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Wash water in waterworks: contaminants and process options for reclamation

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Abstract

Reclamation of clean water from filter backwash water was studied through pilot-scale experiments. The pilot plant consisted of clarification, sand-filtration, and ultrafiltration modules in sequence, with a provision to bypass the sand filter. Clean water that conformed to World Health Organization (WHO) guidelines on Potable Quality was reclaimed. Turbidity, aluminum and iron were found to be critical contaminants in process selection and design. Clarification, followed by sand filtration, was found to be the minimum requirement for recycling filter backwash. However, membrane filtration would enhance reclaimed water quality as the membrane acts as an additional barrier against *Giardia* and *Cryptosporidium*.

Key words: filter backwash; clarification; water treatment; aluminium; *Giardia*

Introduction

Potable water is typically produced by clarification of surface water. Often, alum is used as the primary coagulant for clarification, which results in the production of "alum sludge"; this is also called as "clarifier sludge". After clarification, the water is filtered through sand beds. The sand beds are backwashed after several hours of service, which results in filter backwash water. Alum sludge and filter backwash are waste streams produced during water treatment. Typically, in a waterworks, the flow rate of these two streams is of the order of several hundred cubic meters per day. In an effort to reduce the volume of these waste streams and to conserve as much water as possible, a pilot-scale study was undertaken to identify the major contaminants and to investigate the feasibility of reclamation of clean water.

Certain cases of recycling filter backwash water and recycling filtrate from clarifier sludge were reported. For example, Thompson *et al*. (1995) reported on pilot testing of microfiltration (MF) membranes for filter backwash treatment, where turbidity of 500 NTU were reduced to less than 5 NTU. In another trial, a mixture of filter backwash and clarifier sludge was processed by MF to produce water of turbidity 0.1 NTU. In a laboratory-scale study, Vigneswaran *et al*. (1996) treated filter backwash from a water treatment plant in Thailand using cross-flow microfiltration ceramic tubular membranes. Turbidity, bacteria, and aluminium were removed significantly and their long-term experiments extended for about 20 h. A bench-scale study with MF membranes was reported by Taylor *et al*. (2000). Samples from five water treatment plants in the United States were tested for removal of turbidity, total suspended solid, color, particle count, UV absorbance and microbial counts, which concluded membrane filtration as an economically-feasible recycling technique. Furrey *et al*. (2000) reported on a pilot trial of reclamation from filter backwash and liquid supernatant from the holding basin of a waterworks in New Jersey, USA using pall cross-flow membranes. The performance of the process was said to be consistent and the product water was of potable quality. Noticeably, most of the above reports focused on a single purification process, a membrane filtration.

Arora *et al*. (2001) focused on the presence of protozoa, such as, *Cryptosporidium* and *Giardia*, in filter backwash, examined the use of backwashable depth filter technology in the place of conventional filtration and the use of polymers resulted in excellent removal of turbidity, particles and microorganisms. In a series of articles, Edzwald *et al*. (2003) and Tobiason *et al*. (2003a, 2003b) noted that the quality of water recycled from filter backwash was temporally variable for plants with only flow equalization (without solids removal), exhibiting significant peaks in solid levels that led to a short-term increases in influent turbidity. They studied the suitability of two different clarification methods-dissolved air flotation and inclined plate sedimentation-alone or in combination with dual-media (anthracite/sand) filtration. Further, full-scale backwash recycling practices at six treatment plants in the USA were

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also reported.

While the aforementioned studies highlight some of the issues associated with recycling filter backwash, it is recognized that a proper design of recycling would involve site-specific details on water contaminants and reclaiming water that is of acceptable quality. A treatment plant operator is primarily interested in a process that could withstand the variations in loading while producing clean water of consistent quality which would conform to the Guidelines for Drinking Water established by the World Health Organization (WHO, 2006). Consequently, the primary goal of this research was to understand the level of contaminants in the waste stream and to investigate the feasibility of reclamation of back wash water through pilot-scale trials. Most studies on filter backwash were reported from the United States. The nature and constraints associated with filter backwash were largely unknown in Singapore and also, in this part of Asia, prior to this study.

