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Ultrafiltration, a cost-effective solution for treating surface water to potable standard

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Abstract

Ultrafiltration is increasingly popular in many types of water and effluent treatment, and has been developed substantially since the turn of the century, especially for waters that are difficult to treat – e.g. surface-, waste- and sea-waters, among others. This paper is a case of study of the San Juan Reservoir Water Treatment Plant in Chongon, Ecuador, which uses ultrafiltration for water treatment. The treatment process is described with special focus on the use of ultrafiltration as a cost-effective surface water treatment. San Juan Reservoir suffers from high bacterial loads, turbidity levels and color, and the seasonal presence of algae (cyanobacteria). The advantages of ultrafiltration over conventional treatment are highlighted, as well as the technology's potential for micro-plastics removal. Micro-plastics are an emerging pollutant that has recently gained importance in drinking water treatment.

Key words: algal removal, microplastics, potable water, surface water, ultrafiltration, water treatment

INTRODUCTION

The complexity of some water resources and the increasingly strict regulation of water quality mean that new water treatment technologies need to be considered. This is the case for the San Juan reservoir, in which, due to its characteristics, implementing new technologies to achieve compliance with regulatory requirements has offered a cost-effective solution.

Before installation of its water treatment plant, the water supply to Posorja, Ecuador, and surrounding areas was provided by a drinking water company in Playas district. The main problems with it related to the rationed and interrupted service. Treatment of water from San Juan Reservoir (Chongon) to potable standards was presented as a solution, to provide a continuous supply to Posorja, El Morro, Puerto el Morro, Data de Posorja, San Miguel and San Juan. The main problems in treating water from this source to potable standards are:

- Turbidity;
- Bacterial load; and
- Color.

  In general, color in water may be due to the presence of metal ions, natural organic matter (NOM) such as humus and peat, plankton, and/or industrial effluent.

  The presence of organic compounds in water is important in affecting its quality. In addition to giving color, NOM is considered a precursor of undesirable derivatives during disinfection, such as trihalomethanes (THMs).

  The main source of organic matter in the water is the decomposition of vegetable matter (grasses, leaves, trees, etc), giving rise to humic compounds. These are high molecular weight compounds and are common in surface waters.

- (Argaman *et al.* 1984; Odegaard & Thorse 1989).
  In Chongon, the color of the water is attributed mainly to NOM and the treatment is focused on their removal.
- Precursors of THMs (humic and fulvic acids):
  The NOM compounds affect water quality by forming derivative products that are harmful to health.
- Algae and cyanobacteria:
  The presence of algal biomass increases chemical consumption and causes operating problems in conventional treatment systems – for example, algae tend to float, shortening filter cycles, etc. (Di Bernardo 2010)
  Cyanobacteria cause health problems mainly due to their generation of various substances (Dickens & Graham 1995):

o Compounds causing taste and odor problems, such as geosmin and methyl-isoborneol.
o Toxins that may affect the liver (hepatotoxins) or nervous system (neurotoxins).

In this type of surface water, conventional water treatment processes (chlorine sterilization + PAC flocculation + sedimentation + sand filtration) leave significant treated water quality problems. One of the most problematic issues is associated with the origin of 'color' in NOM, as a potential precursor of both THMs and halo-acids, which are also carcinogenic, when exposed to the action of oxidizing compounds. In addition, sterilization with oxidizing agents breaks the bacterial membranes of algae and cyanobacteria, with probable increases in taste and odor issues. These, in turn, lead to the use of more oxidant, increasing the THM yield (Pérez Gattorna 1995).

In the scenario outlined, the best solution for drinking water treatment is ultrafiltration (UF), the main treatment stage at the San Juan plant. The plant has a net production capacity of 200 L/s with the possibility of expansion later to 600 L/s – it is designed on the multi-functional unit concept.

SOLUTION IMPLEMENTED FOR SAN JUAN (CHONGON) RESERVOIR

The UF treatment scheme proposed includes a sequence of process stages.

Raw water feed

The influent raw water enters an agitated tank where coagulant and powdered activated carbon (PAC) are added. The tank enables suitable contact time for both the coagulant and PAC, and also equalizes the flow to be treated. It was designed to provide good mixing and contact time for the PAC and coagulant, while avoiding interference between them (Snoeyink & Jenkins 1996).

