WATER TREATMENT PLANTS: TECHNOLOGY AND APPROACHES

CHAPTER 6: MICROFILTRATION AND NANOFILTRATION

6.1. Introduction

There are three main substances in the drinking water sources can be presented as colloidal, suspended and dissolved. The suspended substance which is usually characterized by turbidity can be removed by most common treatment methods (Jacangelo et al., 1995; 1997; Mourato, 1998), the most known of which are chemically aided coagulation after that filtration or filtration and clarification. The coagulant amount, in this case, is usually similar to the turbidity level in the source. The existence of *Giardia* cysts and *Cryptosporidium* and oocysts and further parasites in drinking water sources has revealed a fresh field of application for the membranes in the drinking water sector. The incompetence of common filtration plants to purify and filter these pathogens from the drinking water has forced engineers to look into new techniques. Membranes are the natural reply to resolve their problem because these are complete barriers to parasites which size increased the membrane's pore size (Tan & Sudak, 1992; Taylor et al., 1992).

Common treatment methods are also usually not active when Total Organic Carbon (TOC) and color are present in advanced levels in the feed water. As the suspended and colloidal portions of these constituents are comparatively high, they are not readily removed by gravity and settling filtration. Lastly, great levels of manganese and iron in well waters have been tough to treat with the common green sand method and again, these have underway to be decent candidate plants for membrane technologies (Cooper, 1993; Wiesner et al., 1994;l; Cath et al., 2013). Nanofiltration and microfiltration membranes are becoming progressively more used in the drinking water field. For some uses, MF membranes are currently seen as a recognized technology. This comprises *Giardia* cysts and *Cryptosporidium* and oocysts parasites removal and turbidity elimination with color and microfiltration and salty water treatment with nanofiltration. Benefits associated to the use of membranes in potable water treatment are complete barrier effect to microorganisms, low energy requirements, lesser chlorine requirement for disinfection, low chemical (if any) usage, and smaller footprint. The kind of membrane used also impacts some particular advantages (Lee et al., 1999; Ince et al., 2010; Madaeni et al., 2013).

This chapter will present the usual applications of both kinds of membranes in the drinking water field. Subjects discussed here are:

i. Removal of iron and Mn by combining oxidation with microfiltration
ii. Removal of color and TOC by nanofiltration
iii. Removal of parasites and turbidity by direct microfiltration - disinfection MF
iv. Removal of TOC and color by combining superior coagulation with microfiltration

Membrane filtration works on the principle of specific separation based on a pore size distribution and pore size. Microfiltration membranes have pore sizes that differ from 0.075 microns to 3 microns. Depending on the membrane selected, it will permit to detach suspended solids above 0.45 microns, cysts, bacteria and many other parasites which diameter are larger than the greater pore size of the membrane (Carroll et al., 2002; Tahri et al., 2012). Nanofiltration membranes have pore sizes range from 0.005 microns to 0.001 microns and with such an insignificant pore size are capable to remove large molecular weight molecules, for instance, certain humic acids and salts. This allows for the production of a parasite and solids-free water without the need for chemicals (Saboyainsta & Maubois, 2000; Wu et al., 2016).

