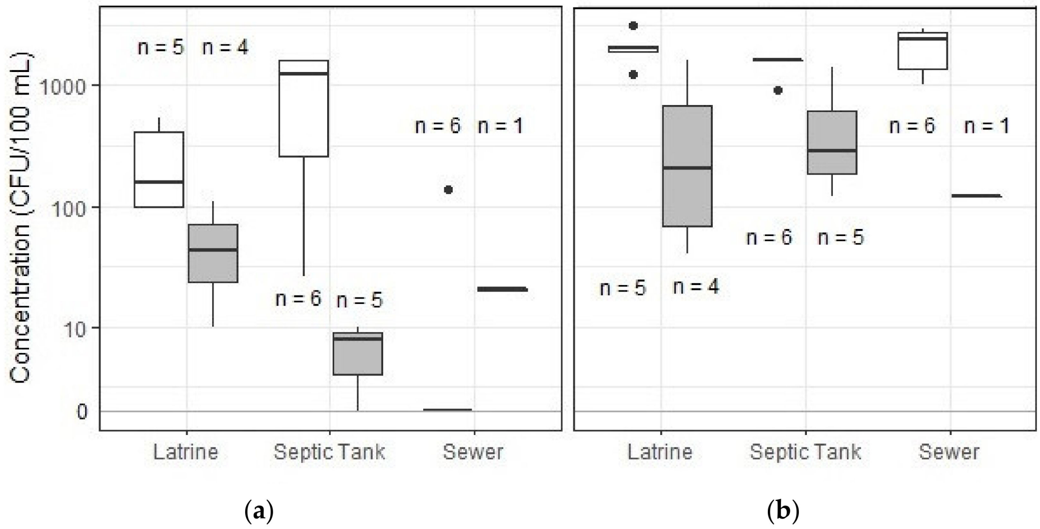


Figure 12. (**a**) *E. coli* and (**b**) TC concentration in water samples from households with a latrine/septic tank/small-scale sewer and a dug well/shallow well.

3.6. Performance of Household Treatment Systems

The evaluation of microbial removal was conducted in the trial using two chlorine tablets and a half-open valve (second trial). The initial concentrations of *E. coli* and TC in raw water were 1.5 $\log_{10}$ CFU/100 mL (30 CFU/100 mL) and 3.0 $\log_{10}$ CFU/100 mL (1070 CFU/100 mL). *E. coli* was not detected in treated water of this chlorination system. Figure 13 shows the change in concentration of TC, free chlorine, and total chlorine.

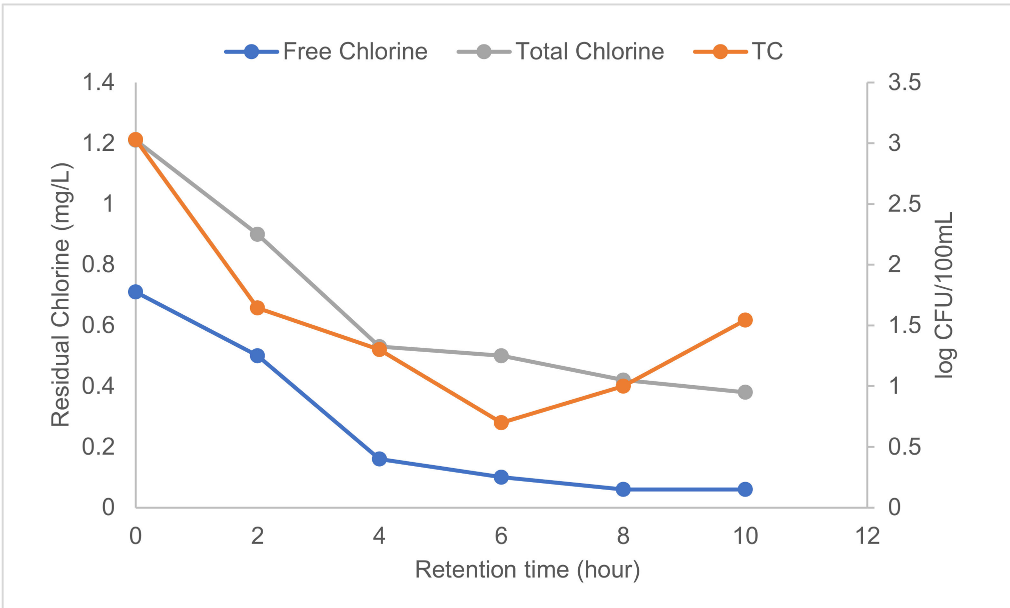


Figure 13. Change in concentration of TC, free chlorine, and total chlorine in treated water.