Singapore has equatorial climate with annual rainfall close to 2,800 mm. The city-state is highly urbanized and the central region of the island is designated as a “protected catchment”, which means the runoff is free of industrial pollutants. Agricultural activity is limited in Singapore to certain peripheral areas. Hence, the use of organic pesticides and impact of nutrients derived (N and P) from fertilizers are minimal. Furthermore, the city’s sewer system reaches hundred percentage of the public, consequently, untreated sewage does not enter pristine surface water sources. In addition, treated wastewater does not flow into reservoirs, which are drawn for the production of potable water. While acknowledging that *Giardia* and *Cryptosporidium* levels impact the treatment strategies for recycle (Arora *et al*., 2001; Nieminski and Ongerth, 1995) and that mammals in the watershed often serve as sources of such protozoa (Rose, 1988), very little information was available on the presence of such parasites, since Singapore has little or no operations relating to animal husbandry. Therefore, this study was undertaken to assess the contaminants in backwash water in the urban environment and treatment strategy for recycle on other parameters, such as, turbidity, color, total dissolved solids (TDS), total organic carbon (TOC), nitrate, fluoride, chloride, sulphate, phosphate, metals, and coliforms.

1 Materials and methods

1.1 Pilot plant

A custom-built pilot plant with a capacity of processing 70 m^3/d of raw water was used in this study. It consisted of modules for clarification, sand-filtration, and ultrafiltration in sequence. Raw (backwash) water was fed to the lamella clarifier, which had about 20 inclined plates. Clarified water was then filtered through a sand bed (about 400 mm in diameter and 500 mm in height) and the ultrafiltration system subsequently. The UF membrane modules were purchased from Koch Membrane Systems Inc., USA. The UF permeate was dosed with sodium hypochlorite for disinfection. After passing through the sand filter the clarified water could be fed directly to the UF system.

1.2 Filter backwash water

The waterworks, where this pilot study was conducted, employed conventional coagulation-filtration process to produce potable water from surface water. There were 12 clarifiers and 16 sand filters in the waterworks. Alum was used as the primary coagulant. Filters were backwashed after approximately 25–28 h of service. Sedimentation tanks were emptied after 10–12 d of service. These two waste streams entered the sludge pond, from which the effluent was discharged to the public sewer. During backwashing a filter, typical flow rate of water was about 45–50 m^3/min and about 150–200 m^3 of wastewater was generated per filter. Filter backwash water was the largest fraction of wastewater and it accounted for about 2% of the raw water entering the waterworks.

1.3 Analytical methods

For water quality analysis, methods outlined by APHA (1998) and USEPA were performed. Color was analyzed by APHA 2120B Visual Comparison Method. Silica was analyzed by APHA 4500-SiO_2 F Flow Injection Analysis. TOC was analyzed by APHA 5310B High-Temperature Combustion Method. Iron, manganese, copper, and aluminum were analyzed by EPA Method 6010B with Plasma-Atomic Emission Spectrometry (Optima 5300DV, Perkin Elmer, USA). Fluoride, nitrate, chloride, sulphate, and phosphate were analyzed by EPA Method 300.0 Ion Chromatography (DX120, Dionex Corp., USA). Total Coliform Count was done by membrane filter technique (APHA 9222B). *Giardia* and *Cryptosporidium* were quantified by Real-Time PCR (SmartCycler II, Cepheid, USA) with two sets of primers (β-Giardin P241f and β-Giardin P241r) for *Giardia* and two sets (COWP P702f and COWP P 702r) for *Cryptosporidium* (Guy *et al*., 2003). The primers were purchased from 1st Base Pte. Ltd., Singapore.

2 Results

2.1 Preliminary assessment

A list of about 17 parameters, as shown in Table 1, was analyzed during the first three weeks of the study. The objective was then to select and to focus on the parameters that would critically influence the treatment strategy and the ultimate water quality.

