Microfiltration pilot plant performance investigations into lake water treatment

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ABSTRACT

A 6-month study was carried out at AMGA's research centre, using a microfiltration pilot plant to treat lake water from the Brugneto dam. Specific tests were carried out to challenge the membrane with respect to its ability to remove high levels of turbidity, *E. coli*, micro-algae, aluminium and *Cryptosporidium* oocysts. The microfiltration membrane used in this study was clearly fully able to reject protozoan oocysts at a level not easily obtainable using conventional treatment technologies, as well as faecal indicator bacteria.

Key words | *Cryptosporidium*, faecal bacteria, microfiltration, particle count, performances, pilot plant

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INTRODUCTION

Azienda Mediterranea Gas e Acqua SpA (AMGA) furnishes the water supplies for the city of Genoa (Italy) mainly from surface waters: a river (Bisagno) and two artificial lakes (Brugneto dam and Valnoci dam). These are treated with conventional flocculation, sedimentation, filtration and with slow sand filtration technology, followed by disinfection with chlorine or chlorine dioxide.

During heavy rainfall it can happen that even well operated technologies for the removal of particles are not able to provide a reduction of 3–6 $\log_{10}$ of *Giardia* cysts and *Cryptosporidium* oocysts, as required by the recent US regulation (Interim Enhanced Surface Water Treatment Rule 1998). Although in Italy there has been no report of any waterborne outbreak related to *Giardia* or *Cryptosporidium*, low pressure membrane filtration can provide an extra barrier.

Studying the mechanism of *Cryptosporidium* and *Giardia* removal by ultrafiltration and microfiltration membranes, Jacangelo *et al*. (1995) concluded that size exclusion is probably the major mechanism responsible for an absolute removal of this microorganism, as long as the membranes were intact.

Even though it is well known, it is important to remember that the use of chemical disinfectants to inactivate protozoa would create high levels of disinfection by-products.

AMGA is currently evaluating the possibility of enhancing the particle removal efficiency of its own drinking water treatment plants. In late 1997 AMGA established a permanent research centre at the waterworks facility of Prato, to investigate technologies to improve water treatment. This location is well suited for the intended purpose because it is possible to feed the pilot installations with surface (lake, river) and well water.

Previous research activity was aimed at investigating the capability of the existing conventional separation technologies, their failures, the weak points and the way to

overcome them, optimising design and operation conditions (Borrelli *et al*. 2000). After that, new technologies, for example membrane separation, were tested. While the conventional systems, based on physico-chemical principles, cannot give an absolute guarantee in terms of separation efficiency (size and number of leaking particles), the membrane is a real physical barrier, theoretically capable of removing any particle exceeding the size of the membrane pores. On the other hand, the conventional system is often credited with being cheaper, more flexible and easier to recover following human mistakes or incorrect operating conditions, while a membrane may be prone to fouling, especially as the pore size is reduced. Such fouling could become irreversible, unless precautions are taken, resulting in heavy economic consequences.

It is also evident that conventional monitoring systems, based on the turbidity meter, are no longer an appropriate tool whenever 'dangerous' particles are dealt with in filtration technologies, mostly because at very low equal turbidities a wide range of particles is possible, in term of both size and concentration (Gregory 1998; Huber and Frost 1998). Therefore the particle counter seems the 'key' instrument for this kind of investigation (Borrill and Mckean 1993; Hargesheimer *et al*. 1992).

Among the different possible membranes, microfiltration (MF) has been selected to start the research. This paper summarises the results of six months of almost continuous activity. Specific tests were performed for investigating removal capacity with respect to different spiked and natural pollutants. The capacity of the system to recover standard long-term performance once the heavier pollution conditions are over, and the capacity to tolerate the new fouling stress of the following test were also investigated. Emphasis was given to monitoring any failure of the membrane and to the possibility of easy repair.

