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Assessing Log Reduction Values of Conventional Water Treatment Plants with Microbially Highly Polluted Raw Water Sources

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Highlights:

- Microbially highly polluted drinking water sources were characterized for pathogens.
- The log reduction value of a conventional water treatment plant was assessed for bacteria and protozoa drinking water safety.
- The log reduction values of the pre-sedimentation and combined flocculation-sedimentation units in conventional water treatment plants need to be (re)assessed.

Abstract. Because of the global outlook of microbial pathogens contributed by river basins that are characterized by highly populated urbanized areas and other activities with poor wastewater management, it is imperative to assess the sufficiency of conventional water treatment plants with microbially highly polluted raw surface water sources in supplying pathogen-free drinking water. By using the log reduction value (LRV), the microbial safety of the drinking water supply from WTP Badaksinga, Bandung City, Indonesia, was assessed, from the raw water sources to the conventional water treatment units. *E. coli*, total coliform, and *Clostridium perfringens* (as a surrogate of the *Cryptosporidium parvum* protozoan) were selected as pathogens. It was found that with *E. coli* concentrations of > 20,000 MPN/100 ml, all the raw water sources should be categorized as not suitable for drinking water sources. The LRVs of conventional treatment units ranged from 0.67 to 1.4 for all pathogens. For the disinfection unit, the LRVs ranged from 3.0 to 3.71 for *E. coli* and total coliform, and 0 for *Clostridium perfringens*. Based on the results, the drinking water from WTP Badaksinga is safe from bacteria contamination but theoretically requires an additional barrier for protozoa safety. The assessment found that the LRVs of pre-sedimentation and combined flocculation-sedimentation units in conventional treatment systems need to be (re)assessed.

Keywords: *conventional treatment; drinking water; LRV; microbial safety; raw water source.*

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1 Introduction

This study aimed to investigate the sufficiency of conventional water treatment plants with microbially highly polluted raw surface water sources, e.g. highly polluted rivers, in ensuring the safety of drinking water from pathogens. In this case, the river basin was characterized by highly populated urbanized areas and livestock activities with poor wastewater management. River basins with highly populated urbanized areas are common globally and are predicted to continually contribute multiple pollutants, including *Cryptosporidium sp.*, to global rivers in the 21st century [1]. Estimates on populations without access to sewers in 60 urban conglomerates in the world show staggering percentages [2], with a total of 5.4 billion people in 2030 [3]. With this outlook, it is imperative to assess the sufficiency of conventional water treatment plants under future conditions in supplying pathogen-free drinking water. The assessment is even more important for rivers with extremely low flow and sustained or increasing pathogen loads.

The World Health Organization (WHO) promotes a risk-based framework to ensure the safety of drinking water, starting from its raw water source to its distribution and its consumption at home, with health-based targets (HBT) as an essential component to determine tolerable levels of contaminants in drinking water. HBT implementation by keeping and/or improving the safety of drinking water quality is critical in protecting human health [4]. HBT are measurable health, water quality, and performance objectives based on the judgment of health risks from waterborne hazards [5]. One of the categories in HBT is the performance target expressed by pathogen reduction expressed in $\log_{10}$, called the log reduction value (LRV).

Provision of safely managed drinking water that is free of fecal and priority chemical contaminations, as defined in Target 6.1 of the Sustainable Development Goals (SDGs) of the United Nations, is included in the Indonesian National Medium Term Development Plan 2020–2024 (RPJMN20), as stated in Presidential Regulation Number 18/2020. As a basis for global reporting, the achievement of Target 6.1 of the SDGs, the WHO/UNICEF Joint Monitoring Programme (JMP) for Water Supply, Sanitation, and Hygiene uses *Escherichia coli*, arsenic, and fluoride as the major parameters for measuring the quality of drinking water [6]. These parameters were also considered in the drafting of the Indonesian Ministry of Health's new regulation related to drinking water quality standards in place of Regulation Number 492/2010 and Regulation Number 736/2010. The new regulation is scheduled to be passed in the year 2022 and will regulate drinking water quality standards and a framework for achieving and monitoring them. It should be noted that, unlike *E. coli* and total coliform, *Cryptosporidium* is not regulated in the current Indonesian drinking water quality standards and is not mandatory in the new standards.