2.1.1 Color, iron, and manganese

Color of the raw water was in the range of 5–25 Hazen and it could be reduced to < 5 Hazen in product water by UF permeate. Since color of the waste streams fluctuated from time to time, continual monitoring was considered to be necessary in the long-term. The iron concentration in raw water was 0.85 mg/L during the first week and decreased to 0.22 and 0.01 mg/L during subsequent weeks. According to the WHO guideline, iron concentration exceeding 0.3 mg/L could lead to an issue on color in potable water and hence, it is considered to be monitor. Presence of manganese could also lead to issues

Table 1 Preliminary assessment of water quality

Parameter	Week 1		Week 2		Week 3		WHO guideline
	Raw water	UF permeate	Raw water	UF permeate	Raw water	UF permeate	
Color (Hazen)	25	< 5	< 5	< 5	< 5	< 5	< 15
Turbidity (NTU)	22.7	1.0	7.9	0.1	2.5	0.2	< 5
pH	7.1	6.95	6.9	6.9	6.75	6.9	Neutral
Conductivity (µS/cm)	72	197	91.7	239	91.2	243	–
TDS (mg/L)	45	120	55	144	55	146	< 1,000
TOC (mg/L)	3.32	4.38	2.65	2.58	2.22	2.53	–
Nitrate (mg/L)	0.18	0.39	0.22	0.31	0.27	0.28	< 50
Fluoride (mg/L)	0.05	0.2	0.07	0.18	0.13	0.19	< 1.5
Chloride (mg/L)	7.82	23.7	8.89	29.3	11.3	31.0	< 250
Sulphate (mg/L)	14.0	20.7	12.6	13.2	12.9	13.5	< 250
Phosphate (mg/L)	< 0.08	< 0.08	< 0.08	< 0.08	< 0.08	< 0.08	–
Silica (mg/L)	0.68	0.79	0.77	0.75	0.79	0.77	–
Iron (mg/L)	0.85	0.04	0.22	< 0.003	0.01	0.004	< 0.3
Manganese (mg/L)	0.04	< 0.003	0.013	< 0.003	< 0.003	0.004	< 0.5
Copper (mg/L)	0.006	0.01	0.007	0.004	< 0.002	< 0.002	< 2
Aluminium (mg/L)	11.9	0.70	3.27	0.09	0.23	0.08	< 0.2
Total Coliforms, CFU/100 ml	> 1,000	< 1	> 1,000	1	> 1,000	1	< 1

Sodium hypochlorite was dosed for disinfection, which contributed to an increase in chloride, conductivity and TDS after treatment. There were natural (minor) fluctuations in the level of sulphate and fluoride from time to time. WHO: World Health organization; TDS: total dissolved solid; TOC: total organic carbon.

on color. Manganese in raw water was less than 0.05 mg/L during the first three weeks and it reduced as the water was processed through clarification and UF. This was one order of magnitude lower than the guideline value (0.5 mg/L) for potable quality. Hence, manganese was not a contaminant of significance in this location.

2.1.2 Nitrate, phosphate and fluoride

Nitrate was normally lower than 1 mg/L in raw water and was lower than the guideline (50 mg/L) of WHO. Consequently, nitrate was not expected to pose a challenge to water quality here. Fluoride (0.5 mg/L) was also lower than WHO guideline of 1.5 mg/L. Phosphate was lower that detection limit. Similarly, the very low levels of chloride, sulphate, silica and copper lead these contaminants were not of significance. Usually the presence of nitrate and phosphate in surface/potable waters were ascribed to non-point source pollution from agricultural runoff. Since agricultural activity was quite limited in the central part of Singapore and the raw water was primarily from the central region, N and P levels were found to be negligible in the current context of recycling.

2.1.3 Aluminum

Aluminum was high in raw water, although it decreased while after passing through clarification and UF, it was still high enough that close monitoring was warranted. The presence of aluminum was primarily attributed to the use of alum as the coagulant.