METHODS

The microfiltration unit

The USF Memcor CMF pilot plant used polypropylene membranes with a nominal pore-size of 0.2 μm. A membrane element comprises about 20,000 hollow fibres, with an outside diameter 550 μm, 1 metre long, potted at each end and supported in a coarse screen material, for a nominal inside area of 15 m^2. Normal service flow is from the outside of the filter to the inside (lumen). Solids accumulate under dead-end filtration conditions and if the unit is operated with a constant flow, the trans-membrane pressure (TMP) will gradually increase. Cake layer removal is achieved by a periodic compressed air backwash lasting 2–3 min. The lumens are pressurised to 6 bar, then the air is allowed to discharge through the fibres to the outside and the dislodged solids are swept away by feed water. The period between backwashes will depend on the feed and operating conditions (usually 15–60 min). Over a longer period (one week to several months) a chemical clean in place (CIP) will become necessary to remove the fouling which is not removed by the backwash. The set point for CIP is 130 kPa TMP. CIP is carried out using a 1.2% w/w sodium hydroxide and 0.6% v/v of a detergent solution.

The unit has a built-in automatic pressure decay test (PDT), which is sensitive to the equivalent of 5 log particle rejection and which is used routinely to monitor the membrane system integrity at daily or longer intervals. The CMF unit is equipped with two membranes, a programmable logic control (PLC), pressure transmitters, flow meter, conductivity meter, pH meter and temperature measurement on the feed side. The pressure transmitters monitor TMP and are connected to a graphic user interface and to a datalogger. The datalogger also provides, at a 2.5 min frequency, data on flow, pressure and temperature.

The experimental apparatus

External to the MF unit, turbidity meters and particle counters are used continuously on feed and filtrate water. During filtration cycles, water is drawn from the break tank by the feed pump and enters the modules at the top end. The filtrate flow is maintained by using a variable speed drive on the feed pump. The pump output is adjusted via a process controller within the PLC program. Changing the filtrate flow is accomplished by changing the

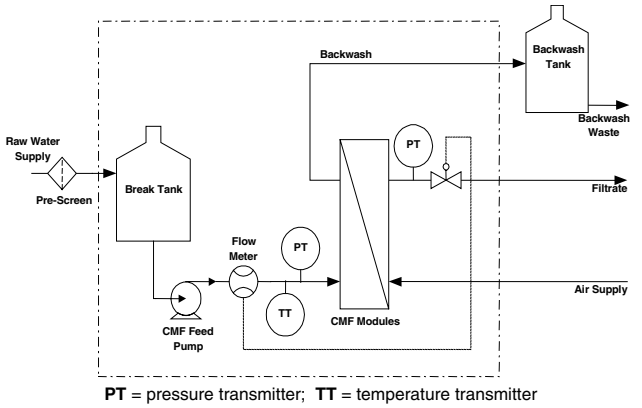

Figure 1 | Schematic view of the 2M10C microfiltration pilot plant.

controller set point. The maximum flow capacity of the apparatus was 3.5–4 $m^3\ h^{-1}$. A schematic view of the pilot plant is presented in Figure 1.

Analytical methods and monitoring instruments

The procedures used for grab analysis (single samples collected at different time frequencies according to the trial conditions) and on-site continuous analysis for raw and treated water are specified as follows.

Grab analysis

- Algae: phytoplankton single-cell counting technique and identification (*Standard Methods* 1995).
- Aluminium: atomic absorption spectrometry (*Standard Methods* 1995).
- Inactivated *Cryptosporidium* oocysts in raw and treated water were concentrated from 600 l of permeate following filtration with an Envirocheck™ capsule. Oocysts were detected with immunofluorescence, according to the EPA 1622 method (EPA 1999).
- *E. coli*, faecal coliforms, streptococci, total coliforms: membrane filtration technique (*Standard Methods* 1995).

On-site instruments

- Turbidimeter: turbidity of raw and filtered waters were determined on site using a HACH 2100C turbidimeter. Turbidity was recorded on-line. The turbidimeter was calibrated with formazine standards, according to Standard Method 2130 B (*Standard Methods* 1995).
- Particle counter: two different particle counters have been used on site (two sensors for raw and filtrate waters); Met One model PCX and PMS LiQuilaz model E20. Both instruments operate on the principle of light obscuration.
- Flowrate: 100 ml min^{-1} (PCX); 70 ml min^{-1} (PMS)
- Particle size range: 2–750 μm (PCX); 2–150 μm (PMS)

The instruments were calibrated with certified American National Institute for Standards and Technology monodisperse traceable spheres of known size. The size category in which particle counters detect *Cryptosporidium* oocysts was experimentally determined to be in the range 2–4 μm (Borrelli *et al.* 2000).