The Citarum River, located in West Java Province, which was home to 24,684,290 people in 2018, was included in the 2013 Blacksmith Institute and Green Cross Switzerland's top-ten list of most polluted sites in the world based on the health risks posed by pollutants. The river was included because of its high domestic and industrial pollution [7]. The Citarum River is currently the only river in Indonesia with a presidential regulation (Presidential Regulation Number 15/2018) to accelerate efforts to control its pollution and catchment damage. The river is also included in the RPJMN20 National Priority Project of Restoration of Four Critical River Basins. Based on the Decree of the Ministry of the Environment and Forestry SK.300/Menlhk/Setjen/PKL.l/6/2017, a reduction of the biochemical oxygen demand (BOD) load from domestic sources (30,106.84 kg per day) is required to meet the targeted river water quality as stipulated by regulations. The second-largest contribution of BOD load is from livestock activities (3,370.66 kg per day, i.e. approximately ten-fold lower than the load reduction from domestic sources). These major pollutant sources and their contributions to the river's water quality have also been reported in Ref. [8]. In terms of pathogens other than *E. coli* and coliform, domestic, and livestock activities have also been linked to *Cryptosporidium sp.* prevalence [9].

Cisangkuy River and Cikapundung River, tributaries of the (Upper) Citarum River, are raw water sources for drinking water supplied by PDAM Tirtawening, the municipal waterworks of Bandung City, West Java Province, Indonesia. Before being distributed to consumers, water from these sources is treated in Water Treatment Plant Badaksinga in Jalan Badaksinga, Bandung City. From a microbiological perspective, the major concerns for WTP Badaksinga are that it uses conventional treatment units and protozoa were not taken into consideration in its design. The prevalence of *Cryptosporidium sp.*, an indicator for protozoa, due to unsafe sanitation and drinking water in Indonesia has been indicated [10]. Because of these concerns, pathogen removal assessment of WTP Badaksinga is required to ensure the safety of the drinking water it supplies to the consumer.

In this study, a pathogen removal assessment of WTP Badaksinga was conducted, from the raw water from Cisangkuy River and Cikapundung River to the treatment units at WTP Badaksinga. This assessment used LRV as an indicator to assess the feasibility of the raw water sources, the performance of the treatment units, and the microbial safety of the drinking water. LRV is an indicator of drinking water safety that uses the pathogen concentration removal rate, from the raw water sources to its consumption by consumers [11]. LRV is a mathematical expression based on log base ten ($\log_{10}$) and is commonly used to express microbial removal in drinking water supply chains.

The pathogen removal assessment done in this paper will lend further insight into the sufficiency of conventional water treatment plants with microbially highly polluted raw surface water sources, e.g. highly polluted rivers, in ensuring the safety of drinking water from pathogens. This needed insight is currently lacking in the literature, not only for Indonesia.

2 Methods

2.1 Study Area and Sampling Points

Bandung City is an important part of the Bandung Megapolitan area. With a population of approximately 2.5 million in 2018 and growing, the city faces challenges in providing services to its inhabitants, including water supply and sanitation services. Currently, PDAM Tirtawening is the major piped drinking water supplier for the city.

PDAM Tirtawening uses four surface raw water sources for its supply [12]. From these sources, water is treated in two water treatment plants before being distributed. Figure 1 shows the four raw water sources and the six sampling pointsused in this study: Cisangkuy River (Cikalong sampling point), Cikapundung River (Bantar Awi, Kolam Pakar, and Dago Bengkok sampling points), Cibeureum River (Cibeureum sampling point), and Cipanjalu River (Cipanjalu sampling point).