The TC concentration decreased from 3.0 to 0.7 $\log_{10}$ CFU/100 mL (1070 to 5 CFU/100 mL) in 6 h. In addition to TC concentration, the concentration of free chlorine and total chlorine decreased from 0.7 to 0.1 mg/L and from 1.2 mg/L to 0.5 mg/L, respectively. The concentration of TC then increased to 1.5 $\log_{10}$ CFU/100 mL (35 CFU/100 mL) with free chlorine below 0.1 mg/L and total chlorine below 0.5 mg/L after 6 h. The log reduction value (LRV) of *E. coli* was calculated as more than 1.5, while that of TC ranged from 1.4 to 2.3. The turbidity in the treated water was 2, 2, 1, 3, 0, and 0 NTU in 0, 2, 4, 6, 8, 10 h, respectively, and the total iron concentration was no more than 0.02 mg/l in both the raw water and treated water, which met the drinking water standards.

Table 3 shows the concentrations of *E. coli* and TC before and after treatment and LRV in the microfiltration system at one of two households for the five-week operation. *E. coli* and TC were detected in all treated water except in the fourth and fifth weeks. LRVs of *E. coli* ranged from 0.4 to more than 1.3 and TC from 0.4 to 0.6. The removal efficiency did not decrease but was extremely low within five weeks. Consequently, the water treated by the system could not meet the drinking water standard.

Table 3. Concentration of *E. coli* and TC and LRV in microfiltration system.

Sampling Week	***E. coli*** **(CFU/100 mL)**			**TC (CFU/100 mL)**			**Turbidity**	
	Raw Water	**Treated Water**	**LRV**	**Raw Water**	**Treated Water**	**LRV**	**Raw Water**	**Treated Water**
1st	28	10	0.4	356	120	0.5	2	0
2nd	136	16	0.9	288	92	0.5	0	0
3rd	28	12	0.4	448	176	0.4	2	0
4th	10	0	>1.0	450	115	0.6	5	0
5th	20	0	>1.3	620	190	0.5	9	1

The turbidity in the raw water was in the range of 0 to 9 NTU, and the concentration of total iron in the raw water was no more than 0.9 mg/L. Turbidity and total iron concentration in all treated water were no more than 1 NTU and 0.02 mg/L, respectively, which satisfied the drinking water standards.

Table 4 shows the concentrations of *E. coli* and TC before and after treatment and LRV in the RO + UV system at one of two households for the five-week operation. *E. coli* was not detected in any treated water, while TC was detected in treated water in the fourth and fifth weeks. LRV of *E. coli* ranged from more than 0.9 to more than 2.5 and of TC from 0.4 to more than 2.8. It must be noted that the UV lamp in the system was turned off by a member of the household after the third week.

Table 4. Concentration of *E. coli* and TC and LRV in RO + UV system.

Sampling Week	***E. coli*** **(CFU/100 mL)**			**TC (CFU/100 mL)**			**Turbidity**	
	Raw Water	**Treated Water**	**LRV**	**Raw Water**	**Treated Water**	**LRV**	**Raw Water**	**Treated Water**
1st	0	0	-	96	0	> 2.0	3	1
2nd	30	0	>1.5	608	0	>2.8	10	4
3rd	312	0	>2.5	688	0	>2.8	0	0
4th	8	0	>0.9	360	132	0.4	8	0
5th	10	0	>1.0	290	20	1.2	2	2

The turbidity in the raw water was in the range of 0–10 NTU, and the concentration of total iron was up to 1.32 mg/L. The turbidity of the treated water of the RO + UV system was found to be in the range of 3–4 NTU, and the total iron concentration was 0.2 mg/L. Although the total iron concentration was below the drinking water standard, the households complained about the iron smell in the treated water. Thus, the turbidity might have been caused by oxidation of iron passing through the RO + UV system.

3.7. Acceptance of Household Treatment Systems

Table 5 shows a summary of the household acceptance of operation and maintenance (OM), OM cost, and investment cost for each treatment system.

Table 5. Household acceptance of operation and maintenance, operation and maintenance cost, and investment cost for each treatment system (yes: acceptable; no: not acceptable).

