CHAPTER 8

Membrane Processes for Water Reclamation and Reuse

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Water reclamation and reuse is being increasingly emphasized as a strategy for rational use of limited freshwater and as a means of safeguarding the deteriorating aquatic environment due to wastewater disposal. Membrane technology is playing a vital role in augment our water supplies and is essential for sustainable production of clean water. This chapter gives a comprehensive review of technological development train of wastewater treatment, as well as the detailed performance of advanced membrane processes in municipal wastewater reclamation and reuse. The technological and economic feasibility of different membrane-based technologies compared to conventional treatment processes is also elucidated in this chapter.

8.1 General Aspects of Water Reclamation and Reuse

8.1.1 Introduction

Water is a unique and essential resource for life on Earth because all living organisms can only exist where there is access to adequate supplies of water. We need water everyday for drink, sanitation, cleaning, production of food and energy, support of commercial and industrial activities, and most important, for sustaining our global ecosystems. During the last half century, scarcity of freshwater sources resulting from consumption and contamination has been accelerated rapidly with population growth and urban expansion. Besides, global climate change, shifting weather patterns and frequent droughts have contributed to inadequate water supplies and water quality deterioration. Today, 1.1 billion people lack safe drinking water, and 2.5 billion lack access to basic sanitation. If people continue with business as usual, two-thirds of the world's population will be living in moderate to severe water stress by 2025 (Skirble, 2003; Guo, 2005).

Nowadays, wastewater often requires an extensive treatment before it can be discharged. Although further purification to obtain high-quality reuse water results in additional treatment cost, the benefits of using reclaimed water always make water reclamation and reuse a realistic option (van der Bruggen and Braeken, 2006). Water recycling and reuse accomplishes two fundamental functions: (a) the treated effluent represents a sustainable alternative supply of fresh water for beneficial purposes; and (b) the effluent is kept out of streams, lakes and beaches, thus, reducing pollution of surface water and groundwater. The foundation of water reuse is built upon three principles: (a) providing reliable treatment of wastewater to meet strict water quality requirements for the intended reuse application; (b) protecting public health; and (c) gaining public acceptance (Asano, 2001). Therefore, water reclamation and reuse has been considered as an unavoidable stage not only for alleviating the contradiction of growing water demand in connection with limiting water resources, but also for protecting existing water sources being polluted (Guo, 2006).

In the planning and implementation of water reuse, the applications of intended water reuse govern wastewater treatment needed to protect public health and the environment and the degree of reliability required for the treatment processes and operations. It is important to understand the terminology used in the arena of water reuse. *Water recycling* normally involves only one use or user and the effluent from the user is captured, recovered and redirected back into the original use scheme. In this context, water recycling is predominantly practiced in industry, such as steam-electric, manufacturing and minerals industries. *Water reclamation* means the treatment or processing of wastewater to make it reusable whilst *water reuse* is the use of treated wastewater for beneficial purposes such as agricultural irrigation and industrial cooling. *Reclaimed water* is a treated effluent suitable for an intended water reuse application, which meets water quality requirements for biodegradable materials, suspended matter and pathogens. *Recycled water* is reclaimed water that meets appropriate water quality requirements and is reused for a specific purpose (Metcalf & Eddy, 2003). On the other hand, the WateReuse Association defines *reuse* broadly as "the reclamation and treatment of non-traditional (or impaired) waters for the purpose of beneficial reuse." Non-traditional or impaired waters include the following: (a) municipal and industrial wastewater effluent; (b) brackish water; (c) poor-quality ground water; (d) agriculture return flows; (e) stormwater; and (f) the oceans (Miller, 2006).