PAC dosing

Dosage occurs in the first section of the influent tank to assist color removal during treatment. On-line algal monitoring helps optimize coagulant/PAC dosage to remove toxins when cyanobacterial blooms occur. This also allows the optimization of ozone dosing for final sterilization.

Coagulation

- Coagulation is thought to improve organic matter removal during the UF stage and is done with an aluminum salt.

Due to the size of the UF membrane pores, the coagulant dose can be reduced, and the flocculation stage eliminated, as large flocs are not needed. This is an advantage over conventional designs.

Filtration with automatic disk filters (130-micron)

The disk filters protect the UF equipment and are designed to minimize plant downtime. The objective is to prevent the entry of particles that could damage and/or clog the UF's hollow fibers.

Direct filtration by UF

UF is a separation process based on size exclusion (screening) using polymeric porous membranes. It achieves separation in the range 0.01 to 0.1 μm (10 to 100 nm), allowing the removal of suspended solids, colloids, viruses, bacteria, endotoxins and other pathogens, and high molecular weight species. It is widely used as pre-treatment for reverse osmosis (RO), since it guarantees a low SDI (Silt Density Index) (an advantage over conventional treatment processes).

General description of UF

UF, typically with 0.01 to 0.1 μm (i.e. 10 to 100 nm) pore size, is capable of retaining not only particles and bacteria, but viruses and proteins to a large extent as well. In water treatment, a combination of coagulation and UF is used, when both particle retention and organic removal are required.

UF capillary membranes can be operated 'inside-out' or 'outside in'. Inside-out means that the feed stream, containing the species to be retained, is pumped through the inside of the capillary and the filtrate leaves the capillary from the outside. Outside-in means that the feed stream is pumped from the capillary's outside to its inside with the species to be removed retained on the outside (American Water Works Association 1998).

Membrane operation

Membrane systems can be operated in different ways. The solutes retained by the membrane build up an increasingly thick layer of foulant (cake), which generates a resistance to flow through the membrane. Because of this, the trans-membrane pressure must be increased to keep production capacity constant. There are two principal operating modes – cross-flow and dead-end.

Cross-flow configuration

To avoid/limit cake build-up on the membranes, early forms of membrane filtration incorporated a cross-flow mode. In this, a relatively large flow is pumped across the membrane surface, creating turbulence. A limited amount of fluid permeates the membrane as product – Figure 1.

The cross-flow system illustrated incorporates two pumps, one to feed the system and the other to generate the cross-flow at the membrane surface. The latter's velocity is typically 1 to 5 m/s and requires a relatively large pump with matching power consumption.

The feed suspension is initially concentrated in the cross-flow loop and, because of the constant bleed of permeate, equilibrium is reached after some time.

The same applies to the contaminant layer that builds up on the membrane surface, so that the contaminants that accumulate on the membrane reach equilibrium with those removed from the surface by the cross-flow turbulence.

In cross-flow operation, not all of the feed suspension becomes product as a portion leaves the system through the bleed discharge as concentrate. Recovery, for such a system, is defined as the portion of feed that is treated – for example, if 10% of the feed leaves the plant as concentrate, recovery is 90% (and the cross-flow loop or bleed concentration is 10 times that of the feed).

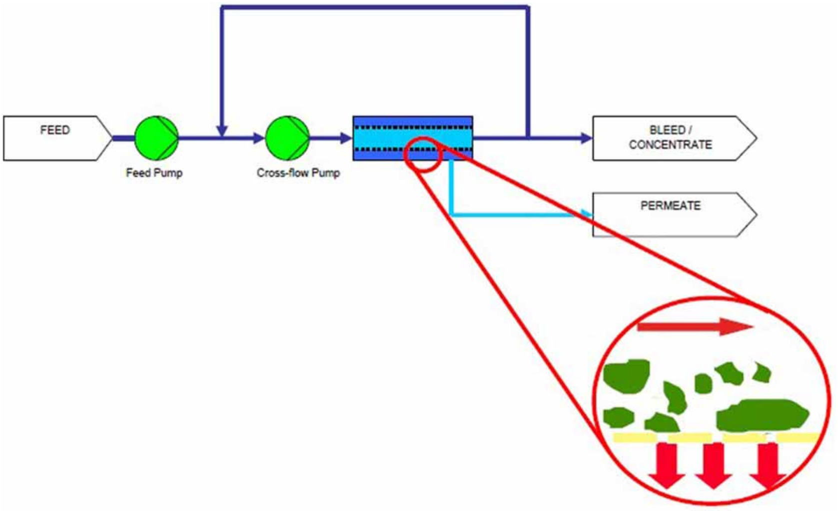

Figure 1 | Cross-flow UF system.