Treatment	Number of Households	OM		OM Cost		Investment Cost	
		Yes	No	Yes	No	Yes	No
Chlorination	2	1	1	2	0	0	2
Microfiltration	3	3	0	1	2	0	3
Reverse osmosis	3	2	1	2	1	1	2

OM—operation and maintenance.

All households using the microfiltration system were willing to operate and maintain the system, as were one household using the chlorination system and two households using the RO + UV system. In total, 75% (6/8) of the households were willing to be involved in the SOPs, such as setting up the chlorinator, adding chlorine tablets, cleaning, and replacing filters or RO membrane filters.

Although all households using the chlorination system were willing to pay the OM cost even though it was the highest cost among the three systems, only one household was willing to pay the OM cost of the microfiltration system, which was the cheapest among the three systems. Two of three households were willing to pay the OM cost of the RO + UV system, the same ones willing to operate and maintain the system. In total, 60% (5/8) of the households were willing to pay for chlorine tablets or replacement filters or RO membrane filters.

The prices of the chlorination, microfiltration, and RO + UV system were 1.2, 1.1, and 5.3 times higher, respectively, than the cost for minimum basic needs in Bantul District. In total, 82% (7/8) of households were not willing to pay the investment cost. All households using the chlorination and microfiltration systems were not willing to pay the investment cost, while one household using the RO + UV system was willing, even though the cost was the highest among the three systems.

Only two households had knowledge about the microbial contamination problem, one willing to pay the OM and OM cost of the chlorination system, and one willing to pay for the OM, OM cost, and investment cost of the RO + UV system. The knowledge of other households was limited to turbidity and smell. These results indicate that providing information could encourage them to pay for the household treatment units.

4. Discussion

4.1. Groundwater Quality

Water samples from the flat area showed a higher *E. coli* concentration compared to water samples from the sloping and hilly areas. One reason would be that only dug wells and shallow wells were used in the flat area, while dug wells and deep wells were used in sloping and hilly areas. *E. coli* concentrations in water samples from dug wells and shallow wells were significantly higher than that those from deep wells. Even though the dug wells and shallow wells extracted water from the same unconfined aquifer as the water source, the groundwater abstraction depths were different depending on the water table level in this study area. The flat area has a higher water table level (0.5–1.0 m below ground level) compared to the sloping area (>14 m) and the hilly area (2.5–20 m). The groundwater abstraction depths of dug wells and shallow wells are 1.5–2.0 m and 5.5–7.0 m below ground level, respectively. In addition, the deep wells extracted water from confined aquifers at a depth of 50–125 m below ground level. The existence of impermeable layer between the unconfined and confined aquifers is a barrier to vertical microbial transport to deeper aquifers [32]. In relation with soil conditions, the microbial contamination in the high hydraulic conductivity area, i.e., the flat area, was higher than in a low area, i.e., the sloping and hilly areas. The groundwater flow system might also influence microbial contamination in groundwater. The flat area that lies in the downgradient region of groundwater flow, showed a higher contamination level of *E. coli* in groundwater samples compared to those taken from the sloping and hilly areas that lies in the upgradient region. Groundwater quality generally deteriorates in downflow of rapidly urbanizing areas [34]. Consequently, the water samples in the flat area had higher *E. coli* concentrations than those in the sloping and hilly areas, which was in agreement with the high microbial contamination of shallow groundwater reported in many papers [34,43,44]. Bacterial transfers to groundwater decreased with the depth of water table level [44]. The microbial transfer is faster in sand and gravel because of larger hydraulic conductivities than those in clay or silt [43].

In addition to the groundwater abstraction depth, the type of well also influenced its protection against microbial contamination. The concentrations of *E. coli* and TC in the samples from dug wells were higher than those from the shallow wells even though both extract groundwater from the same depth, which implies that tube wells (shallow wells) are effective for protecting the groundwater from microbial contamination from the surrounding environment. Because there are many animals in the area, the dug wells are prone to direct contamination. However, the shallow and deep wells are more protected from direct microbial contamination by PVC or iron casing. Previous studies also showed that unprotected wells might allow subsurface water to percolate into the well through fractures or joints [33,45]. The dug wells in the study area are lined with concrete rings, stone, or brick and have been used for more than 10 years. Some potential cracks might occur between the concrete rings, stone, or brick, as run-off can flow from the well wall during rainfall. The water samples from dug wells that were unprotected or made of brick had a higher TC concentration compared to the tube wells protected by PVC casing [33]. Higher microbial contamination often occurred due to insufficient well construction [45]. From the above discussion, the higher median concentrations of *E. coli* and TC in water samples from dug wells in Jatimulyo than in Terong (both in the hilly area) could have occurred because three out of the four wells in Jatimulyo were dug wells 3 to 10 m deep, while 8 of the 13 wells in Terong were 10 to 20 m deep. In addition, animal livestock might have been a cause of the contamination in Jatimulyo, since a cattle farm was located close to the dug wells. The cattle farm can negatively affect groundwater quality through feces dropped associated to erosion and runoff intrusion [46–48].