In addition, water reuse can be categorized as "direct" or "indirect," depending on whether the reclaimed water is used directly or mixed with other sources. *Direct water reuse* requires the existence of pipes or other conveyance facilities for delivering reclaimed water; applications cover agricultural and landscape irrigation, cooling water and other industrial uses, urban applications, and dual water systems. *Indirect reuse* is discharge of an effluent to impoundment, receiving water or groundwater aquifer for assimilation and withdrawal from downstream. On an international scale, *direct non-potable water reuse* is currently the dominant mode for supplementing public water supplies for irrigation, industrial use, river flow augmentation, and other applications, which includes all reuse applications that do not involve either indirect or direct potable use. On the other hand, *unplanned indirect potable water reuse*, through wastewater effluent disposal to streams, rivers, and groundwater basins, has been an accepted practice around the world for many centuries. Communities located at the end of major waterways have long histories of producing potable water from river water sources that have circulated through multiple cycles of withdrawal, treatment, and discharge. Similarly, riverbeds or percolation ponds may recharge underlying groundwater aquifers with wastewater-dominated water, which, in turn, is withdrawn by down-gradient communities for domestic water supplies. *Planned indirect water reuse* involves linking the discharge of treated wastewater with potential downstream water uses (e.g., groundwater recharge, reservoir replenishment, etc.). In contrast to indirect potable water reuse, *direct potable water reuse* incorporates reclaimed water into a potable water supply system without relinquishing control over the resource (Levine and Asano, 2004).

8.1.2 Applications for Reclaimed Water

According to current global water usage patterns, irrigation comprises about 65% of all water use; industries use about 20%; and municipalities consume another 10%. As a multi-disciplined and important element of water resources development and management, water reclamation and reuse not only can help to close the loop between water supply and wastewater disposal., but also can provide a unique and viable opportunity to augment our water supplies. Thus, most water used for municipal purposes is collected as wastewater and has the potential to be reclaimed and reused after treatment. Comparing the reuse pattern with the water abstraction pattern for conventional sources, three types of applications can be distinguished (Hochstrat et al., 2008):

- Reuse to accommodate the existing major water demand (e.g., agricultural irrigation or industrial uses).
- Reuse for additional or new purposes, normally not covered by freshwater demand (e.g., environmental enhancement).
- Reuse to augment or to replenish natural resources (e.g., groundwater recharge, flow augmentation).

In water reclamation and reuse, certain constituents concerned in reuse water need to meet the treatment and monitoring requirements for reclaimed water vary depending on the intended use. Table 8.1 shows the water quality monitoring parameter routinely used to evaluate the quality of reclaimed water.

The dominant applications for water reuse include agricultural irrigation, groundwater recharge, industrial reuse, environmental and recreational uses, non-potable urban uses and domestic uses. A summary of typical applications for reclaimed water is given in Table 8.2 (Levine and Asano, 2004). The relative amount of water used in each category also varies locally and regionally due to differences in specific water use requirements and geopolitical constraints (Asano, 2001).

Table 8.3 compares the share pattern of wastewater reuse in different regions. It shows that agricultural irrigation is the focused reuse of reclaimed water in Europe and California (70% and 50%, respectively), in contrast to the much more diverse pattern in Japan where environmental, urban and domestic uses are predominant. Australia has developed a rather balanced pattern, allocating reclaimed water to different sectors in rather equal shares and supplying the industrial sector to a great extent as well (Hochstrat et al., 2008).

Table 8.1 Summary of water quality parameters relevant to water reclamation and reuse

Parameter	Significance in wastewater reclamation	Approximate range in treated wastewater	Treatment goal[a]
Organic indicators			
• BOD_5	Organic substrate for microbial or algal growth	10–30 mg/L	< 1–10 mg/L
• Total organic carbon	Measure of organic carbon	1–20 mg/L	< 1–10 mg/L
Total suspended solids (TSS)	Measure of particles in wastewater; can be related to microbial contamination, turbidity; can interfere with disinfection effectiveness	< 1–30 mg/L	< 1–10 mg/L
Turbidity	Measure of particles in wastewater; can be correlated to TSS	1–30 NTU	< 1–30 NTU
Nutrients			
• Nitrogen	Nutrient source for irrigation; can also contribute to algal growth	10–30 mg/L	< 1–30 mg/L
• Total organic carbon	Nutrient source for irrigation; can also contribute to algal growth	0.1–30 mg/L	< 1–20 mg/L
Pathogenic organisms	Measure of risk of microbial infection due to enteric viruses, pathogenic bacteria and protozoa	Coliform organisms: < 1–1,000/100 mL	< 1–200/100 mL Other pathogens are controlled by treatment technology