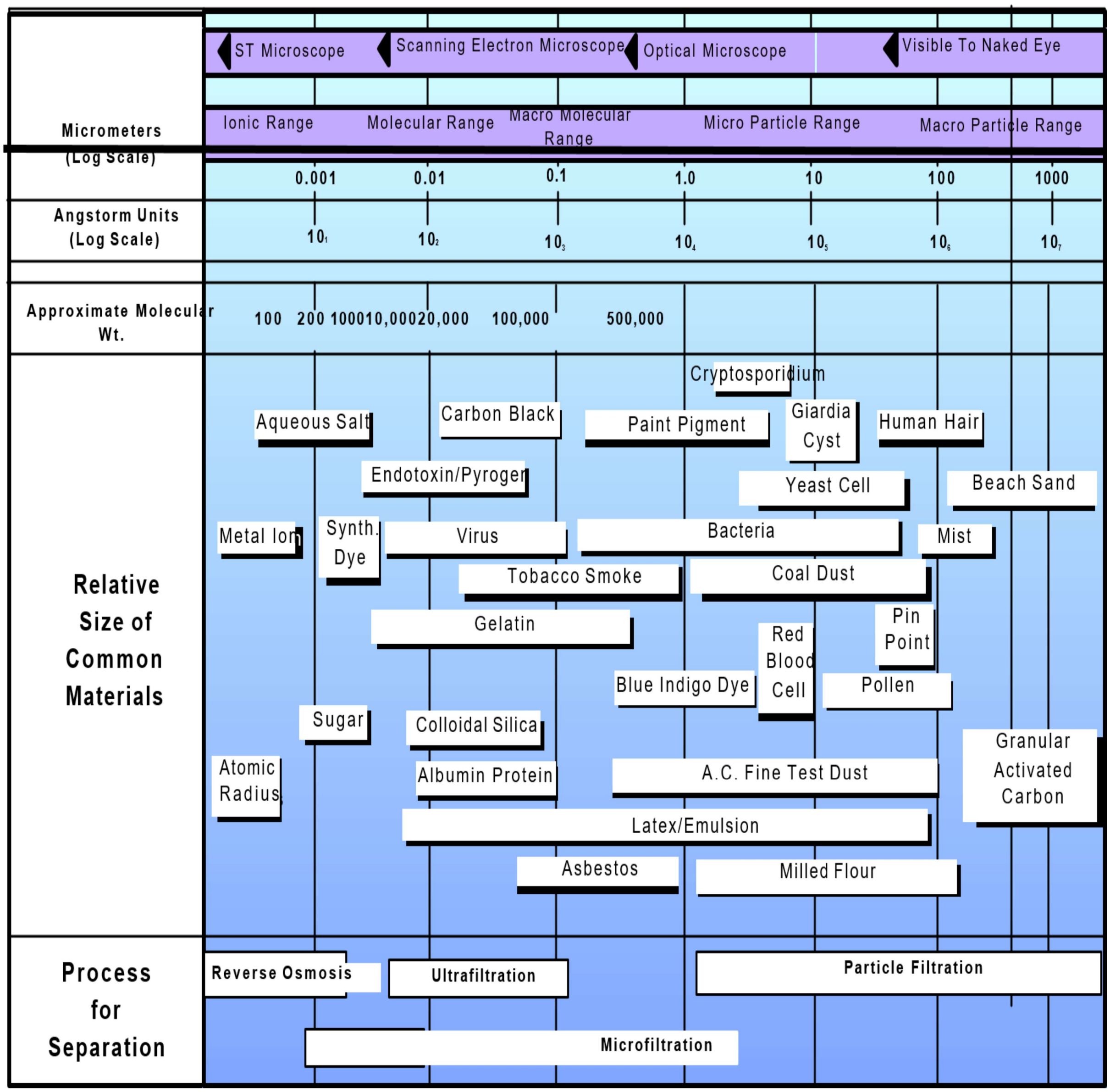

Figure 6.1. The Filtration Spectrum

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Membranes are composed of several materials, with ceramic, polymers and sintered metals being the most common types of membranes. However ceramic and sintered metals are generally have industrial applications, polymeric membranes are becoming a common tool for municipal uses and drinking water treatment. Membranes need transmembrane pressure to force the clean water over the membrane, leaving the concentrate comprising the solids and separated particles. The transmembrane pressure compulsory to drive membrane plants can be induced by vacuum or by pressure (Shirazi et al., 2010; Masmoudi et al., 2014).

Likewise, there are a large number of filtration paths which are generally found in membranes: Dead-end filtration, where the filtrate practices a cake as the sieve becomes plugged, cross-flow filtration in which the filtrate is moved away from the membrane, this evading fast filter plugging and osmosis where the water is clean over a semi-permeable membrane. This paper will emphasis on Cross-flow filtration membranes (Winzeler & Belfort, 1993; Van der Bruggen et al., 2003a; 2003b).

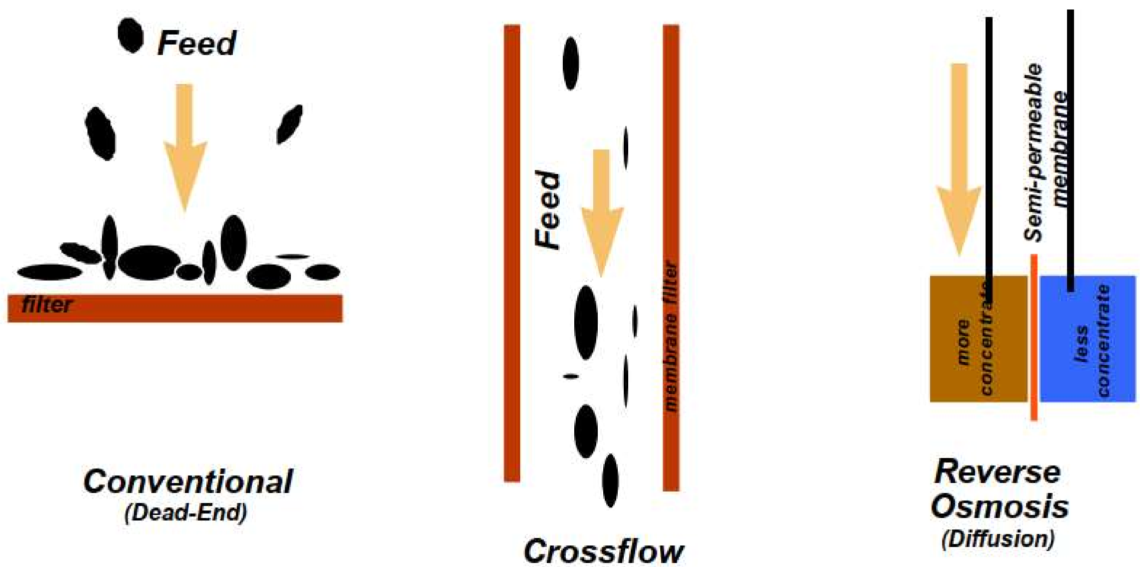

Figure 6.2. Modes of Filtration

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Different types of membranes are discussed below in this chapter.