2.1.4 Total Coliform Count

Total Coliform Count was of the order of several thousands (CFU/100 ml) in raw water. The product water, which was dosed with sodium hypochlorite (4 mg/L dosage) as the disinfectant, showed a count of 1 or < 1 CFU/100 ml consistently. Therefore, it was concluded that dosing of sodium hypochlorite was adequate to reduce Coliform Count.

2.2 Monitoring program

The performance of the pilot plant was monitored for about twenty weeks to gain a better understanding of the level of contaminants, rejection of the contaminants at various stages in the reclamation process, the implications of the contaminants on the treatment strategy and the quality of reclaimed water.

2.2.1 Turbidity

Turbidity of raw water varied between 1 and 300 NTU as shown in Fig.1. Rapid fluctuations in turbidity were observed whenever backwashing was initiated for a filter. Most of the turbidity was removed at the lamella clarifier, where the effluent was generally below 5 NTU (WHO guideline). Further, upon filtration, turbidity reduced to 1 NTU consistently. The UF system further reduced the turbidity below 1 NTU. The bulk of turbidity was removed at the clarifier, particulate load on the filter and UF were minimal. This suggested the possibility that either one of the steps-sand filter or UF module- could be considered to be redundant and be eliminated in full-scale design. This aspect was explored by passing through the sand filter for four weeks of experimental trials.

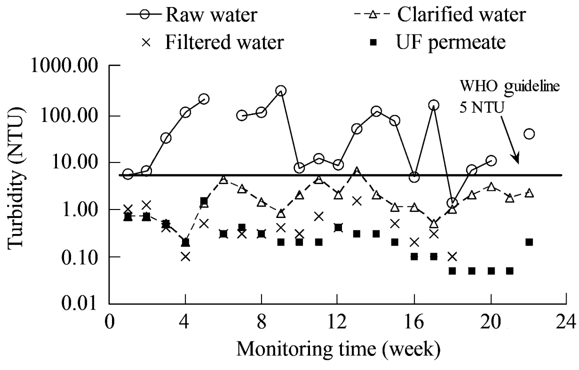

Fig. 1 Turbidity removal at various stages.

2.2.2 Color

Color of raw water fluctuated in the range 15–500 Hazen (Fig.2). Obviously, most of the color was removed at the clarification-stage. Clarifier effluent was consistently of 10 Hazen or less, which conformed to WHO guidelines. Further, this set of evidence led to the conclusion that most of the color-causing contaminants were of in particulate pattern, which settled in the clarifier as flocs. The flocs were often pale brown in color. In comparison to these values, the color of filter backwash exceeded 1,000 Hazen in a surface water treatment plant in New Jersey (Furrey *et al.,* 2000) and often exceeded 15 Hazen even after filtration. Color was usually related to the presence of iron and manganese in raw water (Cleasby, 1975; O'Connor, 1971). Therefore, it was imperative to examine those parameters in conjunction with color.

2.2.3 Metal concentration

Since iron in raw water was in the range of 0.05–9.0 mg/L (Fig.3) exceeding the WHO guideline 0.3 mg/L, removal of iron was important. Iron decreased to the range of 0.05–0.37 mg/L in clarified water, suggesting that a portion of the iron was precipitated in the clarifier. Further, it reduced to the range of 0.003–0.05 mg/L in filtered water, indicating that certain precipitates of iron could be small, and that escaped the clarifier were caught in the filter. Coagulation-sedimentation, followed by filtration, was adequate to remove iron well. Furthermore, iron was reduced to the range of 0.003–0.02 mg/L in UF permeate.