Experimental protocols

Table 1 summarises the testing periods, the type of water used in each activity phase, operational parameters and the main physico-chemical characteristics of the feed water.

The testing period lasted from 15 February to 6 July almost continuously with raw (i.e. not spiked) Brugneto dam water. In accordance with the test programme, the raw water was then spiked with selected pollutants to perform special trials lasting 12–24 hours.

Flow rate and backwashing frequency were sometimes lightly modified, following the recommendation of the membrane manufacturer (e.g. in the case of high turbidity periods) or with the purpose of stressing the test conditions. In one case (*Cryptosporidium* oocyst challenge) the flow rate was substantially decreased from 3,500 l h^{-1} down to 1,000 l h^{-1} and backwashing during the trial was discontinued in order to exploit to the maximum the available quantity of oocysts. However a 'blank test' was carried out previously and it demonstrated that, operating in the flow range 1,000–3,500 l h^{-1}, no noticeable modification in the membrane efficiency is produced, as far as the filtrate quality and the 2–4 μm range particle rejection

Table 1 | Testing protocols, operating parameters and main physico-chemical characteristics of feed water

Period	Feed water	Flow rate l h^{-1}	Backwash time frequency (min)	Temp °C	pH	Turbidity NTU	Total particles count (n ml^{-1})
15 Feb–6 July 1999	Raw surface water except during spikes	3,500	45	5–7	8.3–8.4	1–4	7,000–15,000
9 March–15 April 1999	Spikes with sludge	2,600	25	5.5–8	8.3–8.4	10–85	6,000–22,000
16 April–6 July 1999	Spikes with *E. coli*	3,500	70	7.7	8.3	2.4	7,000–11,000
	Spikes with microalgae	3,000	90	10	8.1	3.3	10,000–11,000
	Spikes with aluminium salt	3,500	45	7.5	8.4	1.4	5,000–6,000
	Spikes with inactivated *Cryptosporidium* oocysts	1,000	120	8.1–8.6	8.4–8.5	0.9–1.1	100–10,000

are concerned. Bottom sediments from the Brugneto dam were placed in the break tank to increase feed water turbidity to 10–85 NTU.

E. coli strains isolated from the Brugneto dam water were cultivated in nutrient broth. The suspension was partially purified. No attempts were made to avoid or control cell aggregation.

Selected microalgae (see Table 5) collected from the Brugneto dam water were placed in separated reactors containing Brugneto dam water and nutrients, maintained at 20°C and under artificial light. The feed water in the break tank was spiked with equal portions of the contents of the reactor.

Poly aluminium chloride was used to spike the feed water.

To feed the break tank with *Cryptosporidium* oocysts, inactivated and purified *Cryptosporidium* oocysts were obtained from infected calves at a initial concentration of 1.10^8 *Cryptosporidium* oocysts ml^{-1}.

Several trials lasting 12–24 hours were carried out in each activity phase. After the completion of each phase a CIP was made whether or not the set point was achieved, with the purpose of eliminating any possible interference with the scheduled test-activity (e.g. where membrane fouling could be suspected to improve the removal efficiency).

RESULTS AND DISCUSSION

During the approximately six months of testing, the pilot plant was operating for a cumulative time of 117 days (83% of period) treating a total volume of about 9,000 m^3 with a specific productivity of 116 l m^{-2} h^{-1}. Interruptions were due to some problems with the air compressor and to organisational aspects. TMP was continuously recorded, but it never reached the set point of 130 kPa. Consequently, any CIP was carried out before the set point and clearly recovered the starting TMP even at the end of the entire period and after artificial challenges. At constant flow TMP is a good measure of resistance, provided the temperature stays nearly constant.

During the testing period , the temperature increased from 5°C to 9°C, producing about a 10% decrease in TMP, because of viscosity effects.