6.2. Pressure Driven Membranes

The primarily commercially accessible membranes were formed using flat sheets rolled to make spiral wound membranes. These membranes may perhaps not tolerate solids and necessary great pressures to function. The great working cost of these membranes caused in occasional use and slight municipal uses in the microfiltration mode (Chen et al., 2013; Pearce, 2007). Spiral wound membranes are usually met in reverse osmosis and nanofiltration applications and are normally used for seawater and desalting brackish water for the production of clean water (Gupta et al., 2012; Jhaveri & Murthy, 2016).

Hollow fiber membranes were advanced in the last ten years as a means to approach microfiltration requirements while by fewer energy costs to work. These membranes shortly became an industry customary and a large number of companies started producing these high surface area membranes and applying them to the potable water field (Jain & Pradeep, 2005; Macedoni & Drioli, 2008).

Two kinds of pressure-driven hollow fiber membranes are found:

i. Inside-out membranes, in which the influent is forced inside the membrane's lumen (inside) and the clean water moves from the interior of the membrane to the outside.
ii. Outside-in membranes in which the influent is forced from the outside of the membrane and the clean water moves from the outside to the interior (lumen) of the membrane.

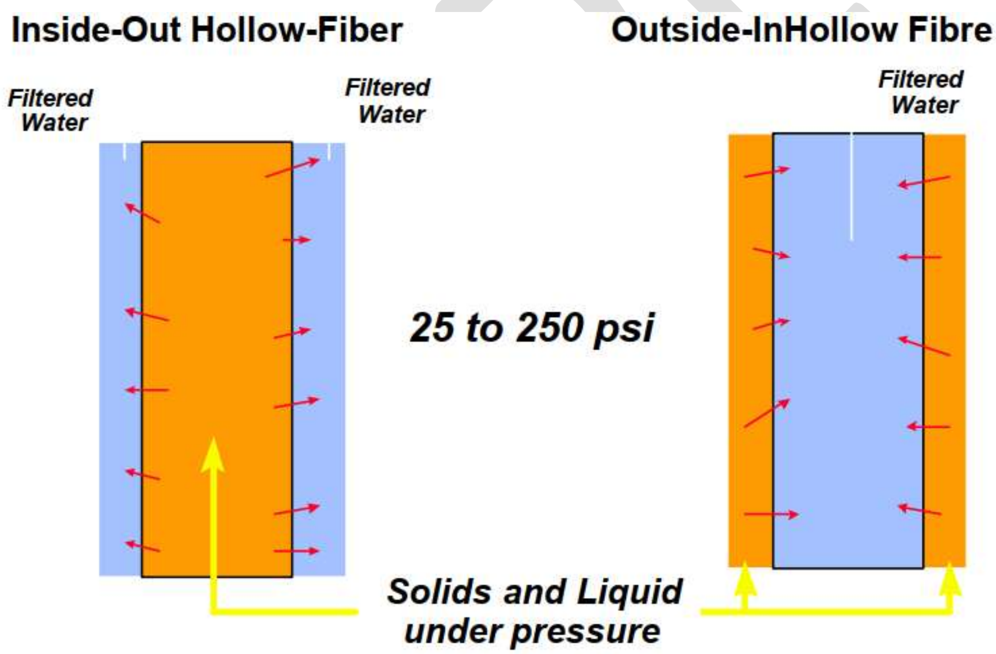

Figure 6.3. Filtration Modes - Hollow-Fiber Membranes

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Entire pressure-driven, hollow-fiber membranes are fixed inside pressure vessels, essential to apply the pressure for appropriate fluid transfer (Wiesne & Chellam, 1992; Drioli et al., 2006). Usual functioning pressure for these membranes is 15 to 30 psi.

6.3. Vacuum Driven Hollow Fiber Membrane - The Zee Weed Membrane

The Zee Weed™ centered potable water practice is a revolutionary less energy membrane method that contains outside-in hollow-fiber microfiltration components absorbed in raw feed-water. This micro-filter has a 0.085 micron minimal and a 0.2-micron entire pore size, confirming that no particulate matter above 0.2 microns will seepage to the treated water stream (Wang et al., 2009; Abu-Zeid et al., 2015).

The membranes work under a small suction created inside the hollow fibers by an infiltrate pump. The preserved water passes over the membrane, enters the hollow fibers and is pumped out to circulation by the invade pumps (Bhaumik et al., 2004; Lee & Kim, 2014). Airflow is presented at the bottom of the membrane component to form a disorder which scrubs and wipes the outside of the membrane fibers letting them operate at a great flux rate. This air will also oxidize Fe (iron) and further organic compounds, producing improved quality water than provided by microfiltration only (Mavrov et al., 2003; Sun & Chung, 2013; Wang & Chung, 2013).