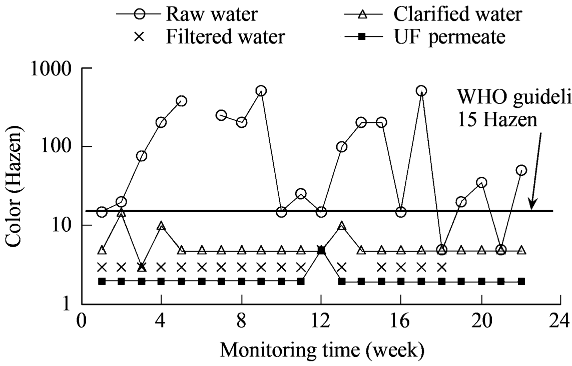

Fig. 2 Colour removal.

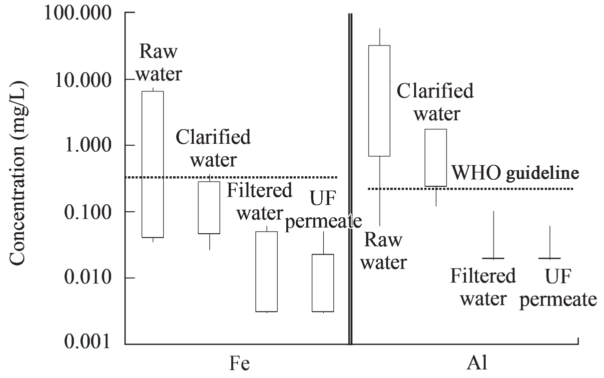

Fig. 3 Removal of iron and aluminium. Horizontal lines represent WHO Guidelines for each metal. The bars represent 10%–90% range of concentration and the sticks (above and below) indicate the maximum and the minimum in the data.

Manganese concentration in raw water did not exceed 0.5 mg/L. Coagulation-Sedimentation, followed by sand-filtration, removed about 70% of the metal so that the level of manganese in filtered water did not exceed 0.1 mg/L. Reduction below this level was infrequent and UF permeate reached about 0.02 mg/L in certain weeks. The data of manganese indicated that coagulation-sedimentation-filtration were adequate to meet WHO guideline (0.5 mg/L) for manganese. Filtered water and UF permeate had almost the same level of manganese, suggesting that the influence of UF on the removal of manganese was minor.

Copper was lower than 0.05 mg/L in raw water all through the monitoring period (WHO guideline: 2 mg/L) and hence, it did not pose a threat to the quality of reclaimed water. Almost always, copper was reduced to 0.002 mg/L in filtered water. After a filtration, copper stayed at about 0.002 mg/L in UF permeate suggesting that the fraction of copper removed by UF was negligible. Thus, coagulation-sedimentation-filtration was adequate for removing most of the copper.

Aluminium was high in filter backwash (1–80 mg/L) as shown in Figs.3 and 4. During the first four weeks, reduction in aluminium was not significant and it exceeded WHO guideline (0.2 mg/L). Interestingly, aluminium was not removed by clarification, filtration, and UF, thus indicating that aluminium was present in soluble form which could passed through the UF membrane. During this period, pH of clarification was not controlled. Starting the 4th week, pH of clarification was adjusted to 5.9–6.0, which was the level of lowest solubility of aluminium in water (Amirtharajah and Mills 1982). After a while, aluminium in filtered water decreased to 0.019 mg/L. Beyond a filtration, aluminium removal was negligible and its concentration in UF permeate was often close to 0.019 mg/L. Raw water fed to the pilot facility (filter backwash) was close to pH 7.0. Hence, acid dosing was necessary to effect the removal of aluminium. On an average, consumption of acid (sulphuric) was 0.1 mg/L. The data on aluminium confirmed that the coagulation-flocculation effect and the solubility of aluminium in water around pH 5.9–6.0 played an important role in its removal at the clarifier. Therefore, pH-control at the clarifier was the proper strategy for aluminium removal.