The PDT was performed weekly and it was always satisfactory. The 0.7 kPa min^{-1} corresponds to 5 log of rejection. This corresponds to a high level of integrity.

'Brugneto' raw water treatment

The objective was to test the MEMCOR CMF efficiency when treating a natural surface water that had not undergone any pretreatment.

Table 2 | Performance of CMF pilot plant when fed with raw surface water (average concentration)

	1 March		2 March		4 March	
Parameter	**In**	**Out**	**In**	**Out**	**In**	**Out**
Turbidity (NTU)	1	0.04	3.9	0.04	1.1	0.04
Total algae cells (n ml^{-1})	4,774	0.11	2,534	0.57	2,726	0.07
Total coliforms (UFC 100 ml^{-1})	10	0	1	0	50	0

Stable operation conditions were achieved at a flux rate typical for this type of water. However, no attempt was made to optimise the parameters of flux and backwash interval, which was automatically fixed at 45 min. The unit did not require a CIP in this period, but based on extrapolation of the rate of resistance increase, the CIP interval would have been about 6–8 weeks. Table 2 summarises the performance of the pilot plant relating to trials carried out near the end of the phase. However performances of rejection and permeate flux production were nearly constant during the whole period of this phase. The treated water was constantly around 0.04 NTU. Removal of faecal indicator bacteria and algae was substantially complete. Particle count data shows that rejection of 2–4 μm particles was at least 3.5 $\log_{10}$, which is close to the limit of resolution for this technique (see Figures 2 and 3).

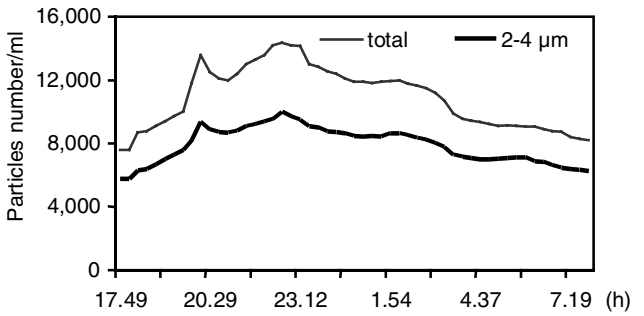

Figure 2 | Particle concentration in raw water.

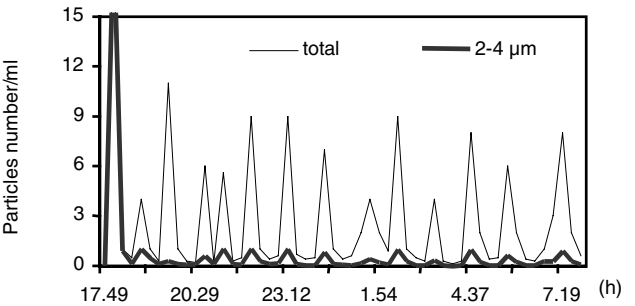

Figure 3 | Particle concentration in treated water.

'Brugneto' raw water spiked with sludge to increase turbidity

The objective of this trial was to test the MEMCOR CMF efficiency and recovery with high turbidity water (up to 85 NTU). The pilot plant performances from a trial of 14 hours are reported in Table 3 and refer to the maximum turbidity level tested. During the trial the pilot plant maintained the same performance when fed with unspiked dam water (1.5 NTU).

The print-outs recorded from the particle counter relating to the same period of 14 hours (several tests were performed with similar results) are shown in Figure 4a and b. The particle counter data show no effect on filtrate counts during the challenges, and removal in the 2–4 μm range was dependent on the raw water particle count (at 85 NTU, about 3,000 particles ml^{-1} with more than 4 $\log_{10}$ removal).

The membrane system coped without difficulty and without significant change in filtrate quality at all levels of

Table 3 | CMF pilot plant performance during high turbidity removal (average concentrations)

	14 April	
Parameter	**In**	**Out**
Turbidity (NTU)	1.5(85)*	0.05
Total algae cells (n ml^{-1})	1,645	0.46
Total coliform (UFC 100 ml^{-1})	35	0

*Peak value.