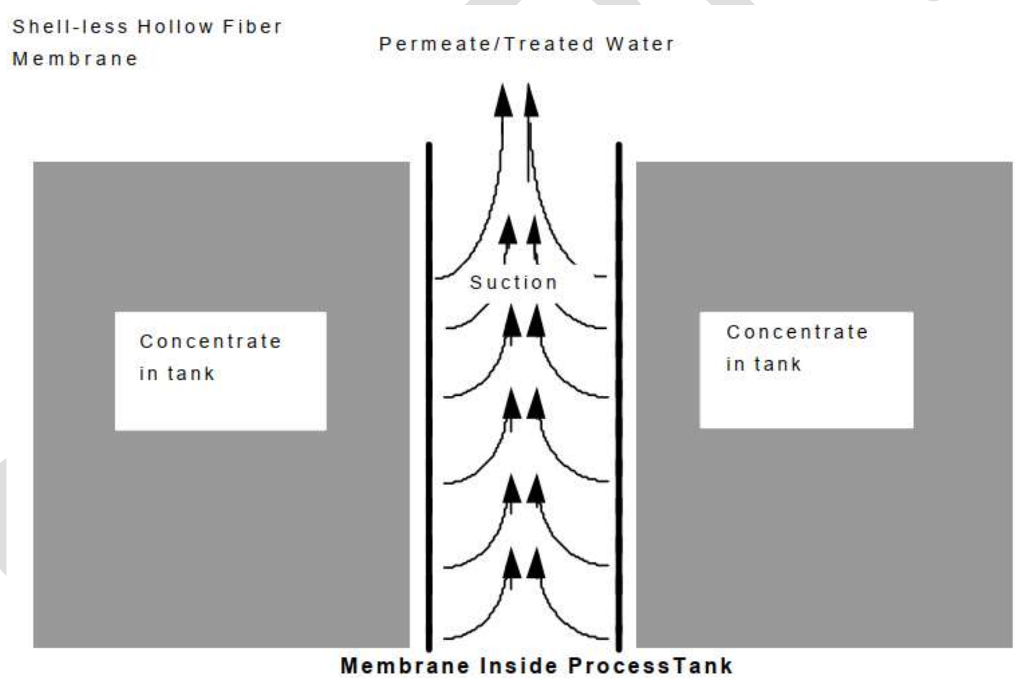

Figure 6.4. Operational Concept of an Outside-in, Immersed, Shell-less membrane

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Being an outside-in hollow fiber membrane, the plant does not require pretreatment, though the feed water has fine particles and clays. So, in a particular step, it swaps the flocculation, coagulation, clarification and sand purification steps of common plants, but also removes the pretreatment essential by inside-out membranes and spiral (Abdallah et al., 2013).

A plant of this kind works with a process tank containing a set of immersed membranes. The water moves over the membranes and the permeate is driven out. The air necessary to retain the membrane clean is produced by an air blower. The plant is easy to function but also easy to gather into slight containerized plants which can be fixed in small to large groups. The plant's process flow diagram is given below.

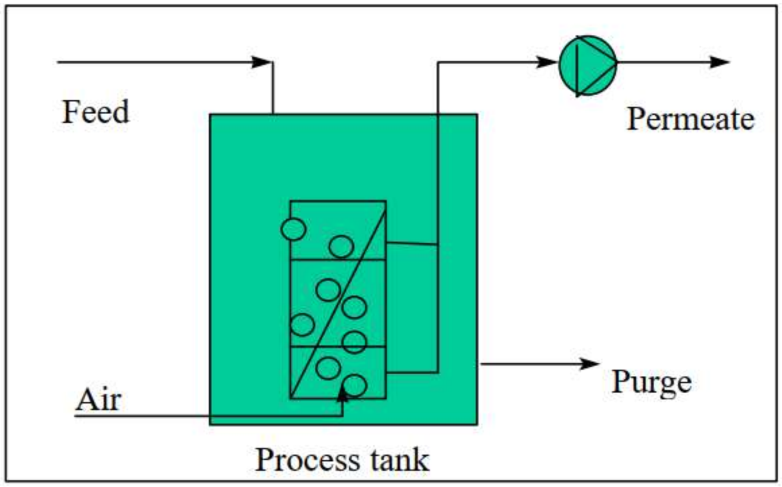

Figure 6.5. PFD of an Immersed Membrane Microfilter

[Source: https://pdfs.semanticscholar.org/7c03/d6949ad668cfcaf50d05df7daf29d22fe880.pdf]

Moreover, the Zee Weed outside-in immersed membrane gives extra advantages:

6.3.1. High Solids

Outside-in membranes in which water flow is from the external of the membrane to the internal of the hollow fiber, sense that the inside just sees clean, micro-filtered water. So the algae cysts, solids, and clays to be removed stay outside the membrane and not ever move in the membrane initiating membrane plugging and fouling. This feature evades the usage of interior recirculation of the permeate to clean the membranes. Moreover, submerged membranes are not fixed inside pressure vessels, they are as a substitute, immersed inside the process tanks, so resistant to the existence of high solids in the tank. Its means that in surface water plants, the performance of the membrane is self-determining of the feed water's high solids peaks and regular turbidity.