Cross-flow systems are usually robust and reliable, because the process is continuous, and most can run for long periods before being cleaned. They have some drawbacks, however:

- relatively high-power consumption, up to several kWh/m^3 of product;
- the shear forces to which the feed fluid is exposed may damage it, if the UF system is not designed correctly for the service required; and,
- a large footprint for the pump and large diameter piping, in some cases.

Dead-end configuration

Dead-end systems were developed for applications with relatively low proportions of retainable contaminants to try to avoid cross-flow's drawbacks. In dead-end systems there is no circulation, all fluid entering the system passes through the membrane, the contaminants being retained on the membrane surface – Figure 2.

The contaminants retained form a cake layer on the membrane surface. As that grows, the resistance to flow through it increases and the trans-membrane pressure must be increased to maintain constant yield.

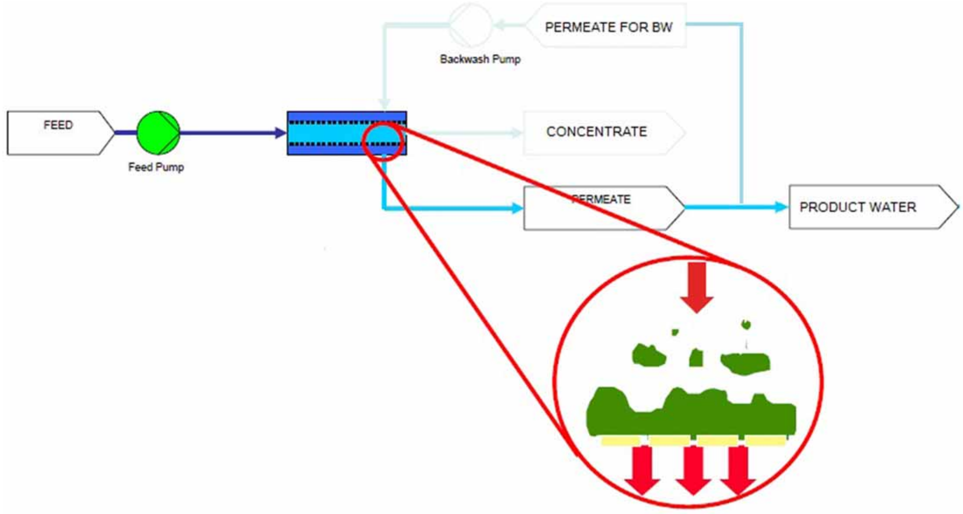

Figure 2 | Dead-end UF system in filtration mode.

Unlike cross-flow operation, contaminants remain on the membrane surface during filtration and must be removed regularly by backwashing – Figure 3.

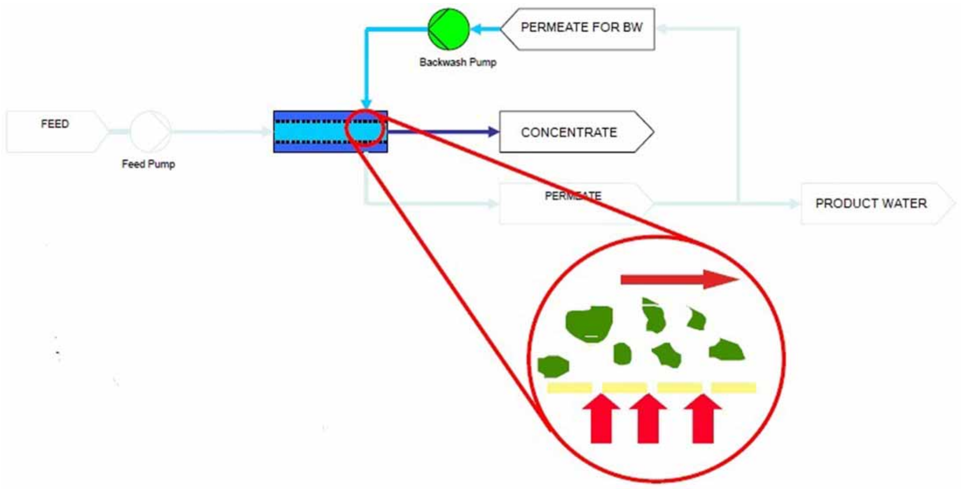

Figure 3 | Dead-end UF system during backwash.