Water in the deep wells showed the lowest microbial contamination compared to the other well types. In addition to the protection by PVC or iron casing, this might be because the deep wells draw water from a confined aquifer at a depth of 50–125 m. Confined aquifers are overlain by low-permeability aquitards that protect the aquifers from microbial contaminants [32]. The confined aquifer source in Bantul District is covered by an impermeable clay layer with a thickness of 25–40 m [49]. However, *E. coli* was detected in three of nine water samples from deep wells, while TC was detected in eight water samples, with concentrations ranging from 0 to 2080. Water in the deep wells is pumped up from a confined aquifer and distributed to 50–100 households via a pipeline, with the length ranging from 20 to 2000 m. The contamination of TC at a concentration comparable to that in the other water samples could have been caused by the breakage and/or improper construction of the pipe. The concentration of TC in the water samples labeled A (70 CFU/100 mL) and B (2080 CFU/100 mL) showed a large difference, although those samples were taken from the same deep well. This may be because contamination occurred during water distribution to D via a pipe with a length of about 2 km, while the pipe to C was 1 km long.

The *E. coli* concentration was significantly higher in water samples from households using latrines (n = 38) and septic tanks (n = 11) than in those from households using the small-scale sewer system (n = 7) although the number of water samples from households using the small-scale sewer system was small. Previous research found that fecal bacteria can leak from latrines constructed with only a thin layer of permeable soil above the groundwater and from the sludge of septic tanks that are not safely managed, particularly in areas with a high-water table [45,50,51]. Therefore, in this study area, pit latrines and septic tanks could not provide sufficient protection for the groundwater, probably due to improper construction and a highwater table level. In addition, since the latrines and septic tanks are located in the same area, the groundwater of the households connected to septic tank might be contaminated by the adjacent latrines. Moreover, there was a possibility that groundwater contamination still occurred from before the septic tanks were constructed in 2019. Further research, including monitoring the groundwater quality, is necessary to evaluate the efficiency of septic tank installation in this study area.

On the other hand, TC was found in similar concentrations in water samples from households connected to a latrine, septic tank, or small-scale sewer system. In addition to the sanitation facilities, TC concentration was not significantly different between different topographies, which indicates that the TC concentration is not much correlated with groundwater abstraction depth. These results indicate that TC comes not only from fecal sources, but also comes from multiple sources such as soil, decaying vegetation, livestock, and surface runoff [52]. Since water samples were collected in rainy season (average monthly precipitation: 332 mm), the microbial concentration of groundwater in dry season (average monthly precipitation: 69 mm) could be less than that in rainy season [28,43,44,53].

Our study shows that the *E. coli* and TC concentrations in water samples from dug wells and shallow wells located less than 12 m from a septic tank or latrine were scattered and there was no correlation with distance. The distance between a well and a sanitation facility has been discussed in several studies. A higher coliform concentration was found in water samples from shallow wells located less than 10 m from pit latrines that were not covered and constructed using concrete casing material [33]. Another study also found that the microbial concentration was high at a distance less than 15 m from the septic tank because of improper well protection without a parapet (wall above the ground surface) [54]. These studies also indicated that the distance from a sanitation facility to a well is not effective protection if it is less than 15 m, which agrees with the results of this study.

4.2. Household Treatment Systems

Both the chlorination and microfiltration systems installed in this study could not provide safely managed drinking water for the households. Chlorine injection by chlorine tablets could not provide a sufficient chlorine dose to disinfect the groundwater from microbes. Since the chlorine dose relied on the contact of chlorine tablets and the injection flow, there was a possibility that water could not contact and mix well with the chlorine tablets because of unstable water injection flow. In addition, turbidity could influence on the disinfection efficiency. The systems may need an additional treatment to remove turbidity before chlorination even though turbidity in raw water meets the drinking water standard.