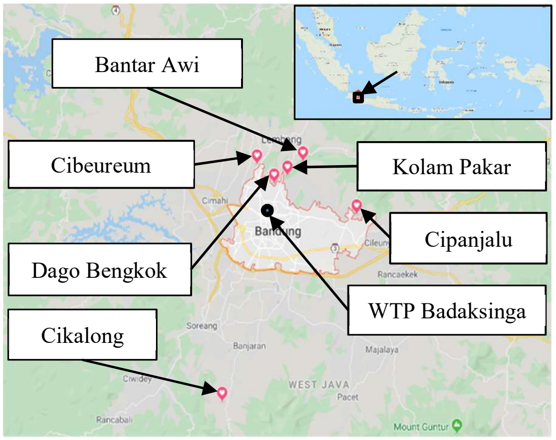

Figure 1 Locations of sampling points at sources and WTP Badaksinga.

Water samples were also taken from each treatment unit in two water treatment plants (WTP I and WTP II) of WTP Badaksinga. WTP I and WTP II use conventional treatment units (consisting of coagulation, flocculation, sedimentation, and granular media filtration) before disinfection at the drinking water reservoir (see Figure 2). Water samples were collected in the rainy season, between October and November 2017, using the grab sampling method. The method is recommended to be used when many treatment plants are evaluated [13]. The samples were analyzed in duplicate and off-site in the laboratory within 24 hours after being taken.

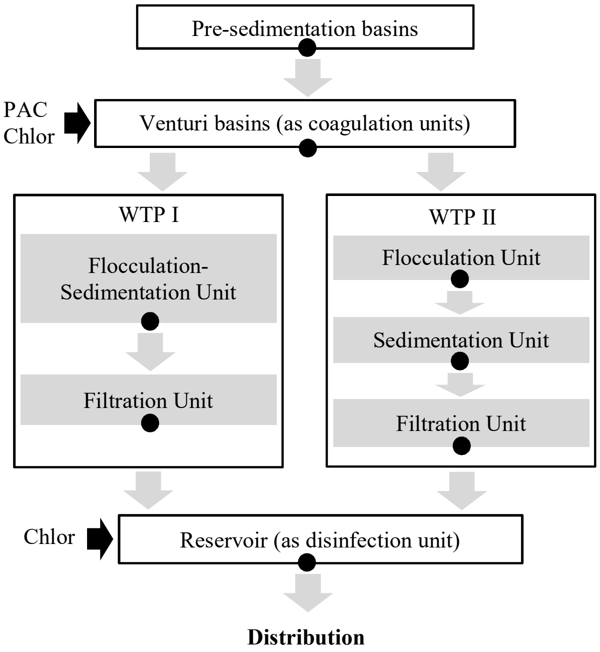

Figure 2 Sampling points (black dots) at the treatment and disinfection units of WTP Badaksinga.

2.2 Microbial Indicators for Pathogens

E. coli and total coliform were selected to indicate the presence of pathogenic bacteria in the water treatment system [14]. *Clostridium perfringens* as a surrogate for *Cryptosporidium parvum* was selected as an indicator for pathogenic protozoa; both species have a similar chlorine-resistant characteristic [15,16]. *C. perfringens* can also serve as a surrogate to indicate *Giardia* cysts and virus removal in water [17]. *C. perfringens* is a spore-forming bacterium with similar size and persistence to *Giardia* cysts and *Cryptosporidium* oocysts [18]. *C. perfringens* resists chemical and physical treatment processes and is little affected by predation. *C. perfringens* rarely multiplies in the environment and its spores are extremely resistant to environmental factors [18,19].

Total coliform and *E. coli* were detected in water samples using the APHA 9221B and APHA 9221C methods, consisting of presumptive, confirmed, and completed tests [20]. Meanwhile, the BAM Chapter 16 method was used to detect *C. perfringens* in the water samples [21].