The need for backwashing makes this form of the process discontinuous; that is, filtration must stop periodically for backwashing. During backwash, a portion of the permeate product is pumped back through the membrane. This lifts the cake layer and removes it, rendering the membrane surface clean.

The main advantages of a dead-end system include:

- relatively low power consumption, typically about 0.02 to 0.05 kWh/m^3, broadly the same as required for pressure filtration.
- small footprint and compact design.

Chemical cleaning

Chemically enhanced backwash (CEB)

CEB is used to enhance the removal of material accumulated in the membranes during filtration. During CEB, chemicals (e.g. chlorine, acids or bases) are added to the backwash stream to increase the effectiveness of cleaning. The chemical(s) used depend(s) on the foulant, which might require a combination or, perhaps, seasonal changes. CEB frequency depends on feed water quality.

CEB is performed using UF permeate and typically programmed to occur automatically at preset time intervals, although it can be field adjusted on the basis of site-specific operating experience. Alternatively, it can be initiated on the basis of a TMP (trans-membrane pressure) set point.

CEB follows the same process set as a normal backwash sequence but with an additional soak-step after introduction of the chemicals to allow them time to react with contaminants attached to the membrane surface or that have penetrated the fiber wall. When operations are restarted after CEB, the initial permeate produced might need to be sent to waste to remove residual chemicals.

Cleaning in place (CIP)

Membrane surface fouling results in gradual performance decline of UF systems in terms of increased operating trans-membrane pressure, reduced sustainable filtrate flow or flux, and/or increased chemical and power consumption.

UF system performance should, therefore, be monitored regularly and frequently. If cleaning is delayed too long, fouling may become irreversible, and potentially result in physical damage to the UF module or other equipment.

The type/types of foulants on the UF membrane surface need to be understood prior to CIP, so that the most effective cleaning solution and sequence can be used. This can be done in different ways:

- Analyzing feed water quality.
- Reviewing the results of previous CIPs.
- Removing and inspecting the UF module's feed end for indications of contaminants.
- Inspecting the waste discharge for indications of contaminants, either visually or by laboratory analysis.
- Analyzing spent SDI filter paper after grab sample SDI-5 tests of the UF feed.
- Destructive autopsy to identify the foulant, if methods above fail.

(X-Flow B.V. Know-How Centre 2006)

UF at Chongon

The Chongon plant operates in dead-end mode, using membrane modules with 0.03 μm pores and inside-out filtration (see Figure 4).

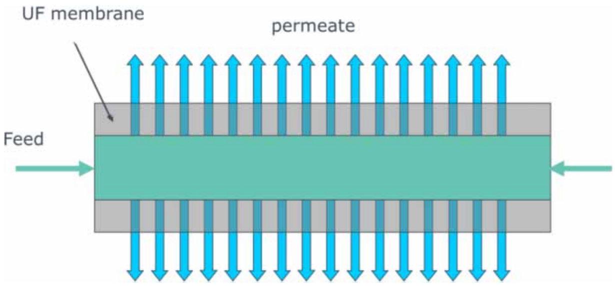

Figure 4 | Inside-out filtration, as at Chongon.

Removal by UF is effective for many species including:

Organic matter: organic molecules vary in size, from less than 1 nm for simple compounds – for example, chloroform – to 1 μm for complex humic polymers. Particle size is effectively increased in the pre-UF coagulation stage, enabling their removal. (Odegaard & Thorse 1989; Montgomery 1985)

Algae: Algae are a diverse group of phytoplankton. Sizes vary by species but range from 0.5 to 500 μm. UF membranes can remove them effectively.

