Relationships between total particle count, aerobic spore-forming bacteria and turbidity in direct filtration

Souleymane Ndiongue, Raymond Desjardins and Michèle Prévost

ABSTRACT

Direct filtration tests were carried out on a pilot plant (20 m^3/h) in order to examine the relationships between the removal efficiency of the total particle count, the spores of aerobic spore-forming bacteria and turbidity. Samples were taken from the raw water of the St Lawrence River (Canada), the turbidity of which is between 1 and 5 NTU, and the treatment objective was to maintain the turbidity of the filtered water at a value less than or equal to 0.10 NTU at all times. The treatment comprises a coagulation step using polyaluminium chloride (PACl) or Percol LT35, followed by filtration (10 m/h) on a bilayer filter of sand and activated carbon. The results show that linear correlations exist between the removal of total particle count, aerobic spores and turbidity. There is a progressive increase in the total particle count in filtered water, which begins just after the ripening period of the filter and continues to the end of the filtration cycle. Increase in the aerobic spores is not evident until much later, and there is only a weak increase in the turbidity.

Key words | aerobic spores, direct filtration, drinking water, in-line filtration, particle count, turbidity

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INTRODUCTION

The production of drinking water from surface waters is usually achieved by a conventional treatment that includes coagulation, flocculation, sedimentation and disinfection. When raw water has low turbidity, low colour, and a low content of dissolved organic matter and microorganisms, it is possible to eliminate the sedimentation step. Initially, a small amount of coagulant is added to the water in a rapid mixer, then the water containing the destabilized particles is routed to a flocculation basin if necessary. It is then directed to a granular filter. This process is defined as direct filtration (Culp 1977).

Giardia lamblia and *Cryptosporidium parvum* are pathogenic protozoa which, in infected individuals, can cause acute diarrhoea called *Giardiasis* or *Cryptosporidiosis*. These protozoa can only reproduce in the intestines of the people or animals they infect. When they are excreted into the environment, they exist in the form of cysts. These cysts are highly resistant to unfavourable environmental conditions and to chlorination. *Cryptosporidium* oocysts, generally called oocysts because of their spherical or slightly oval shape, have an average diameter of 4 to 5 μm (Rose 1988), and *Giardia* cysts, which are oval and slightly asymmetrical, measure 8 to 14 μm in length and 7 to 10 μm in width (Lin 1985).

The transmission of *Giardiasis* and *Cryptosporidiosis* from one host to another occurs through the consumption of contaminated water or food, or through contact with infected individuals or contaminated objects (Solo-Gabriele & Neumeister 1996). It is important, therefore, to protect sources of raw water and to ensure effective treatment for the removal or inactivation of these pathogenic protozoa.

In 1993, an epidemic in Milwaukee (Wisconsin, USA) was caused by *Cryptosporidium* oocysts which were transported in large numbers through all the stages of a water treatment plant in the city of Milwaukee. During the epidemic, the water produced did in fact conform to federal and local water quality standards (Solo-Gabriele & Neumeister 1996). This event clearly demonstrated the limitations of coliform and turbidity measurements in

evaluating the quality of the treated water from the point of view of the health of consumers.

The direct measurement of pathogenic protozoan cysts has its problems as well (Bellamy *et al.* 1993; Rice *et al.* 1994). When cysts are present in small quantities, detection methods involve cartridge or membrane filtration for concentrating the organisms from large volume water samples. The rate of recuperation is low and other particles can interfere during analysis. Furthermore, knowledge about the viability of these cysts and about the dosage required to cause infection is limited. In addition, we note a lack of quality assurance, a scarcity of qualified personnel and of laboratories suitably equipped to perform the analysis (Bellamy *et al.* 1993).

The difficulties associated with the direct measurement of pathogenic protozoan cysts, and the limitations of indicators like turbidity and coliform count, have spawned research focused on finding new indicators which would make it possible to evaluate cyst removal by filtration. Thus, a number of authors have examined the possibility of using particle count or spore concentrations of aerobic bacteria as indicators of treatment performance (Hargesheimer *et al.* 1992; LeChevallier & Norton 1992; Bellamy *et al.* 1993; Rice *et al.* 1994; West *et al.* 1994; Nieminski & Ongerth 1995; Barbeau 1996; Coallier *et al.* 1996; Lytle *et al.* 1996; Rice *et al.* 1996).

Particle counters are devices which count particles in several size ranges. They are more sensitive to variations in filter performance than turbidimeters (Beard & Tanaka 1977; McTigue & Cornwell 1988; Hargesheimer *et al.* 1992; Goldgrabe *et al.* 1993). Significant linear correlations have been observed between the removal of particles larger than 5 μm and that of *Giardia* cysts ($R = 0.879$) and of *Cryptosporidium* oocysts ($R = 0.830$) (LeChevallier & Norton 1992). One study has also shown good correlations between the removal of particles 4 to 7 μm in size and that of *Cryptosporidium* oocysts on the one hand ($R^2 = 0.79$), and between the removal of particles 7 to 11 μm in size and that of *Giardia* cysts on the other ($R^2 = 0.82$) (Nieminski & Ongerth 1995). Particle counting seems, then, to be a promising method for evaluating filtration performance.

The spores of aerobic spore-forming bacteria, which are called aerobic spores in this text, are essentially made up of species of the *Bacillus* group. They are elliptical to spherical in shape, measure approximately $0.5 \times 1.0 \times 2.0$ μm, and are known for their resistance to unfavourable environmental conditions (Rice *et al.* 1996). They are simple to cultivate, naturally present in surface waters, pose no risk to health and can be followed throughout all treatment steps (Rice *et al.* 1994). Because of these properties, aerobic spores have been proposed by a number of authors as a method for evaluating filter performance (Barbeau 1996; Coallier *et al.* 1996; Jakubowski *et al.* 1996; Lytle *et al.* 1996; Rice *et al.* 1996).

The principal objective of this work is to demonstrate the effect of direct filtration on removal of aerobic spores, total particle count and turbidity. In particular, we will highlight the effect of two coagulants as well as the effect of the two filter layers: activated carbon and sand.

EQUIPMENT AND METHODS

Description of the pilot plant

The tests were carried out on a pilot plant of 20 m^3/h which includes a coagulation step followed by rapid filtration at 10 m/h. This pilot plant is fed with raw water from the St Lawrence River (Montreal, Canada). The turbidity at the raw water intake is generally less than 2 NTU, except during short periods in late fall (November or December) and in the spring (April or May). During these periods, turbidity can reach 6 NTU, or even more, during a one- or two-week period.

The treatment objective at the pilot plant is to maintain the turbidity of the filtered water at a value equal to or less than 0.10 NTU at all times. The total head loss acceptable across the filter is 225 cm. Beyond this value, filtration must be stopped and the filter medium backwashed.