2.3 Assessing Drinking Water Safety Using Log Reduction Value (LRV)

In assessing drinking water safety, the guideline from the Water Services Association of Australia (WSAA) [22] (Figure 3) was used.

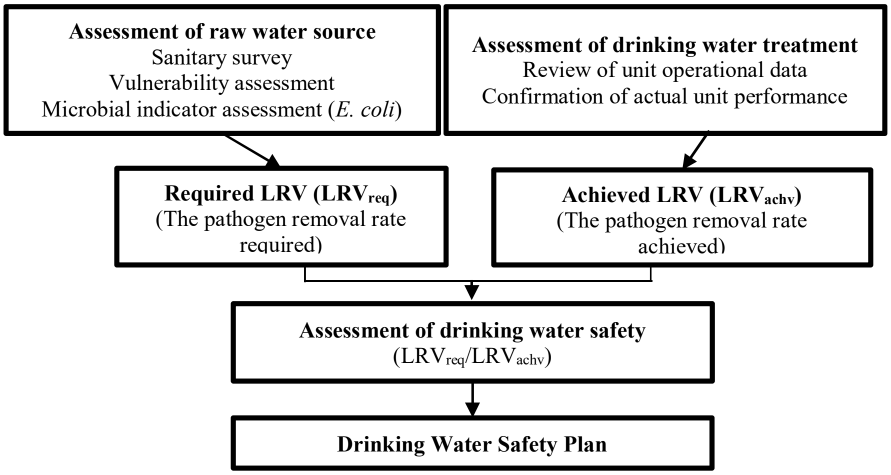

Figure 3 Drinking water assessment process.

Sanitary surveys, vulnerability assessments, and microbial indicator assessments were conducted to get the LRV_{req}. The result of these steps was then compared with Table 1 to get the categorize the source. From the source category, the LRV_{req} could then be determined based on Table 2.

Table 1 Comparison of *E.* coli and vulnerability assessment with source category. Source: WSAA, 2015.

Category based on *Vulnerability Assessment*	***E. coli* concentration per 100 ml**			
	≤ 20 Category 1	**> 20 ≤ 2000 Category 2 & 3**	**> 2000 ≤ 20000 Category 4**	**> 20000 Not suitable**
1	Category 1	Category 2	Anomalous	Not suitable
2	Category 2	Category 2	Anomalous	Not suitable
3	Anomalous	Category 3	Category 4	Not suitable
4	Anomalous	Category 4	Category 4	Not suitable

Table 2 Recommended microbial pathogen reduction.

Source Category	Minimum LRV required		
	Bacteria	**Virus**	**Protozoa**
1	4.0	0	0
2	5.0	3.0	2.5
3	5.0	4.0	3.5
4	6.0	6.0	5.5

Source: WSAA, 2015

The LRV was calculated with Eq. (1). The result obtained from Eq. (1) is the actual LRV. The actual LRV of a treatment unit was used to validate the default LRV of the unit and further to determine the LRV_{achv}. The default LRV of a treatment unit was determined based on the WSAA guidelines. To achieve its default LRV, a treatment unit must be operated within strict performance envelopes. These are expressed in target parameters or criteria, often called process critical limits. If a treatment unit can fulfill its process critical limits, the actual LRV of the unit must be the same as its default LRV. LRV_{achv} is the LRV the treatment unit actually achieves, i.e. the extent to which the treatment unit can improve the microbial quality of the water. The concept of LRV was further used to assess drinking water safety by comparing LRV_{req} and LRV_{achv}, i.e. to determine if the treatment unit can produce safe drinking water from a certain quality of raw water source. Water is suggested to be safe if $LRV_{req} \leq LRV_{achv}$.

$$LRV = \frac{Influent\ Microbial\ Concentration}{Effluent\ \ Microbial\ Concentration} \tag{1}$$