6.3.2. Oxidation and volatilization of contaminants

In the meantime the membrane's scrubbing air is injected in the feed water, it becomes accessible for destroying eagerly oxidizable organics, micro precipitating certain metals, for example, Fe and H_2S and scrubbing volatile organics, therefore generating potable water of improved quality than when treated by microfiltration only.

6.3.3. Energy efficiency

Cure with immersed outside-in membranes is carried out in an energy effective manner because the membrane works underneath a small suction (-2 to -5 psi) and with a too-small blower pressure (5.2 psi). Moreover, in plants constructed at water level, the membranes can be fallen openly into the raw feedstuff well, evading feed pumping costs. Lastly, there is no requirement for spending energy in interior recirculation pumping costs because there are no particles trap within the membrane body.

6.3.4. Chlorine Resistance

The Zee Weed® membrane is resilient to chlorine and any other oxidant in concentrations is as high as 200 mg/L. Its means that a plant can pre-chlorinate its water for zebra mussel regulator deprived of having to increase a dechlorination step. Resistance to oxidants, permits for the addition of oxidation pretreatment stages along with for easy decontamination of the plant and the membranes.

6.3.5. Low Particle Counts

On no time, are the Zee Weed membranes backwashed or stressed below pressure. The product is that submerged membrane plants have the lowermost particle amounts in the microfiltration field, normally with under 3 counts/mL. This permits for on-line 24 hours observing of membrane integrity.

6.4. Treatment with Microfiltration Membranes

6.4.1. Surface Water Treatment - Disinfection by Direct Microfiltration

The usage of a 0.2 microns microfiltration membrane in a potable water filtration plant permits to address, in a single step, few of the most explained current issues with present technologies (Jacangelo, 1995; 1997). The elimination of Giardia cysts, coliforms, Cryptosporidium oocysts, and other parasites and suspended solids;

i. The decrease of settling chemicals and;
ii. The decrease in the use of disinfection chemicals;
iii. The decrease of sludge for disposal;
iv. The decrease in viruses.

This type of treatment is accomplished with any of the microfiltration membranes explained above.

Usual results achieved in drinking surface water treatment by using microfiltration are existing below (Mourato, 1998).

Table 6.1. Surface Water Treatment Data - Direct MF with an Immersed Membrane

Feed Water Element	Treated Water Quality

Giardia and *Cryptosporidium*	Non-Detectable > 6 log removal
Coliforms	< 10 cfu/100 mL
Suspended Solids	Non-Detectable
Particle Counts	< 3 particles/mL
Turbidity	< 0.1 NTU

*Results from work performed in Alberta river water treatment and Egypt on canal water treatment.

Giardia cysts and *Cryptosporidium* are now a huge problem in insecure surface water reservoirs. These oocysts and cysts are found because of contamination by human manure but also by normal living organisms that evacuate inside the water. These parasites are just two between several make clean waters harmful to drink. It seems that daily the WHO is finding additional water parasites that are intimidating human life (Jolis et al., 1999; Sethi & Juby, 2002). The elimination of cysts with membranes is an easy task because the diameter of these is greater than the diameter of many microfiltration membranes. Figure 5 displays the size of two parasites usually present in North American waters: *Giardia* and *Cryptosporidium* when got under a scanning electron microscope. It is easy to understand from these pictures why these parasites would be eagerly removed by a 0.2 microns pore microfiltration membrane deprived of the requirement of chemicals or other treatment procedure (Langlais et al., 1992; Guo et al., 2015).