The results presented in this article were obtained during the months of April and December 1996. Polyaluminium chloride (PACl: Sternson Chemical Products Division, Canada) was used as the coagulant for the tests carried out in April. The PACl was injected into the raw water upstream of a static mixer (Greey Lightnin Model 50

ST4, Canada). The coagulated water was directly routed to the filter. The filter medium was composed of a layer of sand 42 cm thick overlaid with a 93-cm layer of activated carbon. The effective diameter (D_E) and the coefficient of uniformity (CU) of the sand were 0.42 mm and 1.30 respectively. The D_E and the CU of the activated carbon were 0.97 mm and 1.42 respectively. Pilot tests have indicated that when the required PACl dosages are added to produce filtered water with a turbidity less than or equal to 0.10 NTU, the duration of the filtration cycles is short, typically between 11.5 and 24 h.

Based on these results, a small flocculation basin was installed before the filter. This basin was made up of two compartments arranged in series, each equipped with a mechanical mixer. The volume of water and the residence time in each compartment were respectively 0.48 m^3 and 0.82 min. In addition, the sand in the filter was replaced by a coarser sand, with a D_E of 0.60 mm and a CU of 1.40. The thickness of sand and activated carbon layers were reduced to 34.5 and 77.0 cm respectively. During December 1996, tests were performed with Percol LT 35 (Allied Colloids, Canada), which is a liquid grade polyelectrolyte of high cationic charge and low molecular weight, and is supplied as a low viscosity solution. This product makes it possible to maintain the turbidity of the filtered water at a value less than or equal to 0.10 NTU, while at the same time lengthening the filtration cycle to about 40 h. The Percol LT 35 was injected upstream of the flocculation basin.

The filtration speed of 10 m/h was controlled by a pump and a modulating valve installed on the filtered water conduit. The surface of the filter measured 2 m^2. The height of submersion above the filter medium was maintained constant at 90 cm with the aid of an overflow.

Description of the measurement equipment and analysis methods

Turbidity

The turbidity of the raw water was measured continuously with a Hach Surface Scatter 6 turbidimeter, while that of the filtered water was measured continuously with a Hach Ratio 2000 turbidimeter. The results were recorded every 30 min for the raw water and every 5 min for the filtered water. A laboratory turbidimeter, Hach Ratio 18900, installed near the filter, was used to measure the turbidity of the samples taken at various depths in the filter. This instrument also makes it possible to verify and validate the measurements of turbidimeters that function continuously. The turbidimeters were calibrated in accordance with the directions of the manufacturer (John Meunier Inc, Canada).

Particle count

Two Hiac Royco model VC-OL25 particle counters (Pacific Scientific, USA), and two Hiac Royco model VC-OL60 particle counters (Pacific Scientific, USA) were used for the study. For sampling, one model VC-OL25 counter was installed at the inflow of the filter before adding the coagulant and the other in the middle of the carbon layer, and one model VC-OL60 counter was installed at the bottom of the carbon layer and the other at the outflow of the filter. Water samples from inside the media were withdrawn by means of nozzles (Degrémont type D20: Degrémont Infilco Ltd, Canada). All samples were pumped to the particle counters by a four head peristaltic pump (Masterflex 07553-80: Cole-Parmer, USA).

The model VC-OL25 functions with a nominal flow of 25 ml/min. It is designed to measure the size of particles in samples of raw water. The model VC-OL60 functions with a nominal flow of 60 ml/min and is used to measure the size of particles in samples of filtered water.

Both these models of a light blockage counter can detect particles between 2 and 400 μm in size. However, the screen installed at the inflow of each counter limits the maximal particle size to 150 μm. The particles are counted and classified into four channels: particles larger than 2 μm, 5 μm, 10 μm and 15 μm. The flow of the sample is measured with the aid of a flowmeter incorporated into the particle counter and is displayed in ml/min. The concentration of the particles in the sample is calculated based on the particle count and on the flow measured by the counter. The flowmeter is calibrated in accordance with the procedure recommended by the manufacturer.

The counters were first calibrated by the manufacturer prior to delivery. The second calibration was carried out on site (96/09/19) by Inter Basic Resources Inc. (USA). Since calibration uses spheres of controlled diameter with little or no variance, the sizes of the particles measured by the counters will therefore correspond to those of spheres that block the same amount of light as the spheres used in calibration.

The particle counters were connected to a computer running AccuCount software (Pacific Scientific, USA) to enable automatic data acquisition. With AccuCount, it is possible to observe the evolution of the particle count and log removal as a function of the time of filtration. AccuCount also provides the particle count per ml for each minute, or for a longer time interval selected by the user. The data are then exported on Microsoft Excel spread sheets by means of a macro.

Aerobic spores

The method used for enumerating the aerobic spores was the one proposed by Barbeau *et al.* (1997). The water was sampled in sterile bottles. The samples were first pasteurized at 75°C for 15 min. They were subsequently chilled, and then filtered on a Millipore 0.45 μm membrane filter made of inert mixtures of cellulose acetate and cellulose nitrite. The filter was then placed in a Petri dish containing a pad soaked with Tripticase Soy Broth (TSB) culture medium, and incubated at 35°C for 24 h. Following incubation, the colony-forming units (CFU) were counted by eye. The tests were performed in duplicate.

Table 1 summarizes the sampling details. The removal of particles of the size of *Giardia* and *Cryptosporidium* oocysts is generally expressed in terms of 'log removal'. For filtration, the 'log removal' of particles is defined as the difference between the decimal logarithms of the particle count at the inflow and at the outflow of the filter. In this study, the removal of particles is always expressed in the form of log removal.

RESULTS AND DISCUSSION

Figure 1 shows the correlation between the removal of turbidity and the removal of aerobic spores. The data in Figure 1a are from the tests using PACl or Percol LT35. The linear regression model of Figure 1b includes only data from the filtration cycles using PACl, and Figure 1c includes only data from the cycles using Percol LT35. A high linear correlation is found between turbidity removal and aerobic spore removal, the coefficient R is 0.933 for all the pilot-plant trials ($n = 31$), 0.943 for the tests using PACl ($n = 21$), and 0.950 for the tests using Percol LT35 ($n = 10$). Therefore, under the given raw water condition, a reduction in turbidity implies a corresponding efficient removal of aerobic spores. The size of aerobic spores is far less than the size of the *Giardia* cysts or the *Cryptosporidium* oocysts, thus when the turbidity is eliminated, cyst removal could be expected. However, turbidity is a gross parameter that is not sensitive enough to monitor small variations in the filtered water quality. A small increase in the filtered water turbidity could correspond to a high increase in particle count in the filtered water (Hargesheimer *et al.* 1992).