3 Results and Discussion

3.1 Assessment of Raw Water Source

The sanitary surveys identified several possible contamination sources, which were dominated by domestic wastewater from households. The vulnerability assessments further showed that the six intakes of the four raw water sources were classified as Category 4. In addition to these results, laboratory analysis of water samples from the intakes showed *E. coli* concentrations of > 20,000/100 ml for all samples (Table 3). Based on all the results and Table 1, the water from the sources is not appropriate to be used as raw water for drinking water. Based on this, and within the framework for safe drinking water, alternative sources should be identified by PDAM Tirtawening for future use, especially if the reduction targets of pollution loads from domestic and livestock activities wastewater into the river are impossible. If such sources do not exist and resources available to reduce the pollution loads are limited, then PDAM Tirtawening must ensure that their treatment meets and/or exceeds the LRV_{req}.

Table 3 *E. coli* concentration at water source intakes.

Intake	*E. coli* (MPN/100 ml)	Standard Deviation (SD)	Sampling Point Coordinates
Cikalong	215,000	247,487	-7.113594, 107.549835
Bantar Awi	261,500	238,295	-6.843527, 107.648950
Kolam Pakar	35,000	15,556	-6.859050, 107.629535
Dago Bengkok	93,000	0	-6.867865, 107.613658
Cibeureum	930,000	0	-6.846647, 107.592798
Cipanjalu	46,000	0	-6.903225, 107.714391

3.2 Assessment of Treatment Technology

Microbial concentrations in the samples from the treatment units in WTP I and WTP II of WTP Badaksinga (coordinates at -6.896555, 107.610239) are shown in Tables 5 and 6. Table 7 shows the actual LRVs of the conventional and disinfection units in WTP I and WTP II.

Table 4 Microbial concentrations in WTP I.

WTP I	Pre-Sedimentation	Conventional Treatment			Disinfection (Chlor)
		Coagulation	Flocculation-Sedimentation	Filtration	
Total Coliform[a]	24,000 ± 0	19,500 ± 6364	12,150 ± 4,031	2,400 ± 0	<1
E. Coli[a]	24,000 ± 0	15,000 ± 0	9,650 ± 7,566	930 ± 0	<1
C. perfringens[b]	17	20	420	< 1	< 1

[a] Unit of total coliform and *E. coli* = MPN/100 ml

[b] Unit of *C. perfringens* = CFU/ml

Table 5 Microbial concentrations in WTP II.

WTP II	Pre-Sedimentation	Conventional Treatment				Disinfection (Chlor)
		Coagulation	Flocculation	Sedimentation	Filtration	
Total Coliform[a]	24,000 ± 0	19,500 ± 6364	17,500 ± 9192	11,250 ± 5303	6,700 ± 6081	<1
E. Coli[a]	24,000 ± 0	15,000 ± 0	7,800 ± 4526	4,900 ± 3677	930 ± 0	<1
C. perfringens[b]	17	20	29	12	1	< 1

[a] Unit of total coliform and *E. coli* = MPN/100 ml

[b] Unit of *C. perfringens* = CFU/ml

Table 6 Actual LRVs of treatment units in WTP I and WTP II.

	Conventional Treatment			Disinfection		
	Total Coliform	*E. coli*	*C. perfringens*	Total Coliform	*E. coli*	*C. perfringens*
WTP I	1.0 ± 0	1.4 ± 0	1.23	3.4 ± 0	3.0 ± 0	0
WTP II	0.67 ± 0.47	1.4 ± 0	1.23	3.71 ± 0.47	3.0 ± 0	0

The importance of pre-sedimentation before the conventional treatments in significantly reducing the concentrations of total coliform and *E. coli* from microbially highly polluted raw surface water sources is shown by Tables 3, 4, and 5. Even though the concentration of *C. perfringens* was not measured at the intakes, it is most likely that the role of pre-sedimentation in reducing the concentration of *C. perfringens* was also significant; the concentration of *C. perfringens*, i.e. *Cryptosporidium parvum,* was not used in the vulnerability assessment. Removal of *C. perfringens* in conventional treatment plants is done by physical processes. Despite the important role of pre-sedimentation found here, discussion on pre-sedimentation in pathogen removal for drinking water is lacking in the literature.