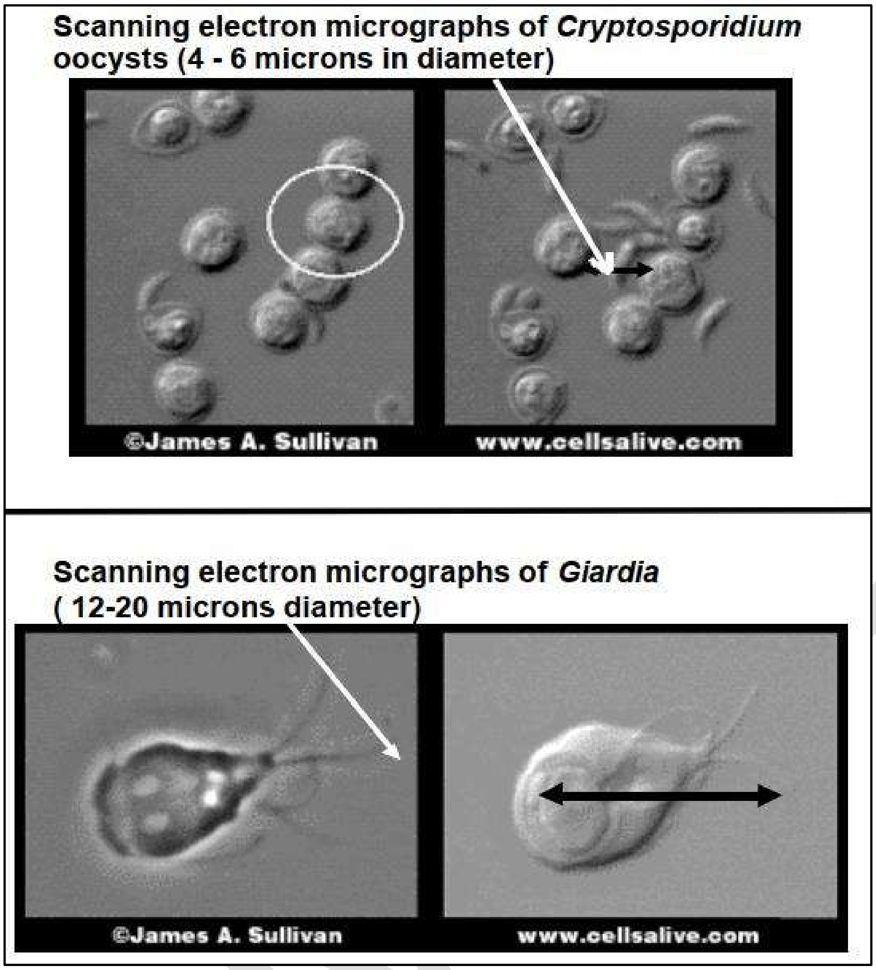

Figure 6.6. Scanning Electron Micrographs of Cryptosporidium and Giardia Parasites

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6.4.2. Surface Water Treatment - Enhanced Coagulation with Microfiltration

Several surface potable water supplies are greatly colored. The majority of soluble organics existing in natural water supplies contain humic materials. These compounds are comparatively great molecular weight polar organic compounds, which feature the yellow to brown color observable in some surface supplies. Whereas these substances themselves do not create any health alarms, chlorination of these waters can end in the creation of trihalomethanes (THM) which are supposed to be dangerous to health, and which are coming under progressively stringent government strategies (Zhu et al., 2005; Arnaldos & Pagilla, 2010).

When joined with coagulation, microfiltration has the capability to remove organic carbon and color from water sources. This is achieved by precipitating dissolved organics into micro-flocs which can then be disconnected by the membrane (Carroll et al., 2000; Lee et al., 2000).

Color and Total Organic Carbon (TOC) are in large amount in the certain river and lake water supplies, the most conventional drinking water sources in North America. The United States, EPA ruling for TOC elimination differs with water alkalinity (Leiknes et al., 2004; Kimura et al., 2008). Table 3 presents these requirements.

Table 6.2. US EPA's TOC Removal Requirements

TOC in water	**Alkalinity levels in the feed water (mg/L CaCO3) mg/L 0 - 60 mg/L**	**60 - 120 mg/L**	**> 120 mg/L**
2.0 - 4.0	.35%	25%	.15%
4.0 - 8.0	.45%	35%	25%
8.0	50%	. 40%	30%.

Microfiltration only does not remove TOC or color from the water. Nevertheless, when joined with coagulation, these can be efficiently removed, therefore combining the absolute blockade advantage of MF with coagulation procedures.

This exceptional process for TOC, color and THM precursor elimination has been developed by using ZENON's submerged microfiltration membrane technology Zee Weed®. The capability to build high solids levels in the process tank permits, by a mutual mechanism of co-precipitation, coagulation, and adsorption on solids, to reach high levels of TOC elimination with minor dosages of coagulants. Two coagulants can be used: iron chloride or alum.

Realizing the water's chemistry, higher levels of elimination can be achieved with greater dosages of coagulants and with modifying the water's pH. Removals as great as 95% color elimination and 85% TOC removal are achievable with an improved process. Process optimization often needs pH modification which translates in the usage of more chemicals and can be tougher to work in small plants.

Lebeau et al. (1998) has joined the used of the immersed microfiltration through coagulant and powder activated carbon as a means to efficiently eliminate natural organic matter (NOM) from surface water. Though this procedure is more difficult to function, it considerably improves the quality of the finished water with slight chemical consumption.

Classic results of microfiltration improved coagulation with Zee Weed® are given below:

Table 6.3. Typical Results of Microfiltration Enhanced Coagulation

FEedwater Color: 35 units

Feedwater TOC: 10 mg/L		
	Alum coagulation (60 mg/L)	**$FeCl_3$ coagulation (60 mg/L)**
Permeate color (% Removal):	74%	66 %
Permeate TOC (% Removal):	49%	66 %
Permeate THM (% Removal):	48%	66 %

Note: The maximum TOC removal using non-membrane coagulation was 40%

6.4.3. Groundwater Treatment by Microfiltration

Well, water frequently has manganese and iron which need to be removed in advance human consumption. Several small communities depend on communal groundwater supplies and need systems which guarantee removal of turbidity, metals, microorganisms and hydrogen sulfide while reducing chemical usage and sludge production (Ellis et al., 2000).