Correlations between particle removal and aerobic spore removal are shown in Figure 2. Low correlations were observed when linear regression is calculated for all pilot plant trials (Figure 2a, $R = 0.657$, $n = 34$) or for tests using PACl only (Figure 2b, $R = 0.633$, $n = 21$). It is possible that the high dosages of PACl injected, to produce water with a low turbidity (0.10 NTU), result in the presence of floc particles in the effluent of the filter, which give a false low value of the particle log reduction. High correlation exists between the removal of particles and the removal of aerobic spores for the tests using Percol LT35 only (Figure 2c, $R = 0.883$, $n = 13$). Particle removal is used as an indicator of cyst and oocyst removal effectiveness. The correlations between particle removal and aerobic spore removal imply that aerobic spore removal may also be used to assess cyst and oocyst removal.

Monitoring the quality of the water as a function of depth in the filter medium

During a cycle monitored on 96/04/23, in which 10.0 mg/l of PACl were used, samples were taken from the raw water, at two depths in the activated carbon (49 cm and 88 cm), and from the filtered water; therefore three

Table 1 | Details of sampling campaign for aerobic spores, turbidity and total particle count

Date	Number of filter run	Coagulant	Dosage (mg/l)	Sampling points	Filtration time (h:min)	Raw water turbidity* (NTU)	Filtered water turbidity* (NTU)
96-04-23	358	PACl	10.0	Raw water	02:00	2.16	0.13
				49 cm down in carbon			
				88 cm down in carbon			
				Filtered water			
96-04-24	359	PACl	10.0	Raw water	01:00	2.44	0.13
				49 cm down in carbon			
				88 cm down in carbon			
				Filtered water			
96-04-25	361	PACl	10.0	Raw and filtered water	0:05, 0:10, 0:15, 0:20, 0:30, 1:00, 2:00, 3:00	3.77	0.21
96-04-30	367	PACl	17.5	Raw and filtered water	0:05, 0:10, 0:15, 0:30, 1:00, 4:00, 8:00	4.77	0.09
96-12-04	580	Percol LT35	0.12	Raw water	40:19	0.90	0.07
				37.7 cm down in carbon			
				75.5 cm down in carbon			
				Filtered water			
96-12-04	582	Percol LT35	0.12	Raw and filtered water	0:10, 0:16, 0:24, 0:31, 1:06, 3:01, 24:00	1.06	0.07
96-12-16	585	Percol LT35	0.16	Raw and filtered water	01:00	1.50	0.13
96-12-17	585	Percol LT35	0.16	Raw and filtered water	17:01		
96-12-18	585	Percol LT35	0.24	Raw and filtered water	41:05		

*The value of turbidity indicated is the average for the filter run. Data of the first 30 min of filtration are not included in the average calculation.

layers of filter medium are considered. The first two, which are 49 and 39 cm thick, are in the carbon, and the third, which is 47 cm thick, includes the entire layer of the sand and the interface between the sand and the carbon.

Figure 3a shows the variation of the total particle count, of the turbidity and of the aerobic spores as a function of depth in the filter medium. In this figure, the first and the last points appear to be coincident. Note however that this is purely coincidental since the scales for all three curves are different. Turbidity, aerobic spores, and particle count are significantly reduced over the two layers in the carbon. In the sand layer, the removal of turbidity and aerobic spores remains satisfactory, particle removal however is poor.

The variation of the cumulative log removal as a function of depth in the filter medium is shown in

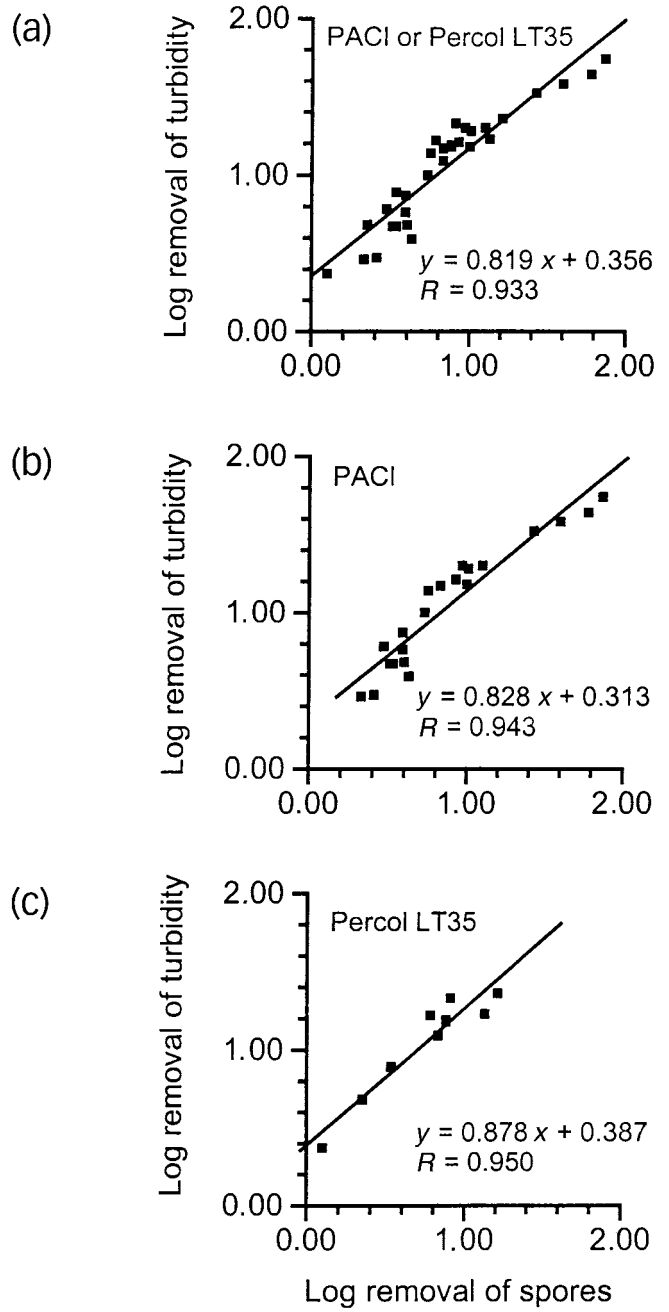

Figure 1 | Relationship between the removal of aerobic spores and the removal of turbidity: (a) data from all trials, (b) data from trials using PACl only, (c) data from trials using Percol LT35 only.