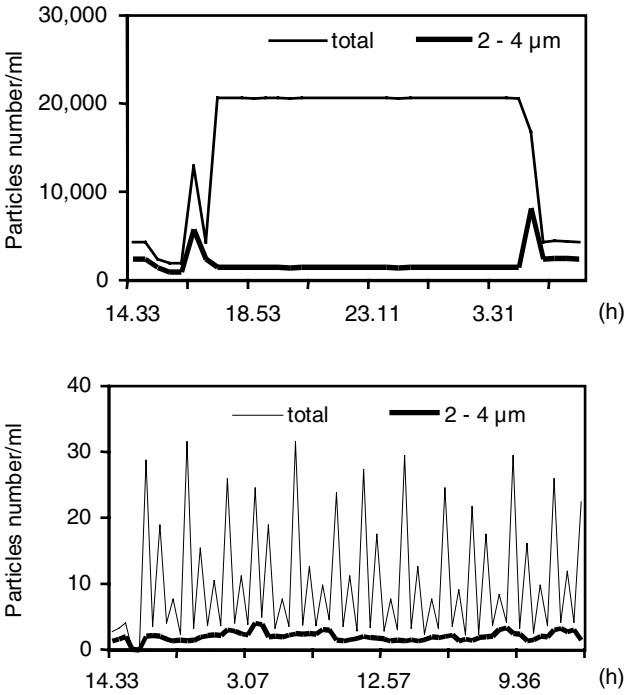

Figure 4 | (a) Particle concentration in raw water spiked with sludge. (b) Particle concentration in treated water.

artificially increased turbidity in the feed. This will give an indication of real performance, but the sludge introduced may have a different distribution of particles than in naturally occurring turbidity events. In fact, only in late summer does the run-off related to heavy rainfall elevate the water turbidity (up to 100 NTU) at the abstraction point.

Table 4 | CMF pilot plant performance during *E. coli* removal (4 May)

	E. coli (UFC 100 ml^{-1})	
Parameter	**In**	**Out**
Run time 10 min	1,800,000	0
Run 30 min	1,700,000	0
Run time 60 min	2,000,000	0
Turbidity (NTU)*	2.4	0.05
Suspended solids (mg l^{-1})*	16	Below d.l.

*Average concentrations.

'Brugneto' raw water spiked with *E. coli*

The objective of the trial was to test the CMF pilot plant efficiency in *E. coli* rejection, the most specific indicator of faecal contamination. A single trial was carried out because of the difficulties encountered in preparing the concentrate of *E. coli* suspension to feed the break tank. The required level in the inlet water should allow detection of an elevated $\log_{10}$ rejection.

The trial started after a backwashing and lasted 70 minutes. Table 4 summarises the performances. The *E. coli* challenge showed the membrane achieved a rejection of greater than 6 $\log_{10}$. As *E. coli* has a size of 0.5–1.5 μm, less efficiency might be expected. As we mentioned, cell aggregation in the suspension and in the feed water could explain these results. Particle counts in the range 2–4 μm of the treated water record levels higher than those obtained in previous experiments (see for example Figure 5a and b). This is due to the presence of the culture broth in the feed water.

'Brugneto' raw water spiked with micro-algae

The objective of the trial was to test the CMF pilot plant efficiency with a high concentration of cultivated micro-algae. A single test was carried out lasting for 90 minutes. This was a compromise between the duration of the test and the available amount of algae biomass cultivated