Cyanobacteria: cyanobacteria include a very large and heterogeneous group of phototrophs with diverse morphologies. Sizes range from 0.1 to 0.7 μm, typical bacterial sizes, and up to 60 μm for oscillatory species. Like algae, they are removed effectively by UF.

Comparative data from an algae removal study are shown in Table 1. The effectiveness of UF removal is very clear. UF also simplifies the process scheme compared with other treatment systems, which, to achieve similar removals, require a greater number of unit operations.

At San Juan Reservoir, pre-oxidation with chlorine is not an option as it causes lysis of cyanobacteria cells and releases toxins. Also, due to the presence of NOM, it could generate THMs. Using UF as the main removal treatment for these species, however, efficiencies exceeding Log 6 can be achieved, without pre-oxidation, and hence avoiding its pitfalls. Table 1 also shows that UF enables reductions in unitary operations compared to other processes, while achieving better algal removal.

Disinfection with ozone

Ozone is one of the commonest sterilizers in modern surface water treatment plants. It is widely known for its ability to oxidize compounds producing color, taste and odor. In San Juan Reservoir

Table 1 | Efficiency of different algal removal processes – adapted from Mouchet & Bonnéyle (1998)

Process	% Removal	Log removal
Screening	40–70	0.2–0.5
Screening + direct filtration	90–98	1–1.7
Clarification + filtration:		
Without pre-oxidation	95–99	1.2–1.3
With pre-chlorination	99–99.9	2–3
With pre-oxidation with ozone	97–99.8	1.5–2.7
DAF + filtration:		
Without pre-oxidation	96–99	1.4–2
With pre-oxidation	99–99.9	2–3
Clarification or DAF+ filtration + ozone+ GAC	99.9–99.99	3–4
UF or microfiltration (MF)	>99.9999	>6

there are high concentrations of natural, organic coloring substances that are also THM precursors. Ozone sterilization is used as the final process stage, taking into account that a large proportion of the NOM is removed in the UF stage. As a result, algal toxins, color, smell and taste are eliminated with low doses of ozone at reduced contact times, because the number of competitive reactions that could be generated in the presence of NOM is reduced.

Final disinfection

The last stage of the process is disinfection with chlorine, using sodium hypochlorite (generated *in situ*). This ensures a residual concentration of free chlorine in the treated water, allowing bacteriological control of the treated water throughout the distribution network. An electrolytic system produces high purity hypochlorite suitable for drinking water and has the benefit of a compact design.

Effluent recovery from UF backwashes

Backwash water (BW) recovery and sludge treatment are carried out in a conventional, compact plant. The BW is treated in a clarifier whose effluent is recirculated to the main feed tank. The thickened sludge is dewatered in a centrifuge, increasing total recovery and improving water resource use efficiency.

CEB and CIP effluent treatment

CEB and CIP effluents are treated in another compact plant independent of the BW recovery plant. The two are neutralized and chemically conditioned, and the neutralized effluent filtered and treated with activated carbon to remove chlorine, if any residual is detected. The final neutralized and conditioned effluent is suitable for discharge to sewer.

OUTCOMES

Sampling results from different process stages at San Juan are shown in Table 2, and SDI samples taken from different process stages are shown in Figure 5. They relate to the parameters of concern. The other inorganic parameters in the raw water are all below the maxima acceptable under Ecuadorian Standard for drinking water NTE 1108, version 5 (INEN 2014), and are not presented.

Table 2 | Analytical results from the San Juan plant

Parameter	Raw water[a]	UF-treated water[b]	Plant final water[c]	Regulation INEN N°1 1108, 2014
Turbidity (NTU)	6–8	0.1	0.1	<5
Temperature (°C)	24	24	24	–
pH	7.8	7.7	7.9	–
Conductivity (uS/cm)	249	249	268	–
Apparent color (Pt-Co)	78	25	0	<15
TOC (mg-C/L)	19.4	16	12.8	–
Iron (mg/L)	0.06	0.02	0.02	–
Manganese (mg/L)	0.1–0.3	0.05	0.05	0.4
Ammoniacal nitrogen (mg-N/L)	0.3	0.23	0.08	–
Alkalinity (as mg-$CaCO_3$/L)	91	87	88	–
SDI	Not measurable	1–2	1–2	–

[a] Sample from reception tank.
[b] Sample from UF water tank/filtered water collector.
[c] Sample from treated water tank, after chlorination.