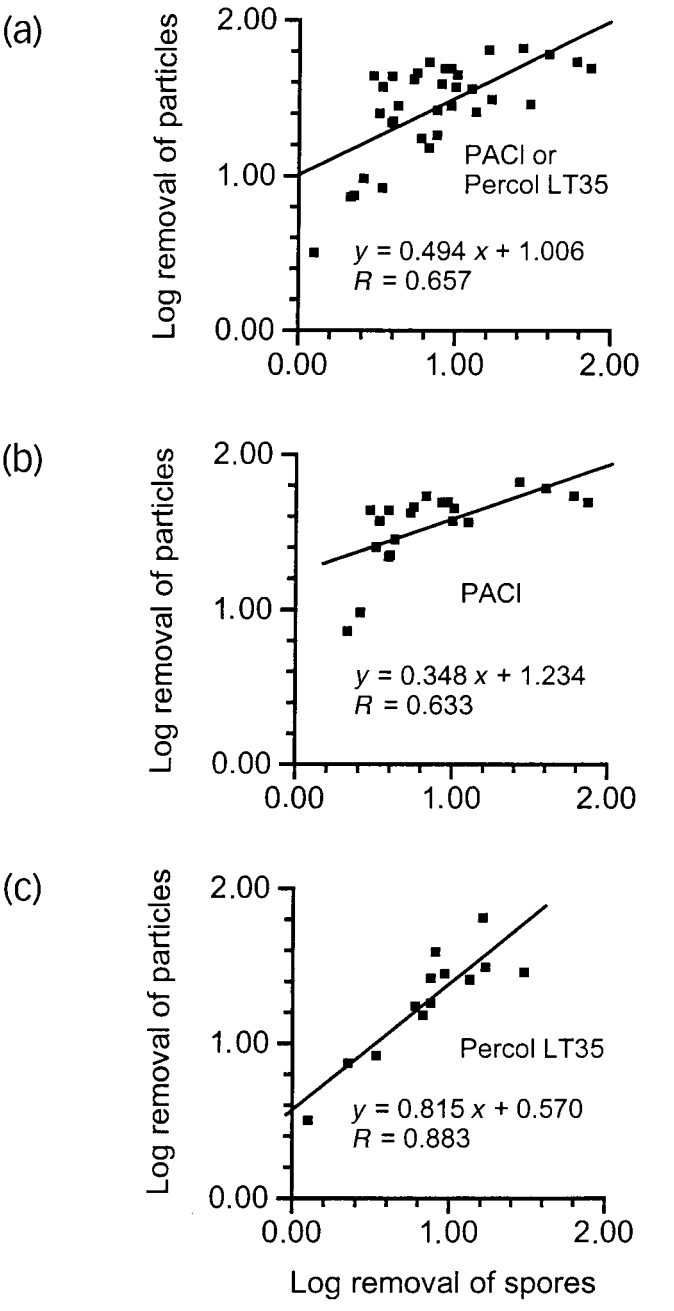

Figure 2 | Relationship between the removal of aerobic spores and the removal of total particle count (2–150 μm): (a) data from all trials, (b) data from trials using PACl only, (c) data from trials using Percol LT35 only.

Figure 3b. The cumulative log removal is calculated based on the results of the measurements carried out on the raw water and at the sampling point selected. For all sampling points, the cumulative log removal of particles is higher than the cumulative log removal of aerobic spores; however, when the water infiltrates into the sand, the increase

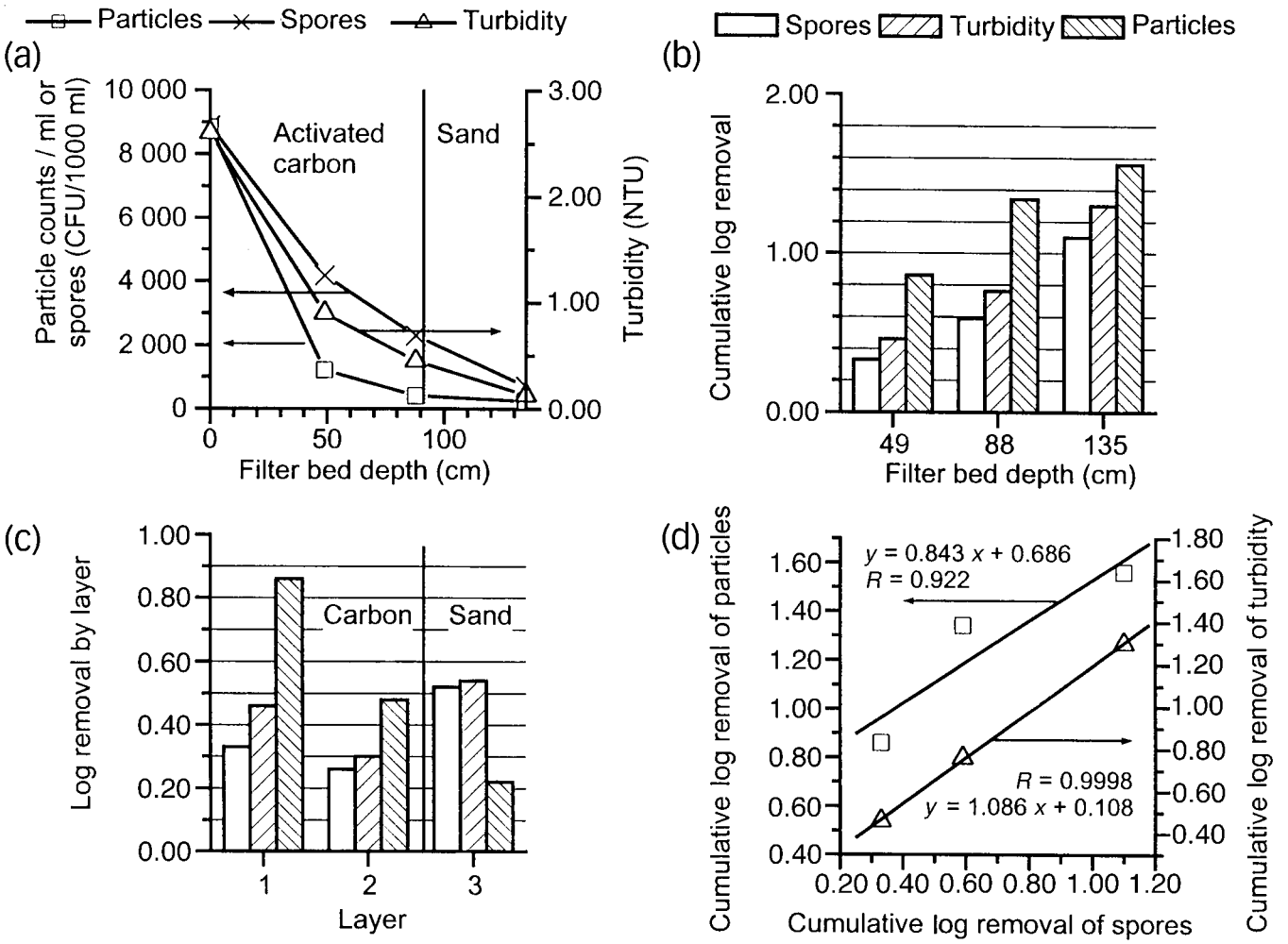

Figure 3 | Monitoring the quality of the water as a function of depth in the filter medium, after 2 h of filtration, cycle No 358, PACl 10.0 mg/l, 96/04/23: (a) variation of the total particle count (2–150 μm), turbidity and aerobic spores, (b) cumulative removal, (c) removal by the layers of filter medium (d) relationship between the removal of aerobic spores and the removal of total particle count or turbidity.

in the cumulative log removal of the total particle count is less than that of the aerobic spores. The cumulative log removal of aerobic spores is always the lowest of the three parameters.