Wells with great levels of manganese and iron are conventional in certain parts of the world, dependent on the geological development. Common technologies like green sand and oxidation/settling are operational at low to medium concentrations. When well waters have Iron in surplus of 5 mg/L and Manganese in surplus of 1 mg/L, common technologies are no longer effective because of filter blinding produced by the iron bacteria films and precipitated iron. Moreover, many wells under the effect of surface waters also contain microorganisms, oocysts, and cysts that essential to be effectively removed for safe potable water intake. Deep wells also usually have H_2S and organics which also need to be removed, frequently resulting in a more difficult treatment plant than essential by these clear waters (Thompson et al., 1995; Drewes et al., 2003). The Zee Weed membrane, because of its design features resolves many of these problems deprived of the adding of needless steps.

Table 6.4. Mechanisms for Groundwater Contaminant Removal

Contaminant Removal	**Removal Mechanism**
Fe	Air oxidation
turbidity, microorganisms	Direct microfiltration
Giardia, Cryptosporidium	Direct microfiltration
H_2S	Air scouring
Mn	In-line Oxidant admixing

The process flow diagram for the outside-in immersed membrane process for the treatment of complex groundwater is given below:

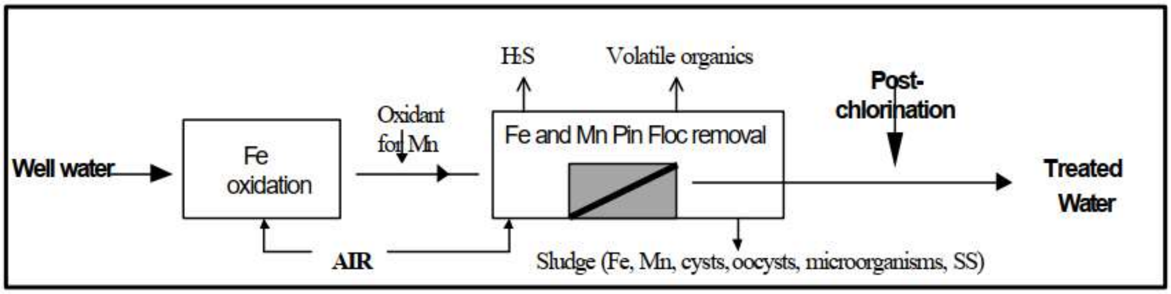

Figure 6.7. Typical ZeeWeed Treatment Plant for a Complex Groundwater

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Usual results attained with an immersed outside-in membrane in groundwater usage is presented in Tables 6 and 7. These results have been gathered from full-scale plant operation in New Brunswick in an iron and manganese polluted well under the impact of surface water and in Egypt, in deep wells comprising a mixture of manganese, iron, H_2S, organics, and bacteria (Lee et al., 2000; Soares et al., 2000).

Table 6.5. Results of Well Water Treatment in New Brunswick, Canada

Contaminant	ZeeWeed Treated Water		Well Water Feed
Manganese	< 0.1 mg/L		2 - 10 mg/L
Iron	< 0.1 mg/L		2 - 10 mg/L

Note: The ZeeWeed plant is enhanced with permanganate injection for Mn removal.

In more polluted waters, the other process mechanisms come into play, paying to treatment. This is mainly true when we preserved well water in Egypt. These waters contained great levels of biodegradable BOD and ammonia, causing from sewage pollution of the well. The air in the ZeeWeed procedure tank oxidized the H_2S but also curved the process tank into a biooxidizing, bioreactor the biodegradable BOD and nitrifying the ammonia (Bellona & Drewes, 2007). Typical results of this work are presented below:

Table 6.6. Results of Well water treatment in Egypt using ZeeWeed

Contaminant	ZeeWeed Treated Water	Well Water Feed
H_2S	non-detectable	10 mg/L
Manganese	< 0.1 mg/L	0.5 - 10 mg/L

Ammonia	< 1 mg/L	8 mg/L
Iron	< 0.1 mg/L	0.5 - 20 mg/L
Oxidizable BOD	< 1 mg/L	50 mg/L
Coliforms	< 1 mg/L cfu/100 mL	> 100 cfu/100 mL

6.5. Application of Nanofiltration Membranes for Drinking Water Treatment

Nanofiltration departure combines a membrane with operating pressures and pore sizes, among the ultrafiltration and (RO) reverse osmosis membranes. They are usually operated at pressures in the range of 70 to 200 psi.

Nanofiltration membranes avoid the passage of only a percentage of the total dissolved solids (TDS) (primarily the divalent ions), and they eliminate most dissolved organic matter arising in natural waters.

Nanofiltration membranes are usually used in the Municipal field for:

1) Desalting of Salty waters
2) Elimination of Organics and THM precursors from surface waters

Nanofiltration membranes have a slighter pore size and can thus remove organics as well as medium to large molecules from waters deprived of the need for chemicals. The cost to pay for requiring smaller pores is the requirement of higher pressure to drive the clean water over the membrane this translates in higher energy requirements.