Tables 4 and 5 show that, in general, the concentrations of total coliform and *E. coli* decreased during the treatment in WTP I and WTP II, i.e. the conventional treatment units performed well in reducing the concentrations of total coliform and *E. coli*. The tables show that each unit in WTP I and WTP II contributed to lowering total coliform and *E. coli*. However, it should be noted that the performance of the combined flocculation-sedimentation unit in WTP I was lower than that of the individual flocculation and sedimentation units together in WTP II in reducing the concentration of *E. coli*. In general, this performance difference was not seen for total coliform.

Although concentrations of *C. perfringens* also showed decreasing values during treatment in WTP I and WTP II, i.e. the conventional treatment units also performed well in reducing the concentration of *C. perfringens*, the concentration of *C. perfringens* from the coagulation unit to the flocculation-sedimentation unit in WTP I increased significantly (by one order of magnitude). In general, because microbes and other particles form flocs during the flocculation process, when a sample from the process is cultured and enumerated in a medium, the sample tends to have a higher concentration of microbes when compared to the sample taken from coagulation. As flocculation and sedimentation are combined in one unit in WTP I with a low-shear rotor impeller and a sludge deposit at the bottom of the unit, there is a high chance that *C. perfringens* concentrated in this unit, as *C. perfringens* resists chemical and physical treatment and is little affected by predation [18,19].

The performance differences on *E. coli* and the significant jump of *C. perfringens* concentrations discussed above should be important in designing a conventional treatment system for drinking water with a combined flocculation-sedimentation unit, especially from the perspective of the multiple barriers principle within the framework of safe drinking water. This principle expects a continuum of barriers, with each barrier contributing to the lowering of the concentrations of the targeted parameters to ensure drinking water safety. Lower performance of one barrier will place a higher burden on the next barrier.

Table 6 shows that the actual LRVs of the conventional treatments in WTP Badaksinga ranged from 0.67 to 1.4 for bacterial removal (*E. coli* and total coliform). These numbers are smaller than their default LRV of 2.0 for bacterial removal in conventional treatment [22]. The lower actual LRVs may be caused by the high turbidity of the water entering the filtration units; the turbidity of the water was from 1.54 to 8.03 NTU [23]. This high turbidity exceeded the critical limit for pollutant removal by conventional treatment. To achieve their default LRVs, the turbidity of the water entering the filtration units must be < 2 NTU. As explained above, the critical limits of a water treatment unit are important to achieve its default LRV.

For protozoa removal (with *C. perfringens* as the surrogate), the actual LRV of the conventional treatments was 1.23, i.e. less than half the default LRV of 3.0 for protozoa [22]. This happened because water entering the conventional treatment units contained a small concentration of *C. perfringens* so the actual LRV was smaller than the default LRV. Similar to this result, a study of microsporidia removal has shown that conventional treatments that use rapid sand filtration have an 81.8% removal rate [24], or an actual LRV of approximately 0.74. After passing the conventional treatments, the water enters the disinfection unit. Based on Table 6, the actual LRV of the disinfection unit for bacterial removal ranged from 3.0 to 3.71. These numbers are lower than the default LRV of 4.0 for bacterial removal by conventional treatments [22]. Because the bacterial concentration in the water entering the disinfection unit was not very high ($\leq$ 2400 MPN/100 ml), the actual LRVs were smaller than the default LRV.

For protozoa, the actual LRVs of the disinfection unit were 0, i.e. there was no removal; these actual LRVs matched the default LRV [22]. *C. perfringens* spores have a similar chlorine-resistant characteristic as *Cryptosporidium parvum* oocysts [25].