The log removal of each layer of the filter medium is illustrated in Figure 3c. For a given layer, the log removal is calculated based on the measurements taken at the inflow and at the outflow of the layer. In the two carbon layers, particle log removal is the highest followed by turbidity with log removal of aerobic spores being the lowest. In contrast, in the third layer of the filter medium, the log removal of the aerobic spores and of the turbidity (which are about equal) are much higher than that of the total particle count. This is true even though at the inflow to the layer, the total particle count (40,300 particles/100 ml) is much higher than the number of aerobic spores (230 CFU/100 ml). In addition the aerobic spores, which are smaller than the particles which are larger than 2 μm, are more difficult to remove by filtration.

Flocculation in the pores of the sand and detachment of the flocs that had been retained on the surface of the grains may be advanced as hypotheses to explain why the log removal of particles in the sand layer is lower. Since the sand is fine, floc is essentially removed in the first few

centimetres of the filter medium, which thus becomes a zone of intense flocculation. It is therefore possible that the flocculation of particles smaller than 2 μm produces larger particles detectable by the counter. This increases the number of particles measured in the filter effluent and reduces the log removal. In addition, the accumulation of flocs, especially in the first few centimetres of the sand, reduces the porosity of the filter medium, which in turn increases the interstitial flow velocity. Thus, flocs previously retained on the surface of the grains of sand may be detached and entrained into the filtered water flow, with the result that the log removal of particle count is lower.

The fact that the log removal of aerobic spores by layer does not vary in the same way as the total particle count is consistent with the flocculation hypothesis. The agglomeration of small particles (<2 μm) to produce measurable flocs may increase the total particle count in the filtered water on the one hand and may reduce the number of spores on the other. This may be explained by the fact that a number of aerobic spores may be retained in a floc, and, since there is no homogenization in the measurement method, this floc will yield only one colony, which would underestimate the number of colonies in the filtered water.

The fact that the removal of turbidity does not vary in the same way as the removal of particle count may be explained by the dependence of turbidity measurements on the size of the particles present in the water and by the greater precision of the particle counters, which are more sensitive to variations in the performance of filters than turbidimeters (Beard & Tanaka 1977; McTigue & Cornwell 1988; Hargesheimer *et al.* 1992; Goldgrabe *et al.* 1993). It has been shown that turbidity is a function of the size of the particles present in the water (Sigrist 1975). For a given mass of particle concentration in the water, turbidity is maximum when the diameter of the particles is about 0.3 μm. This implies that the turbidity is lower when the particles are larger or smaller than 0.3 μm. Considering the flocculation hypothesis, it is possible that particles of about 0.3 μm flocculate to yield a size of floc that has less effect on turbidity. Based on the detachment hypothesis, the small particles responsible for turbidity may agglomerate with the flocs removed from the grains of the sand and produce particles which have little effect on turbidity, thereby resulting in a possible lowering of turbidity values.

Figure 3d shows the relationships between the removal of the aerobic spores and the removal of the total particle count or of the turbidity. There is a linear correlation between the removal of aerobic spores and turbidity ($R = 0.9998$), and between the removal of aerobic spores and total particle count ($R = 0.922$), but the regression is based on only three points. The correlation between aerobic spore removal and the removal of total particle count appears to be less satisfactory than that between the aerobic spores and turbidity. This may be due to the increase in the number of particles in the sand layer, which was discussed earlier. A trial performed on 96/04/24, but not reported in this paper, confirms the conclusions drawn from the 96/04/23 test (Figure 3).

Figure 4 illustrates the results of a test carried out to monitor the quality of the water as a function of the depth of the filter medium when Percol LT35 is used as the coagulant. Again, there is a linear correlation between the removal of aerobic spores and the removal of turbidity (Figure 4d, $R = 0.998$, $n = 3$) or the removal of total particle count (Figure 4d, $R = 0.982$, $n = 3$). For particles, there is a better correlation than was the case in the tests performed with PACl (Figure 3d). Furthermore, the lowering of the rate of removal of particles when the water infiltrates into the sand seems less perceptible (Figure 4a). For the sand layer (Figure 4c), the log removal of turbidity and aerobic spores increases and is larger than that of the total particle count. It must be emphasized that for this test, in addition to the difference between the coagulants used, the sand was replaced by a coarser sand, and the April water temperature (between 5.9 and 6.9°C) is different from that in December (2.0 to 3.3°C). The conclusions of the Percol LT35 trial are consistent with those of the PACl trial discussed earlier.

Monitoring the evolution of the quality of the filtered water

Figure 5 shows the evolution of the quality of the filtered water during the first 3 h of a filtration cycle using PACl. During the period that follows backwashing of the filter, there is a peak followed by a continual improvement in the quality of the filtered water measured by turbidity, particle