Tighter porosity nanofiltration membranes also have the capability to eliminate a small percentage of salts from water and therefore are used to desalt salty waters. This is usually seen in Florida, the USA where the water's Total Dissolved Solids is too great for human intake but low enough not to produce the high osmotic pressures needing treatment by reverse osmosis. Desalting by nanofiltration is of slight need in South America and will not be additionally discussed in this paper.

6.5.1. Removal of Color and TOC by Nanofiltration

Nanofiltration is commercially practical for treatment of colored salty waters, nevertheless, systems are still at pilot or demonstration scale for applications via surface waters, which are usually adaptable in quality and turbidity. Nanofiltration membranes are commercially existing, and improvements in membrane structure and system design have newly taken place which will expressively increase its cost-competitiveness.

With reduced limits being applied for a variety of impurities in the U.S., the U.S. EPA is investigative technologies which can be reflected best available technology (BAT) for particular parameters. Treatment with nanofiltration membranes is measured proficient of meeting many goals for disinfection byproduct formation and displayed promise as a cost-effective means of meeting new values (Clark et.al., 1991), though the need for more data on surface water applications was known.

Furthermore, to being dependent upon the sort of membrane used, the costs and performance of a membrane system are also reliant on the module formation. Commercially existing nanofiltration membranes are configured in helix, hollow fiber, or slight tube configuration and function in a cross-flow mode.

It has been shown by Tan and Sudak (1992) that commercially existing NF spiral modules are well suited for eliminating trihalomethane formation probable from colored groundwater, which usually has a low suspended solid contented. In contrast to this, turbidity in surface waters is frequently high and seasonally inconstant. Outdated spiral modules need pretreatment to eliminate particles >5 microns in size. A report set by Taylor et. al. (1992) for the EPA displayed that to decrease polluting of spiral wound modules on surface water nourish to satisfactory levels, alum coagulation settling and fast sand filtration, microfiltration or granular initiated carbon pretreatment were essential (Eriksson, 1988; Riera-Torres et al., 2010).

Nanofiltration has been tested for the elimination of color and TOC in 8 different water bases in Ontario and Quebec. These had variable levels of alkalinity, humic acids, and water chemistry. The level of color in the raw feeds throughout the testing program signified the poorest case scenarios, with raw color stages ranging from 100 to 120 TCU in particular tests. Both hollow and spiral fiber membranes were tested, fallouts were comparable. Nanofiltration was skilled in meeting Ontario potable water objectives for color, with levels >2 TCU in the permeate upheld for more than 1200 hours under improved operating conditions. Provincial objects for TOC (5 mg/L), Turbidity (1 NTU) and THMFP (350 ug/L) were also attained.

Table 6.7. Summary Of Field Testing Results Using Nanofiltration For Treatment Of Surface Water

LOCATION	Color			TOC			Turbidity			THMFP		
	Raw (TCU)	(TCU)	Removal (%)	Raw (mg/L)	Permeate (mg/L)	Removal (%)	Raw (NTU)	Permeate (NTU)	Removal (%)	Raw (µg/L)	(µg/L)	Removal (%)
Fauquier,, Ontario (1993)	110	6	95	10	2.8	72	0.65	0.18	72	1200	175	85
Caramat Lake, Ontario - 1992	100	1	99	14	2.6	81	0.3	<.01	>96	1350	150	89
Lac Deux Montagnes	25	1	96	6	1.8	70	10	<0.2	>92	200	64	68
Rawdon, Quebec (1991) (Lac Vail)	65	2	97	7	1.1	84	1.3	<0.1	>92	260	60	77
Sept-Isles, Quebec (1992) (Lac des-Rapides)	90	5	94	10.4	1.6	85	ND	ND	ND	154	71	54
Contra Costa Water District, CA (Sacramento-San Joaquin	ND	ND	ND	5.2	2.1	60	12	0.05	>99	330	205	38
East Bay CA (1991) Molkelumme River)	ND	ND	ND	1.4	0.4	74	0.64	0.05	92	50	6.5	87
Ottawa, Ontario (1991) (Ottawa River)	45	<1	>98	7.4	1.1	85	1.4	0.05	96	160	27	83

An initial economic assessment was undertaken to associate the expenses of the transverse flow module to a common package management process (coagulation, sedimentation, filtration, with powdered initiated carbon addition) capable of providing similar water feature for the water supply at Fauquier. The cost study displayed that nanofiltration was less costly than common treatment plus powdered initiated carbon for flows up to 100 gpm. These assumptions are stable with others (Wiesner et. al., 1993; Liang et al., 2014) which have shown that NF in both hollow fiber (crossflow) and crosswise flow formations are cost-competitive with common treatment were improving by powdered initiated carbon, or GAC/ozone would be required to attain THM limitations (Watson & Hornburg, 1989; Tuhkanen et al., 1994; Patterson et al., 2011).

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