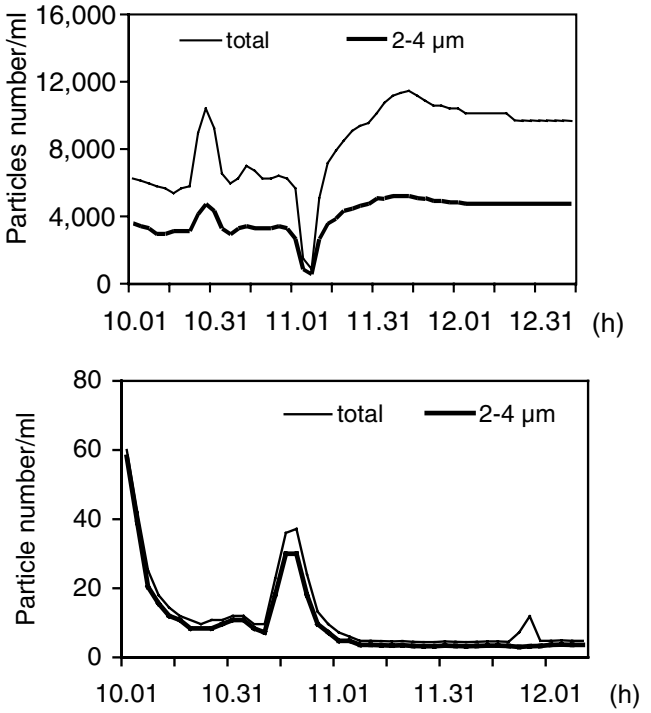

Figure 5 | (a) Particle concentration in raw water spiked with *E. coli*. (b) Particle concentration in treated water.

artificially. Table 5 summarises for each species of algae the performance of the system at different run times. In the table the approximated sizes (diameter and other parameters) are also reported. Only the *Chlorella* was present at a low level (less than 1 ml^{-1}) in the filtered water. A low number of algae cells was also found in other trials with natural dam water (see Tables 2 and 3). The 2–4 μm range particle count in the filtered water (see Figure 6a and b) was never less than 8 particles ml^{-1}. The reported sizes are typical for this kind of algae. However, attempts have not been made to investigate the actual size distribution of the cultivated algae.

'Brugneto' raw water spiked with excess aluminium salt

The objective of the trial was to simulate possible water pretreatment with an incorrect (large excess) aluminium dosage and at an inappropriate water pH, to test the fouling effect on the CMF pilot plant and efficiency in aluminium removal (see Table 6).

The high aluminium level did not cause any significant modification to the build-up of the TMP during the 15 hour dosing period, indicating that overdosing lasting for an unusual period would be unlikely to cause fouling in the membrane which is very difficult to remove. The measured residual aluminium (at 0.2–0.3 mg l^{-1}) is high, but after dosing a non-optimal 8.2 pH was reached and it was deliberately not modified. No attempts have been

Table 5 | CMF pilot plant performance during algae removal

		After 10 min		After 30 min		After 60 min		After 90 min	
Algae species (n ml^{-1})	**Approx. size (μ)**	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**
Cyclotella sp.	10–45	2,086	0	2,057	0	2,586	0	2,147	0
Ceratium sp.	100–300	6.12	0	4.16	0	4.72	0	3.44	0
Chlorella sp.	5–10	990	0.40	890	0.24	862	0.32	850	0.24
Scenedesmus sp.	3.5–20	1,838	0	1,730	0	1,841	0	1,830	0
Ankistrodesmus sp.	7–100	70	0	94	0	110	0	0	0
Closterium sp.	4–300	11.7	0	10.8	0	9.6	0	13.2	0

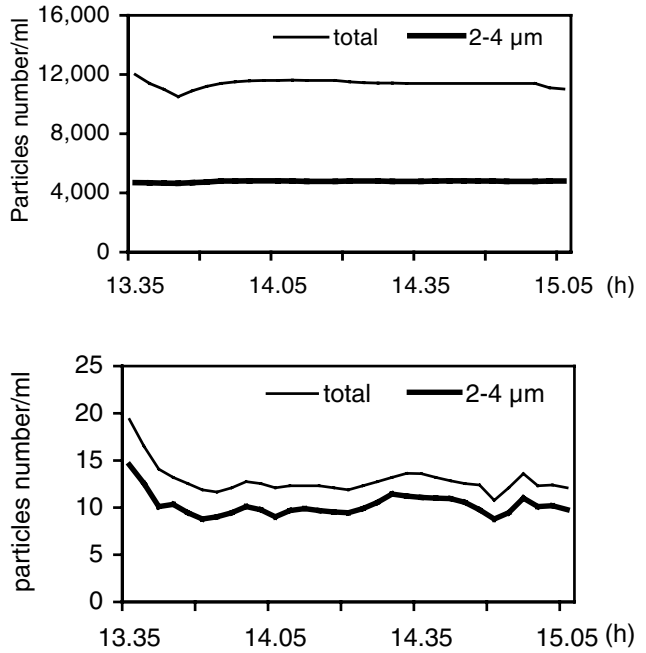

Figure 6 | (a) Particle concentration in raw water spiked with micro-algae. (b) Particle concentration in treated water.

made to speciate aluminium in the permeate. The particle counts (total and 2–4 μm range) did not show any significant variation from the expected levels (see Figure 7a and b).