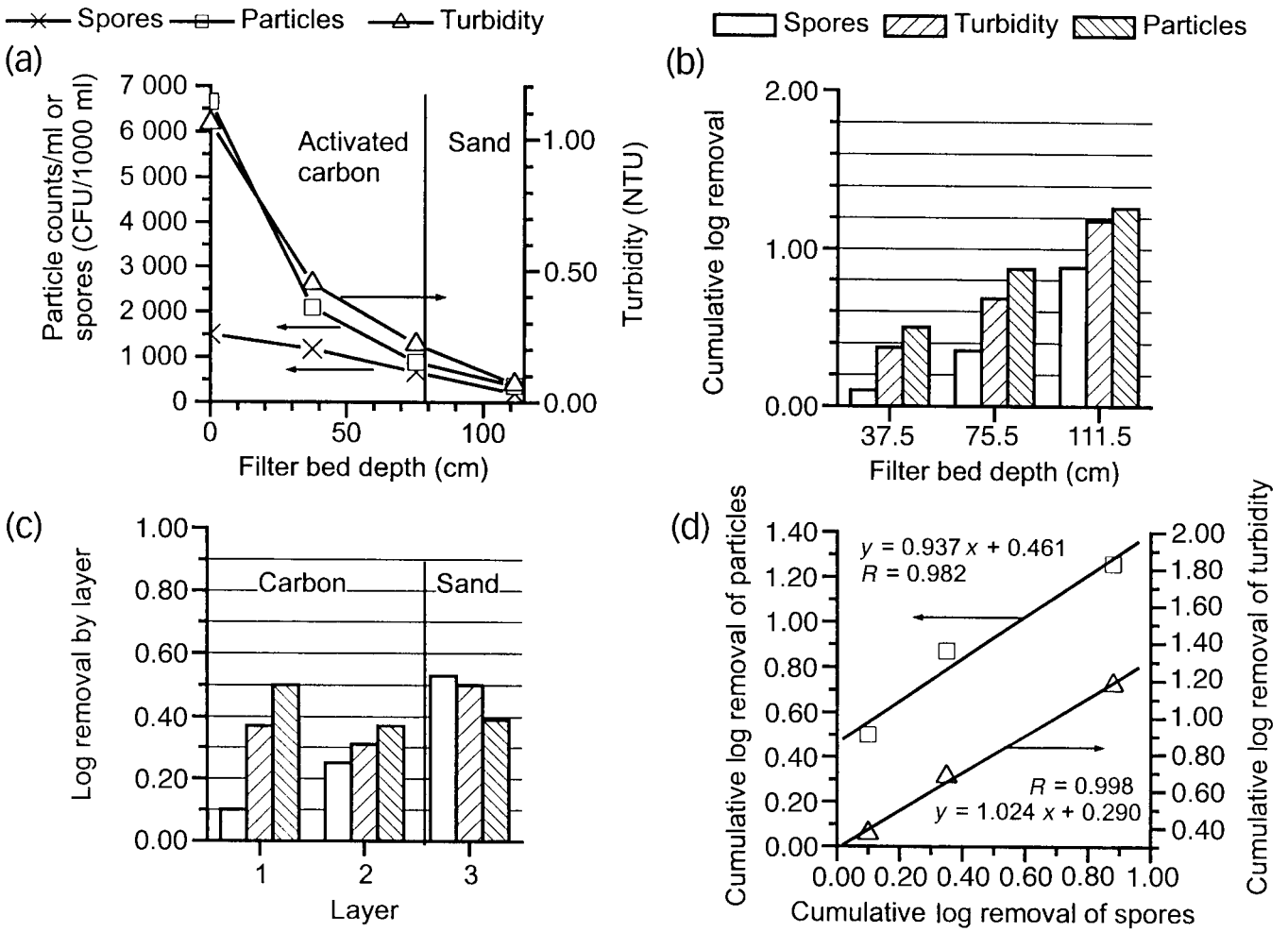

Figure 4 | Monitoring the quality of the water as a function of depth in the filter medium, after 40 h 19 min of filtration, cycle No 580, Percol LT 35, 0.12 mg/l, 96/12/02: (a) variation of the total particle count (2–150 μm), turbidity and aerobic spores, (b) cumulative removal, (c) removal by the layers of filter medium (d) relationship between the removal of aerobic spores and the removal of total particle count or turbidity.

count and aerobic spores. After this period, which is defined as filter ripening and lasts for about 1 h in this example, the total particle count increases slightly in the filtered water (from 255 to 286 particles larger than 2 μm/ml), while the turbidity and the aerobic spores, which vary in a similar fashion, seem to stabilize (Figure 5c). There is a correlation between the removal of aerobic spores and the removal of turbidity ($R = 0.961$, Figure 5d); however, the correlation between the removal of aerobic spores and the removal of the total particle count seems to be weak ($R = 0.644$, Figure 5d). Figure 6 shows the evolution of the quality of the filtered water during the first 8 h of filtration of another cycle using PACl. As was the case in Figure 5, there is a marginal increase in total particle count (from 235 to 298 particles larger than 2 μm/ml), while the turbidity and the aerobic spores tend towards stabilization. Because the aerobic spores and the total particle count do not vary in the same way, after about 8 h of filtration, the log removal of aerobic spores is slightly larger than that of the total particle count (Figure 6b), while at the inflow the total particle count is much larger than that of the aerobic spores (Figure 6a). There is also a linear correlation between the removal of the aerobic spores and the removal of turbidity ($R = 0.951$, Figure 6d),