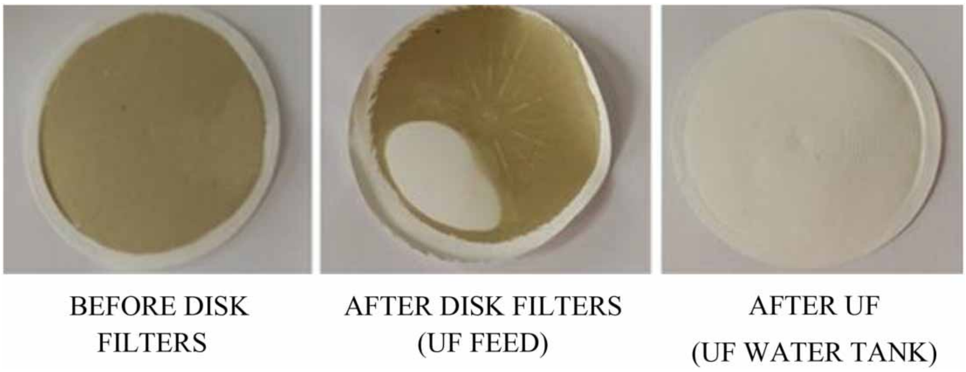

Figure 5 | SDI samples from different treatment stages.

PROCESS SCHEMATIC

See Figures 6 and 7.

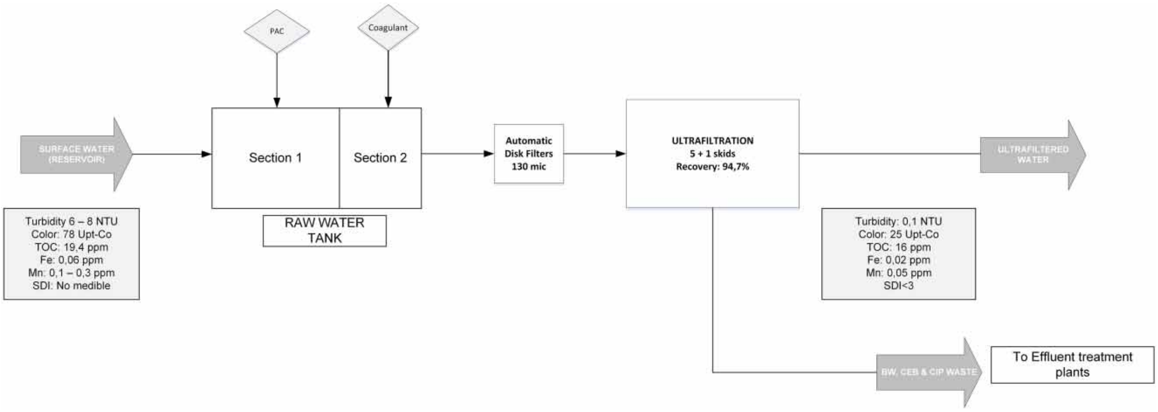

Figure 6 | Process schematic.

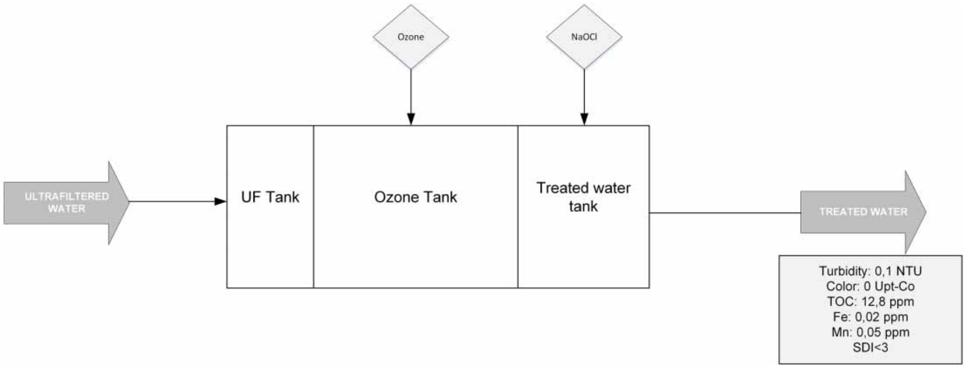

Figure 7 | Process schematic (continued).