[a]: in reclaimed water, depending on specific application.
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Table 8.2 Applications for using reclaimed water

Water reuse	Treatment goals [a, b]	Examples of applications
Urban use		
• Unrestricted	Secondary, filtration, disinfection BOD_5: ≤ 10 mg/L Turbidity: ≤ 2 NTU Fecal coliform: ND/100 mL Cl_2 residual: 1 mg/L; pH 6–9	Landscape irrigation (parks, playgrounds, school yards), fire protection, construction, ornamental fountains, recreational impoundments, in-building uses (toilets, air conditioning)
• Restricted-access irrigation	Secondary, disinfection BOD_5: ≤ 30 mg/L TSS: ≤ 30 mg/L Fecal coliform: ≤ 200/100 mL Cl_2 residual: 1 mg/L; pH 6–9	Irrigation of areas where public access is infrequent and controlled (golf courses, cemeteries, residential, greenbelts)
Agricultural irrigation		
• Food crops	Secondary, filtration, disinfection BOD_5: ≤ 10 mg/L Turbidity: ≤ 2 NTU Fecal coliform: ND/100 mL Cl_2 residual: 1 mg/L; pH 6–9	Crops grown for human consumption and consumed uncooked
• Non-food crops and food crops consumed after processing	Secondary, disinfection BOD_5: ≤ 30 mg/L TSS: ≤ 30 mg/L Fecal coliform: ≤ 200/100 mL Cl_2 residual: 1 mg/L; pH 6–9	Fodder, fiber, seed crops, pastures, commercial nurseries, sod farms, commercial aquaculture
Recreational use		
• Unrestricted	Secondary, filtration, disinfection BOD_5: ≤ 10 mg/L Turbidity: ≤ 2 NTU Fecal coliform: ND/100 mL Cl_2 residual: 1 mg/L; pH 6–9	No limitations on body contact (lakes and ponds used for swimming, snowmaking)
• Restricted	Secondary and disinfection BOD_5: ≤ 30 mg/L TSS: ≤ 30 mg/L Fecal coliform: ≤ 200/100 mL Cl_2 residual: 1 mg/L; pH 6–9	Fishing, boating, and other noncontact recreational activities

Table 8.2 Applications for using reclaimed water (continued).

Water reuse	Treatment goals [a, b]	Examples of applications
Environmental enhancement	Similar to unrestricted urban uses Dissolved oxygen; pH = 6–9 Coliform organisms; nutrients	Artificial wetlands, enhanced natural wetlands, and sustained stream flows
Groundwater recharge	Site-specific	Groundwater replenishment, salt water intrusion control, and subsidence control
Industrial reuse	Secondary and disinfection BOD_5: ≤ 30 mg/L TSS: ≤ 30 mg/L Fecal coliform: ≤ 200/100 mL	Cooling system makeup water, process waters, boiler feed water, construction activities, and washdown waters
Potable reuse	Meet requirements for safe drinking water; specific regulations do not exist and specific goals remain unresolved	Blending with municipal water supply (surface water or groundwater)

[a]: Adapted from U.S. EPA, Guidelines for Water Reuse, EPA/625/R-92/004, Sept 1992. [b]: BOD_5 = biochemical oxygen demand; ND = not detected; NTU = nephelometric turbidity units; and TSS = total suspended solids.
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Table 8.3 Percentage uses of recycled water production in different regions (%).