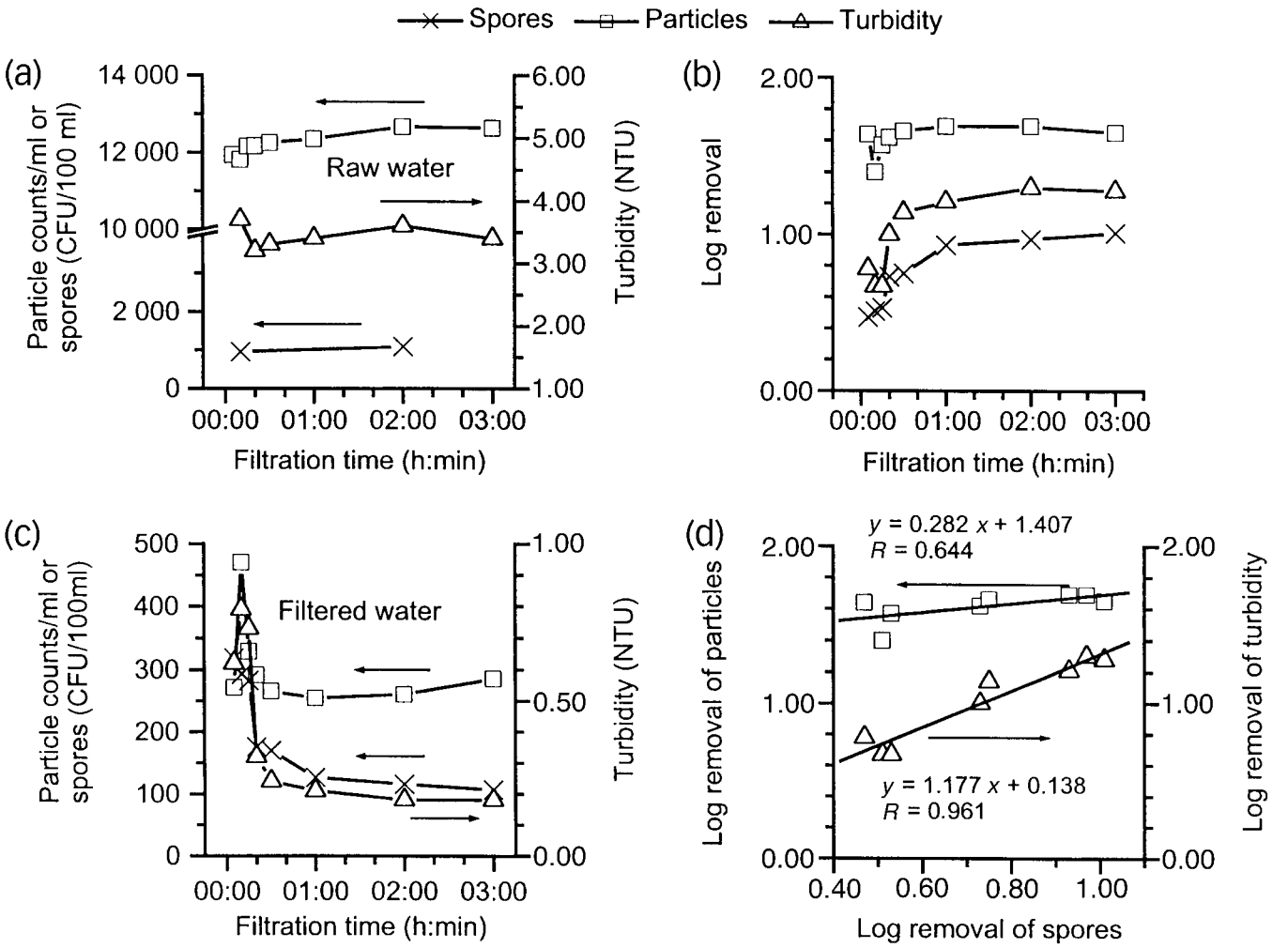

Figure 5 | Monitoring the evolution of total particle count (2–150 μm), aerobic spores and turbidity during the first 3 h of filtration, cycle No 361, PACl 10.1 mg/l, 96/04/25: (a) raw water, (b) log removal, (c) filtered water, (d) relationship between the removal of aerobic spores and the removal of total particle count or turbidity.

but the correlation between the removal of aerobic spores and the removal of particles seems to be weak ($R = 0.602$, Figure 6d).

Figure 7 presents the results of monitoring the evolution of the quality of the filtered water for about 40 h when Percol LT35 was used. Although there was a slight improvement in the quality of the raw water towards the end of the cycle (Figure 7a), the aerobic spores and the total particle count increase considerably in the filtered water, while turbidity increases slightly. The correlation between the removal of the particles and the removal of the aerobic spores improved ($R = 0.880$, Figure 7d), while the correlation between aerobic spores and turbidity dropped ($R = 0.735$, Figure 7d).

In summary, Figures 5 and 6 show that, during the first 3 h of filtration and immediately following the filter ripening, there is a continual increase in particle count in the filtered water, while turbidity and aerobic spores tend towards stabilization. For a longer period of observation (40 h), the degradation of the quality of the filtered water is well illustrated by aerobic spores and total particle count, and poorly shown by turbidity. The small variations in turbidity confirm the conclusions of the authors (Beard & Tanaka 1977; McTigue & Cornwell 1988;

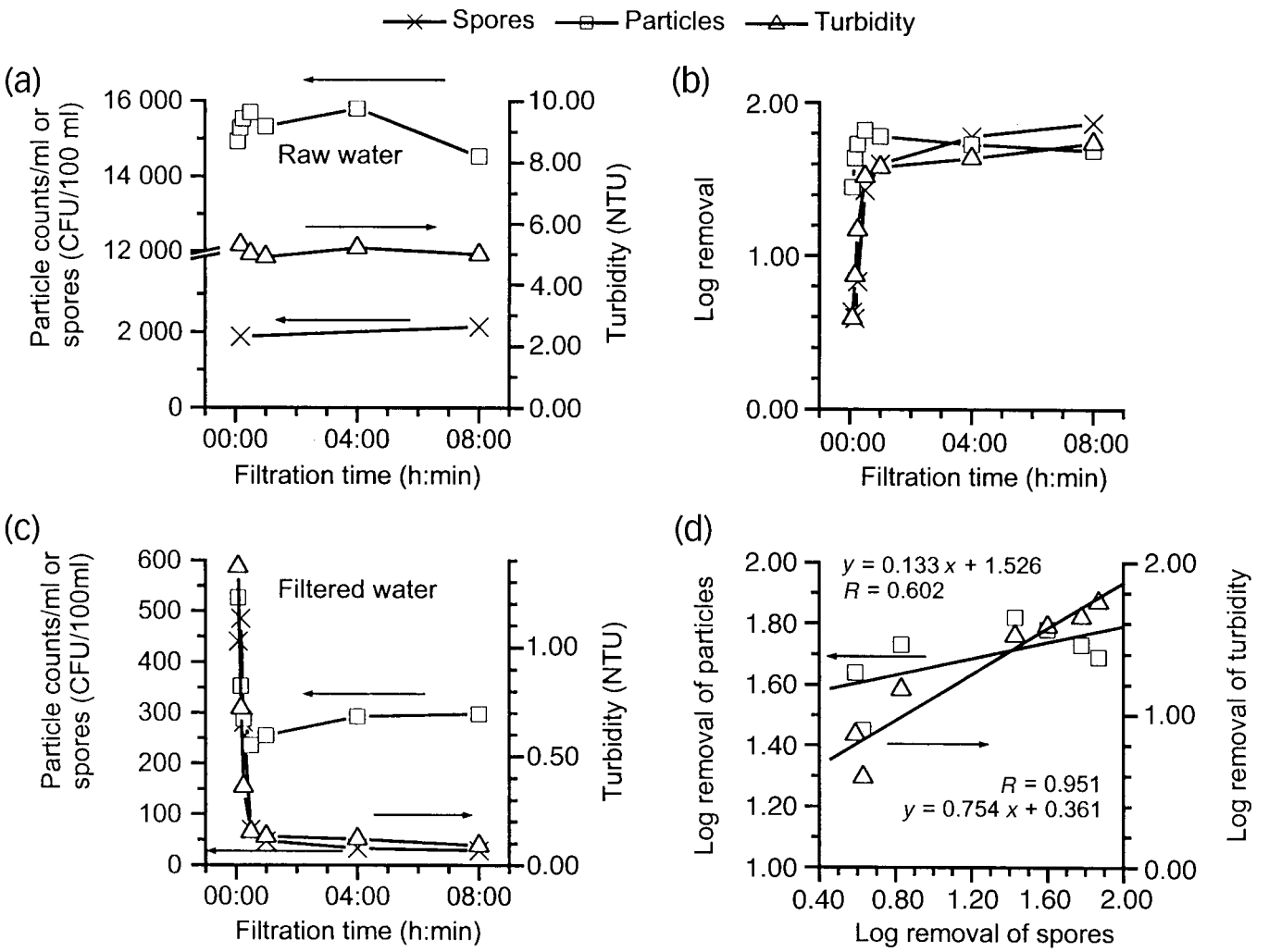

Figure 6 | Monitoring the evolution of total particle count (2–150 μm), aerobic spores and turbidity, cycle No 367, PACl 17.5 mg/l, 96/04/30: (a) raw water, (b) log removal, (c) filtered water, (d) relationship between the removal of aerobic spores and the removal of total particle count or turbidity.