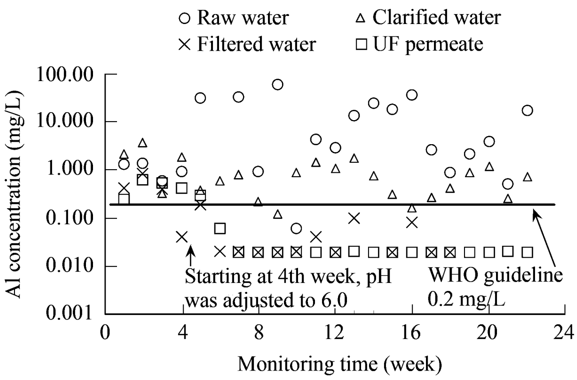

Fig. 4 Removal of aluminium and significance of pH.

2.2.4 TOC

TOC in raw water was 2–8 mg/L. However, TOC of filtered water was mostly in the narrow range of 1–3 mg/L, indicating that the balance of organic content was in particulate form and was removed by the clarifier and filter. While WHO did not have a guideline on TOC, USEPA had recommended enhanced-coagulation if TOC in treated water were to exceed 2 mg/L. In the present case, the surface water that reached the waterworks had TOC in the range of 1–2 mg/L. Further, if recycling of filter backwash were implemented on full-scale, it would contribute to only 1% of the flow through the waterworks. Consequently, the recycled water would not significantly alter the TOC level when mixed with the total flow. Hence, removal of TOC from filter backwash water was not important at this location.

3 Discussion

3.1 Bypassing the filter

It was observed that filter backwash water could form good flocs without the addition of any coagulant and the flocs settled readily leaving clear water on the top. This indicated the possibility that more than 99% of filter backwash water could be reclaimed by simple flocculation and sedimentation. Clarified water was largely clear and the clarity of the water enhanced on passing through the sand filter and membrane filter. This led to that either one of the filters-sand filter or membrane filter could be dispensed with.

During the last four weeks of the study (since 20th week), the sand filter was by-passed and clarified water was directly pumped to the ultrafiltration system. This was done to investigate the efficiency of such a process configuration. The relevant data points were included in Figs.1, 2, and 4. Under this scenario, as there was no “filtered water”, the points (x) are absent. Product water (UF permeate) conformed to WHO guidelines. This confirmed that the sand filter could be dispensed with. Clarification followed by membrane filtration was adequate for reclaiming filter backwash.

In addition, it could be assessed whether the membrane filter could be dispensed with. Under such a scenario, “clarified water” and “filtered water” would be present in Figs.1, 2, and 4 and the data points (rectangles) on “UF permeate” would be absent. “Filtered water” conformed to the guidelines of WHO. Therefore, sand filter could be retained and membrane filter could be dispensed with. These heuristically indicate that either one of the filters was adequate for reclaiming filter backwash.

3.2 Membrane fouling

Because the backwash water was high in aluminium content and aluminium remained largely in colloidal form during the reclamation process, it could be likely that such colloids could lead to fouling of membrane surfaces. Specifically, flocs formed from alum were sticky in nature and thus, were likely to be trapped within the membrane pores. Such fouling was not observed during the pilot study, which suggested that aluminium flocs were removed at the sand filter and thus, the tendency for membrane fouling was minimal. Data in Figs.3 and 4 confirmed that aluminium content of filtered water was usually 0.02 mg/L and the maximum was 0.1 mg/L, while the feed could have aluminium as high as 60 mg/L. Therefore, most of the aluminium was removed at the clarifier and at the sand filter. Due to those reason, it could be concluded that sand filter acted as a major barrier against colloidal aluminium and membrane fouling did not occur in this study. Moreover, if membrane filtration were to be adapted as a part of the reclamation process, it would be good to keep the sand filter in the front to minimize membrane fouling.