'Brugneto' raw water spiked with inactivated Cryptosporidium oocysts

As protozoan water pollution is probably the most important problem in current water treatment practice, the objective was to test the removal capacity of CMF in two different trials in order to investigate any potential interference by other suspended particles (accumulated in the cake layer) with the removal efficiency of *Cryptosporidium*.

In the first trial the raw water was previously clarified with a multimedia filter to obtain feed water with a total particle count down to 100 ml^{-1}. In the second trial the raw 'Brugneto' water was used (total particle count approx. 10,000 ml^{-1}).

Table 6 | CMF pilot plant performances during the removal of aluminium (average concentrations)

	19 May	
Parameter	**In**	**Out**
Turbidity values (NTU)	1.5	0.05
Total algae cells (n ml^{-1})	358	0.13
Total coliforms (UFC 100 ml^{-1})	7	0
Total aluminium (mg l^{-1})	11.7	0.2

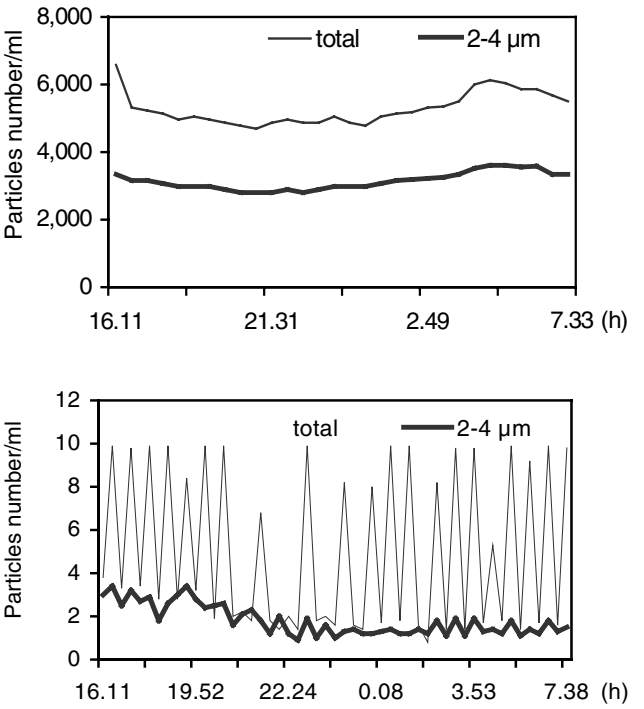

Figure 7 | (a) Particle concentration in raw water spiked with aluminium. (b) Particle concentration in treated water.

Both trials lasted for about an hour, at a reduced flow (1 m^3 h^{-1}), due to the available quantity of inactivated oocysts. Both of the tests were carried out at a TMP of 70 kPa (set point 130 kPa). The oocyst concentrations in samples taken after 0.5 h and near the end of the test were averaged. The performances in the test are summarised in Table 7.

Table 7 | CMF pilot plant performance in *Cryptosporidium* removal

Trial	Total particles count in feed water (n ml^{-1})	In after 0.5 h (oocysts l^{-1})	In after 1 h (oocysts l^{-1})	In average (oocysts l^{-1})	Out (oocysts l^{-1})	Log removal
1	100	8,850	18,250	13,550	0.12	5.05
2	10,000	22,950	35,250	29,100	0.075	5.58