Hargesheimer *et al.* 1992; Goldgrabe *et al.* 1993), who have shown that turbidity is less sensitive than particle count for detecting small variations in the quality of filtered water. The tests show that, in terms of sensitivity, aerobic spores fall between turbidity and total particle count. This is because it was the particle count that first revealed the beginning of degradation of the quality of the filtered water. When the filtration cycle was more advanced, the degradation of the quality of the filtered water was more readily perceived based on aerobic spores than on turbidity.

The continual increase in the number of particles in the filtered water may be explained by the detachment of the previously retained flocs and by flocculation in the pores of the filter medium. During filtration, the particles accumulate on the surface of the grains of the filter medium. The deposits reduce the volume of the pores, thereby increasing the interstitial flow velocity, which in turn makes it possible for the flocs to be re-suspended into the filtered water flow. At the beginning of the filtration cycle, this phenomenon is less significant since the filter is still relatively clean, which is why the aerobic spores that

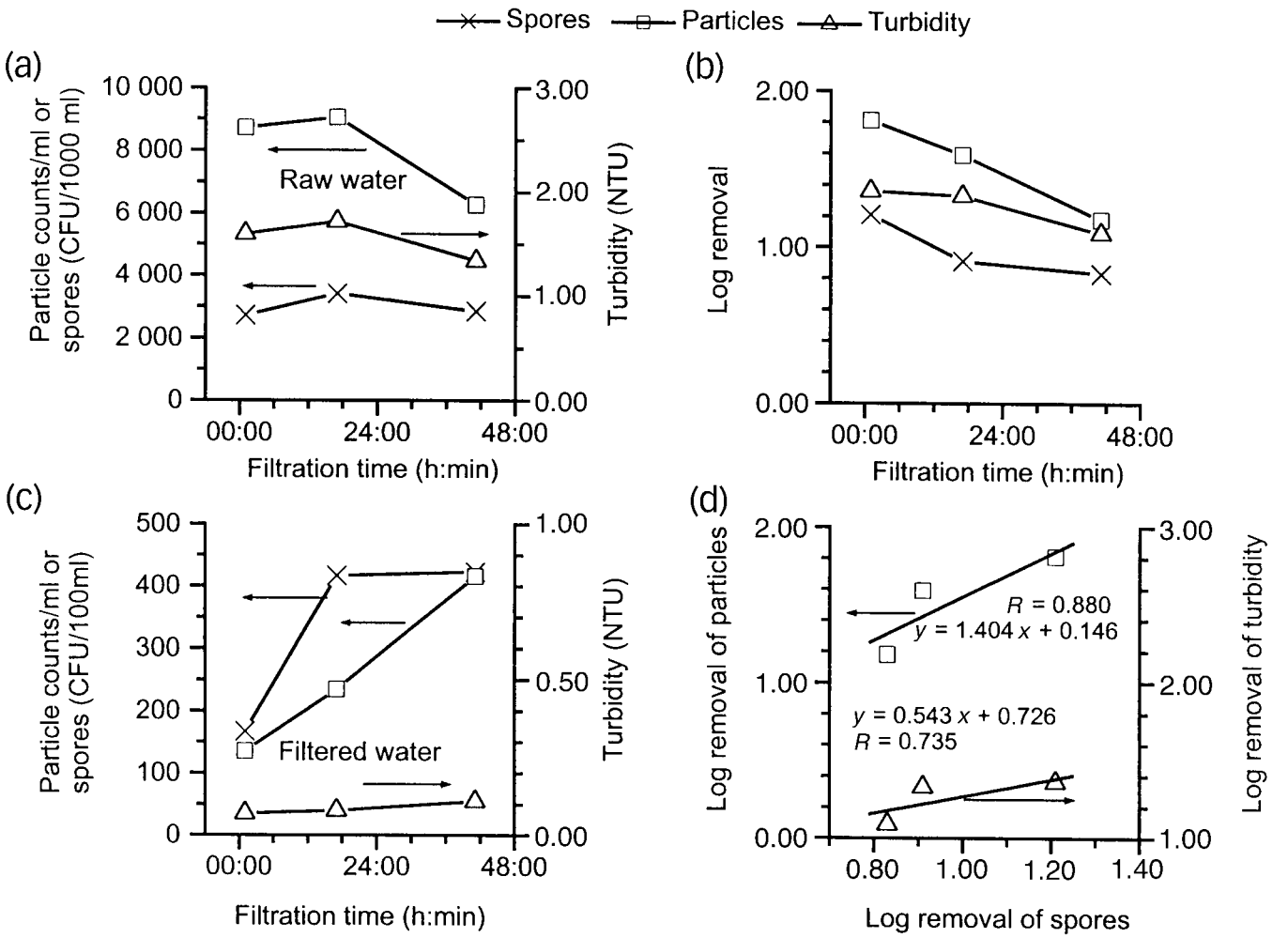

Figure 7 | Monitoring the evolution of total particle count (2–150 μm), spores and turbidity, cycle No 585, Percol LT35, 0.16 to 0.24 mg/l, 96/12/16: (a) raw water, (b) log removal, (c) filtered water, (d) relationship between the removal of aerobic spores and the removal of total particle count or turbidity.

seem less sensitive than the particle count do not show it. In contrast, when the filtration cycle is more advanced and the filter is moving towards the breakthrough point, detachment is such a major event that it is revealed by the aerobic spores and by the particle count as well.

CONCLUSIONS

- When PACl is used, a poor linear regression between the log removal of the aerobic spores and the log removal of the particles is observed. It is possible that high dosages of coagulant used to produce a low turbidity (less than 0.10 NTU) result in the presence of flocs in the filter effluent. This generates a false low value for the log reduction of particles.
- When Percol LT35 is used, a good linear correlation between the log removal of aerobic spores and the log removal of total particle count is observed. This implies that the removal of aerobic spores may be used as an indicator of the removal of the cyst-sized particles.

- All tests reveal a linear correlation between the removal of aerobic spores and the elimination of turbidity.
- Monitoring the evolution of the quality of the filtered water reveals that particle count is more indicative of water quality variation than aerobic spore count or turbidity level. Turbidity level is the least sensitive of the three parameters.
- Additional research is needed to optimize the direct filtration process in order to avoid any presence of floc in the filtered water.

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