3.3 Occurrence of protozoa

Filter Backwash Recycling Rule (FBRR), published by the United States Environmental Protection Agency (USEPA, 2002), was established to regulate management of the recycle streams in water treatment plants. The objective of FBRR was to ensure adequate level of public health protection by minimizing the risk associated with *Cryptosporidium* and *Giardia* in recycle flows. FBRR attempeted to regulate three recycle streams in conventional treatment plants, viz., Filter backwash water, Thickener supernatant, and Liquids from dewatering processes. Pathogenic protozoa, such as, *Cryptosporidium* and *Giardia*, were known to present at elevated levels in these recycle streams and these were not easily inactivated by commonly used disinfectants, such as chlorine and chloramines. Sedimentation and filtration were known (USEPA, 2002) to be the main barriers for the removal of these pathogens. USEPA methods 1622 and 1623 were employed for detection for past several years. *Giardia* and *Cryptosporidium* were not detected in samples of fresh water entering the waterworks and also, in the finished water exiting the waterworks. Incidentally, the raw water for the waterworks came from a protected catchment and hence, the threat associated with these protozoa was considered to be minor.

Since the beginning of this pilot study, data on *Giardia* and *Cryptosporidium* were actively sought and there was a renewed attempt to employ methods that were more sensitive than USEPA methods 1622 and 1623. Consequently, the technique based on real-time PCR was chosen (Guy *et al*., 2003). Again, *Giardia* and *Cryptosporidium* were not detected in the surface water entering the waterworks and in the finished water leaving the waterworks. Within the waterworks, filter backwash and clarifier sludge were discharged into a Sludge Pond. In other words, Sludge Pond was the place where the cysts could be present in concentrated form. Three samples (originating on different dates) from the Sludge Pond were then analyzed. *Giardia* lamblia was detected at the level of 3–4 cysts/L in all the three samples and *Cryptosporidium* parvum was not detected in the same samples. Fluorescence of *Cryptosporidium* wall protein gene did not increase through forty cycles of amplification.

Interestingly, based on the total flow through the waterworks, only about 1% was discharged into the Sludge Pond, which amounted to 10 L/m^3 of fresh water entering the waterworks. Even within the Sludge Pond, while sampling, we ignored the clear supernatant (which was about 70%) standing at the top and sampled the "concentrated sludge" at the bottom (which made up of 30%). Consequently, the detected level of 4 cyst/L would approximately correspond to 10 cyst/m^3 of fresh water or 0.01 cyst/L, which was an extremely small number. Further, Ongerth (1989) noted that the recovery efficiency of membrane filtration averaged about(21.8 ± 6)% in the analytical protocol. Hence, out of the 0.01 cyst/L, the actual number that could possibly be recovered would be 0.0025 cyst/L or less, which is a significant tiny number (< 1 cyst in 100 L). These results indicated that *Giardia* cysts were present in extremely low numbers in the watershed and hence, eluded detection in the past years while using USEPA methods 1622 and 1623. Becuase PCR was more sensitive and the samples came from Sludge Pond which was holding the particulate solids from the raw water in concentrated form, it was possible to detect the protozoa in this study.

Giardia was not detected in the finished water at the waterworks for many years in the past. This implied that coagulation and sedimentation tanks in the waterworks were doing a very good job in all these years by rejecting all the cysts (along with all particulates) into the Sludge Pond. In other words, clarification was very effective in removing the protozoa and this was proven by time.

Cryptosporidium was not detected at the site. Ongerath *et al*. (1995) noted that pristine water sources might have as low as 1 cyst in 20 L. In the United States, the frequency of occurrence of *Giardia* and *Cryptosporidium* in surface waters were in the range of 60%–96%. The low numbers of *Giardia* in Singapore were attributed to the fact that the raw water for the waterworks came from a "protected catchment", which implied the absence of industrial runoff entering the fresh water supply, the absence of large animal farms in the watershed, and the diversion of municipal waste or treated effluent away from fresh water reservoirs.

4 Conclusions

Clarification was found to be a key purification step and it removed the bulk of the turbidity, color, iron and aluminium present in filter backwash water. Filter backwash had pre-formed flocs and it did not have a demand for coagulant. It was necessary to control the pH of flocculation at 5.9–6.0 for low level of residual aluminium.

The level of manganese, copper, silica, phosphate, chloride, sulphate, and nitrate were so low in raw water, so that these contaminants did not influence the selection of treatment steps or water quality.