3.3 Assessment of Drinking Water Safety

Because all the surface water sources were not suitable for use as drinking water source based on the raw water source assessments, the raw water sources could not be categorized. However, getting the LRV_{req} requires the categorization of the raw water sources. To get the source categories, the microbial indicator in the raw water assessment was ignored and only results from the vulnerability assessment were used. Hence, the raw water sources were categorized as Category 4, and based on Table 2, the $LRVs_{req}$ for Category 4 is 6.0 for bacteria and virus and 5.5 for protozoa.

For the treatment technology assessment, the total LRVs were calculated by adding up the LRVs of the conventional treatments and the disinfection units. The total actual LRVs for WTP Badaksinga were 4.4 for bacteria and 1.23 for protozoa. These total actual LRVs were smaller than the total default LRVs of the treatment technology in WTP Badaksinga (6.0 for bacteria and 3.0 for protozoa). As mentioned above, this was because the water entering WTP Badaksinga had relatively small microbial concentrations. Based on this, the default LRVs were validated to be identical to the $\text{LRVs}_{\text{achv}}$. The $\text{LRVs}_{\text{achv}}$ of WTP Badaksinga were 6.0 for bacteria and 3.0 for protozoa.

The LRVs_{req} and $\text{LRVs}_{\text{achv}}$ from the above assessments were then compared to determine the microbial water safety. Because the LRV_{req} for bacteria was identical to the LRV_{achv}, the drinking water from WTP Badaksinga was categorized as safe. However, because the LRV_{req} for protozoa was higher than the LRV_{achv}, the drinking water was theoretically not safe. The results also showed that the protozoa concentration at the end of treatment was not 0. Because of this, an additional unit or barrier is theoretically required to ensure drinking water safety for protozoa. For this, a disinfection unit using UV light may be used because *Cryptosporidium parvum* oocysts are highly susceptible to UV [16]. The additional barrier requirement is to be validated and ensured by PDAM Tirtawening.

Besides comparison of LRV_{req} and LRV_{achv}, drinking water assessment using Quantitative Microbial Risk Assessment (QMRA) is commonly used [26]. But good initial input data for the model is needed when applying QMRA and there are also no practical cases of QMRA implementation to determine the critical limits of the processes [27].

4 Conclusions

The assessment of raw water sources showed that all raw water sources for WTP Badaksinga were not suitable as raw water sources for drinking water based on the microbial indicators. *E. coli* concentrations in all raw water sources were > 20,000 MPN/100 ml. Using only the vulnerability assessments from the raw water source assessments, all surface water sources for WTP Badaksinga were categorized as Category 4. Therefore, the LRVs_{req} for this category were 5.5 for protozoa and 6.0 for bacteria and viruses.

For the treatment technology assessment, the LRV_{achv} was obtained from the default LRV, although some of the actual LRVs did not meet the default LRV. The actual LRVs of the conventional treatment units did not reach their default LRV because water turbidity entering the treatment did not meet the critical limits of treatment plants. On the other hand, the actual LRVs of the disinfection unit showed bacteria removal and hence the actual LRVs could reach the default LRV. Therefore, the $\text{LRVs}_{\text{achv}}$ for the treatment technology were 3.0 for protozoa and 6.0 for bacteria and viruses.

Comparisons of LRVs_{req} and the $\text{LRVs}_{\text{achv}}$ showed that the LRV_{req} for bacteria was the same as the $\text{LRVs}_{\text{achv}}$ and therefore the drinking water could be categorized as safe. In contrast, the LRV_{req} for protozoa was much higher than the LRV_{achv} so the drinking water was theoretically not safe. Also, at the end of all treatments, the concentration of *C. perfringens* was not 0. An additional barrier is theoretically required, such as a UV disinfection unit, to ensure drinking water safety for protozoa. The additional barrier requirement is to be validated and ensured by PDAM Tirtawening.

The LRVs of pre-sedimentation and combined flocculation-sedimentation units within conventional treatment systems for drinking water need to be (re)assessed. The assessment should be based on the multiple barriers principle within the framework of safe drinking water.

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