MICROPLASTIC REMOVAL BY UF

Although microplastics (MPs) are not a problem in San Juan Reservoir, they do merit mention in relation to removal by UF. They are an emerging pollutant and have garnered much attention recently, especially because of their eco-toxicological effects in marine environments and on health.

Plastics are organic polymers and are used worldwide. Their residuals are easily transported long distances by hydrodynamic processes and ocean currents. Mechanical action, biodegradation, and photo-oxidative degradation over time generate tiny plastic particles gradually, those below 5 mm diameter are known as MPs.

It has been demonstrated that MPs are stable in water, potentially for thousands of years, because of their chemical stability (Cózar *et al.* 2014). It has also been reported that they can induce serious environmental and health problems, including:

- Acting as excellent carriers of organic chemicals, owing to their large specific surface and strong hydrophobicity (Hoffman & Turner 2015);
- Adsorbing heavy metals, including Zn, Cu, Pb, Ag, as well as some nano-scale like TiO_2 (Ashton *et al.* 2010; Fries *et al.* 2013);
- Being mistaken for food by marine organisms because of their tiny particle size, leading to mechanical damage to the organism. They can also change the gene expression of fish after being adsorbed and threaten human health through the food chain (Thompson 2006; Rochman *et al.* 2014; Anderson *et al.* 2016).

UF for MP removal

As the density of MPs (0.92 to 0.97 g/cm^3) is close to that of water, they are easily suspended or float, increasing the potential risk of their not being removed by conventional treatment. UF, however, is effective for their removal.

UF is widely used for water and wastewater treatment and yields high-quality effluents. The removal of MPs using coagulation and UF has been investigated. One study produced these fairly typical conclusions (Baiwen *et al.* 2019):

- Al-based are better than Fe-based coagulants at removing MPs.
- UF removes MP particles completely because of the small membrane pore diameter.
- Membrane fouling was aggravated with increasing coagulant dosage owing to the thick cake layer formed.
- The larger the MP particles, the more heterogeneous the cake layer preformed with coagulant, leading to less UF membrane fouling.

Beyond these types of conclusions, the studies indicate that UF is a potential technology for MP removal.

CONCLUSIONS

UF is well-known for its multiple advantages – for example, as a pre-treatment in RO systems – and has been demonstrated to be an effective and cost-effective solution in this study. Due to this, UF is now the main process stage in the San Juan Treatment Plant and solves the problems of supplying drinking water to the communities involved. It offers a number of advantages:

- Process simplification and reduced installation footprint.
- Enabling process automation and control, as well as chemical consumption optimization, including reduced ozone use (as an oxidizing agent for odor, taste and color elimination). As a result, operating costs are reduced.
- Versatility, because it can be adapted to changes in water characterization. In San Juan, unacceptably high manganese concentrations are detected occasionally but can be reduced easily in the treated water by modifying the coagulant dose.
- Enabling the removal of algae and cyanobacteria (by six orders of magnitude), as well as suspended solids, bacteria and viruses, etc.
- Reducing odor generation.
- Reducing the risks of THM generation.
- Reducing sludge generation, while total water recovery is increased by effluent recirculation to the treatment plant.
- Minimizing the risk of plant downtime and making planning future extensions simple because of modularization.
- Ensuring consistent treated water quality regardless of changes in the feed.
- Offering the potential for efficient MP removal.

The potential benefits of UF are summarized quantitatively compared to conventional water treatment processes in Table 3:

Table 3 | Treatment comparison

	Ultrafiltration	**Conventional processes**
Treated water quality	• Consistent • SDI always <3, usually <1.5 • Turbidity <0.1 NTU • Disinfection: 6 log bacteria and 4 log viruses	• Quality depends on influent quality • SDI <4 approx. 90% of time • Turbidity <1.0 NTU
Plant footprint	30 to 60% of conventional plant	100%
Operation	Fully automatic	• Not fully automated
Operating costs	5 to 10% lower than conventional treatment, partly due to lower chemical consumption	100%
Modularity	Expansion possible by mounting new skids in parallel by sharing chemical cleaning systems.	True modularization not practical. Increasing production capacity requires new plant.
Sludge production	Reduced sludge generation.	100%.

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