Pilot study confirmed that water of quality conforming to WHO guidelines could be reclaimed from filter backwash. The quality of reclaimed water was consistent over time. Clarification and sand filtration were the essential steps for water reclamation in this case. Ultrafiltration was not a key requirement. However, UF was a better barrier against protozoa.

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References

APHA (American Public Health Association), 1998. Standard Methods for the Examination of Water and Wastewater. 20th ed. Washington: APHA, AWWA and WEF.

Amirtharajah A, Mills K J, 1982. Rapid-mix design for mechanisms of alum coagulation. *J Am Water Works Assoc*, 74(4): 210–216.

Arora H, Giovanni G D, Lechevallier M, 2001. Spent filter backwash water: Contaminants and treatment strategies. *J Am Water Works Assoc*, 93(5): 100–112.

Cleasby J L, 1975. Iron and manganese removal – A case study. *J Am Water Works Assoc*, 67(3): 147–149.

Edzwald J K, Tobiason J E, Udden C T, Kaminski G S, Dunn H J, Galant P B, Kelley M B, 2003. Evaluation of the effect of recycle of waste filter backwash water on plant removals of *Cryptosporidium*. *J Wat Suppl: Resarch Technol-AQUA*, 52(4): 243–258.

Furrey M, Schaefer J, Geho M, Gallo T, 2000. Microfiltration for treatment of waste filter washwater at a north Jersey surface water treatment plant. Proc of Water Quality Technol Conf., American Water Works Assoc. Denver, USA.

Guy R A, Payment P, Krull U J, Horgen P A, 2003. Real-time PCR for quantification of *Giardia* and *Cryptosporidium* in environmental water samples and sewage. *Appl Environ Microbiol*, 69: 5178–5185.

Nieminski E C, Ongerth J E, 1995. Removing *Giardia* and *Cryptosporidium* by conventional treatment and direct filtration. *J Am Water Works Assoc*, 87(10): 96–106.

O'Connor J T, 1971. Iron and manganese. In: Water Quality and Treatment: A Handbook for Public Water Supplies (3rd ed). New York: American Water Works Assoc, McGraw Hill.

Ongerth J E, 1989. *Giardia* cyst concentrations in river water. *J Am Water Works Assoc*, 81(9): 81–86.

Ongerath J E, Hunter G D, DeWalle F B, 1995. Watershed use and *Giardia* cyst presence. *Water Res*, 29: 1295–1299.

Rose J B, 1988. Occurrence and significance of *Cryptosporidium* in water. *J Am Water Works Assoc*, 80(2): 53–58.

Taylor J S, Norris C D, Mulford L A, 2000. Recovery of backwash waters by size exclusion membrane filtration. In: Proceedings of the AWWA Water Quality Technology Conference. American Water Works Association. Denver, USA.

Thompson M A, Vickers J C, Wiesner M R, Clancy J L, 1995. Membrane filtration for backwash water recycle. In: Proceedings of the AWWA Annual Conference on Water Quality. Denver, USA.

Tobiason J E, Edzwald J K, Gilani V, Kaminski G S, Dunn H J, Galant P B, 2003a. Effects of waste filter backwash recycle operation on clarification and filtration. *J Wat Suppl: Resarch Technol-AQUA*, 52(4): 259–275.

Tobiason J E, Edzwald J K, Levesque B R, Kaminski G K, Dunn H J, Galant P B, 2003b. Full-scale assessment of waste filter backwash recycle. *J Am Water Works Assoc*, 95(7): 80–93.

USEPA (US Environmental Protection Agency), 2002. Filter Backwash Recycling Rule: Technical Guidance Manual, USEPA.

Vigneswaran S, Boonthanon S, Prasanthi H, 1996. Filter backwash water recycling using crossflow microfiltration. *Desalination*, 106: 31–38.

WHO (World Health organization), 2006. Guidelines for Drinking Water Quality. 3rd ed. Geneva, Switzerland.