Although the microbial concentration in raw water has a significant impact on microbial removal by microfiltration systems using ceramic filters [17], the microfiltration system should be able to remove *E. coli* from the raw water (groundwater) based on the manufacturer's instructions. The microfiltration system in this study showed very low rates of microbial removal from well water, even though the raw water had low turbidity. This might be because of the poor integrity of the ceramic filters purchased in the local market in this study. It would be necessary to improve and control the product quality to ensure the safe drinking water.

On the other hand, the RO + UV system could provide microbially safe drinking water for the households if the system was operated following the SOP. It was found that activating a UV lamp in the system was important to guarantee bacteria-free (at least *E. coli* and TC) water, considering that the RO membrane could be compromised for bacteria to pass through. The reason why the UV lamp was turned off by the household was that the water temperature increased from 27 to 34 °C after UV treatment, which is too warm to drink. Thus, an effective cooling system needs to be considered in the design and installation of the RO + UV system.

There was only one household that was willing to take responsibility for OM and pay the OM and investment cost. This is probably related to their understanding of the health risks of microbial contamination of their drinking water. The households' understanding of groundwater quality problems was limited only to turbidity and smell. In addition to the lack of awareness of water quality, the unwillingness to pay the investment cost was probably related to the income level of the households in the study area, which were categorized as poor. The price of chlorination, microfiltration, and RO + UV were still too high for them, even though these systems priced the lowest at the market.

5. Conclusions

This study evaluated factors that influence the microbial contamination of groundwater, such as topographic conditions, well type, groundwater abstraction depth, sanitation facility type, and the distance between the well and the sanitation facility. The topographic conditions determined the most commonly used well types and depth of groundwater abstraction; thus, they were the most influential factors for groundwater contamination by *E. coli* and TC in Bantul District. Contrary to the common understanding, the distance between the sanitation facilities and the well was not a factor that influenced the level of microbial contamination if it was within 12 m. However, there were significant differences in the levels of *E. coli* and TC between dug wells and tube wells (shallow and deep wells) even if they extracted water from nearly the same depth, indicating the direct contamination of dug wells from the surroundings. Only the small-scale sewer system seemed to contribute to protecting the well water from fecal contamination, while the other sanitation facility types (pit latrine and septic tank) were not significantly effective in protecting the groundwater from microbial contamination. Thus, installing not only septic tanks but also tube wells should be promoted in the district to improve the quality of well water as drinking water.

Although the influence of other factors such as hydrogeological characteristics on the groundwater quality should be considered, that information is often limited not only in our study area but also other regions and countries. However, available and site-specific conditions such as topographic condition can be useful to understand general groundwater quality and determine the strategy for groundwater protection.

Among the three types of systems investigated in this study, the RO + UV system was the only household water treatment system with the high efficiency of removing microbial contamination in the village setting, if it was operated in accordance with the SOP. The chlorination system was simple, but it was not so easy to adjust the chlorine dosage at levels that were high enough for disinfection but not too high to cause a chorine smell. The log reduction of *E. coli* and total coliform by microfilters was the lowest among the three household treatment systems.

The limited acceptance of the household treatment systems with regard to the OM, OM cost, and investment cost could be associated with a lack of awareness of water quality problems and associated waterborne diseases, and the low incomes of the households in the study area. Therefore, raising awareness of water quality problems, especially microbial contamination, and providing financial support for the installation of household treatment systems would help more households to use household treatment systems, and thereby reduce the cases of waterborne diseases and stunting problems. This information can be useful for the implementation the household treatment system in other regions.

Author Contributions: Conceptualization, I., S.K. and S.T.; methodology, I. and S.K.; data analysis, I. and S.K.; investigation, I.; data curation, I. and S.K.; writing—original draft preparation, I.; writing—review and editing, S.T. and S.K.; visualization, I.; supervision, S.T. and S.K.; project administration, S.K. and S.T.; funding acquisition, S.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Japan International Cooperation Agency (JICA) though a collaborative program with the University of Tokyo and a scholarship provided to Indrastuti for her graduate studies.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are openly available in FigShare at https://doi.org/10.6084/m9.figshare.14784237.

Acknowledgments: The authors would like to express their gratitude to Balai Prasarana Permukiman Wilayah (BPPW) Ministry of Public Works and Housing of SRY Province; the Planning Agency (Bappeda) of Bantul District; the PPSP City Facilitator of Bantul District; the Head of the Sub-Village of Gadungan Kepuh Canden; the Village Officer of Triwidadi, Terong, and Jatimulyo; and Mega Prawithasari Lubis.

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

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