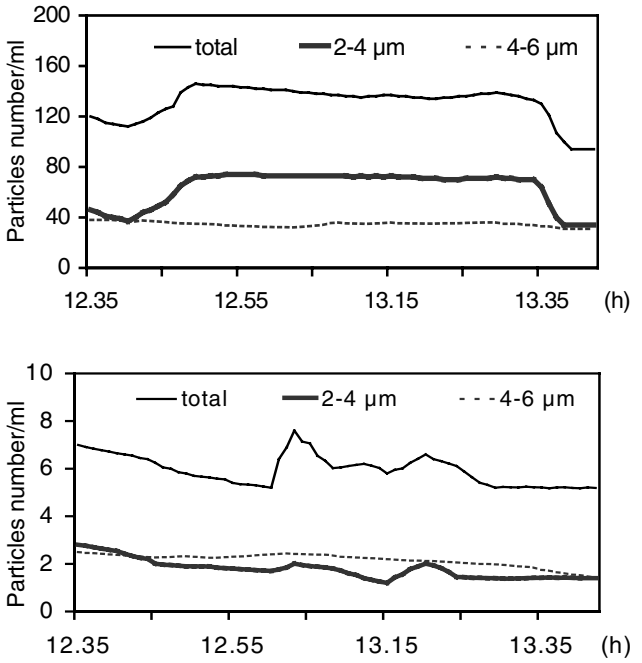

Figure 8 | (a) Particle concentration in raw water spiked with *Cryptosporidium* oocysts. (b) Particle concentration in treated water.

Cryptosporidium oocysts are spherical, about 3–7 μm in diameter, and should be removed by the membrane at the level to which it is integral. The results indicate that this level is greater than 5 $\log_{10}$.

No substantial differences in performances can be seen between the two trials. Particle counter records demonstrate that for the instruments used only the 2–4 μm range accounts for the oocysts' size in spiked water (see Figure 8a and b).

CONCLUSIONS

The 0.2 μm cut-off MF membrane used in this study was clearly fully able to reject protozoan oocysts at a level not easily attained using conventional treatment, as well as rejection of faecal indicator bacteria and micro-algae, naturally occurring or spiked. These performances are in agreement with the results of pilot plant experiences with 0.2 MF membrane treating reservoir lake waters (Panglish *et al*. 1998*a*; Kothari and Taylor 1998) regarding the spiked *E. coli* rejection, turbidity and particle count levels in the permeate. Panglish *et al*. (1998*a*) also found 6 log removal of 0.3 μm diameter *B. subtilis*. A pilot plant operating with 0.2 μm MF cross-flow membrane showed no Cryptosporidium oocysts after feeding with 10^6 100 l^{-1} with a removal higher than 6 $\log_{10}$ (Jacangelo *et al*. 1995). The particle counters, from two different manufacturers, gave entirely consistent performances and were able to indicate system rejection at 3.5–4 $\log_{10}$ depending on the feed level of contamination. They gave figures during the *Cryptosporidium* test that corresponded very closely to the calculated seeding level. This indicates that the 2–4 μm range is useful for monitoring plant performance for *Cryptosporidium* removal.

Any justification for the use of microporous membrane technology for potable water will depend not only on the theoretical characteristics of the membrane in rejecting particles above a certain size, but also in the robustness and operability of the overall process. The membrane plant was convincingly able to cope with high transient loads of solids of different nature and overdosing with coagulant at a reduced flow but consistent filtrate quality and then recover full performance on returning to the normal feed.

The control of the membrane integrity is critical when we need to assure efficacy in terms of microbial removal. The pressure decay test (PDT) was carried out weekly. During the entire period it was always 0.7 kPa min^{-1}, indicating a high level of integrity (5 $\log_{10}$ rejection).

Membrane integrity is not necessary reflected by a change of the filtrate quality. Only a very sensitive particle counter with a threshold of 0.5 μm could be an integrity monitor. However, according to Panglish *et al*. (1998*b*), the maximum membrane area which can be checked by only one particle counter in case of dead-end microfiltration (out-in operation) is 18 m^2 and for a feed particle concentration higher than 200,000 ml^{-1}, whereas it is 22 m^2 for a feed particle concentration higher than 7,000 ml^{-1} (in-out operation; Xflow). The PDT seems to be an acceptable solution as regards costs, operation and accepted risks.

LIST OF ABBREVIATIONS

AMGA	Azienda Mediterranea Gas e Acqua
CIP	chemical cleaning in place
MF	microfiltration
PDT	pressure decay test
PLC	programmable logic control
TMP	trans membrane pressure

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