Types of Reuse	Europe + Israel	California, USA	Japan	Australia
Agricultural irrigation	70	49	8	30
Groundwater recharge	17	14	0	0
Industrial uses	4	5	8	40
Environmental/ecological applications	5	13	32	3
Urban applications	4	19	38	24
Domestic applications	0	0	14	3

8.2 Current Status

Conventional water and wastewater treatment processes have been long established in removing many chemical and microbial contaminants of concern to public health and the environment. However, the effectiveness of these processes has become limited because of three new challenges (Langlais et al. 1991; Mallevialle et al. 1996). First, increased knowledge about the consequences from water pollution and the public desire for better quality water have promoted the implementation of much stricter regulations by expanding the scope of regulated contaminants and lowering their maximum contaminant levels (MCLs). The second factor is the diminishing water resources and rapid population growth and industrial development. The reuse of municipal and industrial wastewaters and the recovery of potential pollutants used in industrial processes become more critical. In addition, advances in the manufacturing industry and the growing market associated with advanced treatment processes have resulted in substantial improvements to the versatility and costs of these processes at the industrial scale (Zhou and Smith, 2002). Therefore, now our society has to face the challenge of modifying the traditional industrial growth to a sustainable growth that focuses on 'making social, economic, and political progress to satisfy global human needs, desires, aspirations, and potential without damaging the environment' (Drioli and Fontananova, 2004).

A treatment system for water reuse must have a better performance than that for simple discharge according to the limits imposed by legislation (Chandramowleeswaran and Palanivelu, 2006). However, in an increasing number of cases, conventional treatment has proved to be insufficient to protect the receiving waters or to provide reusable water for industrial and/or domestic recycling. To solve these challenges and better use economical resources, advanced wastewater treatment has become an area of global focus as individuals, communities, industries and nations strive for ways to keep essential resource available and suitable for use.

Advanced wastewater treatment technologies, coupled with wastewater reduction and water recycling initiatives, offer hope of slowing, and perhaps halting, the inevitable loss of usable water (Sonune and Ghate, 2004). Various advanced treatment technologies (e.g., membrane processes, advanced oxidation processes (AOPs), UV irradiation, etc.) have been proposed and developed. As specification-driven processes and being able to provide much higher quality treated water, membrane-based separations have been increasingly popular over the last 25 years. So far membrane processes have been included in a number of prominent schemes world-wide, such as artificial groundwater recharge, indirect potable reuse and industrial process water production (Melin et al., 2006). The key drivers for membrane-based reclamation for sustainable water supply are (Côté and Liu, 2003; Fane, 2007; Hunter, 2007):

- the cost of processing wastewater to the standard for high quality use is about 50% of that for seawater desalination, while capital costs are 34% lower;
- reclamation and reuse can be done locally which favours decentralized processing and could avoid long distance transfers of the product water; and
- the need to find new protected catchments, usually distant from the users, is avoided.

Besides, the increase in water reuse has been driven largely by innovative membrane treatment technologies that are both cost-effective and reliable in removing harmful microorganisms and pathogens (Frost and Sullivan et al., 2007). Currently, the most widely used membrane processes for water reclamation and reuse are reverse osmosis (RO), ultrafiltration (UF) and microfiltration (MF). Among them, RO is emerging as the dominant technology for water reuse. Such implementation of wastewater desalination by RO can renovate secondary/tertiary urban wastewater effluent by satisfying the increasing agricultural, domestic and industrial demands for good quality water which is free from viruses, bacteria and other microbes, as well as meeting unexpected emergency cases of shortages in freshwater produced from the desalination of seawater for certain domestic applications (Abdel-Jawad et al., 2002). However, technologies employed to treat recycled water should depend on the application and bacteriological water quality standards established based on the expected degree of public contact with recycled water. For example, if the primary application is irrigation or cooling tower water, dual-media filtration after secondary treatment is sufficient to achieve the required water quality criteria. On the other hand, if the intended application is indirect potable reuse, sophisticated technologies such as MF, RO and UV must be employed to ensure chemical and microbiological safety of the reclaimed water (Miller, 2006).

In urban wastewater treatment, microfiltered effluent is likely to contain some microorganisms at very low concentrations, albeit MF presents significant microbial rejection in treating primary or secondary treated sewage effluent. Meanwhile, viruses (28 nm) also can be quite effectively retained by a 0.2 μm MF membrane in the presence of shear and biomass/turbidity (Judd and Till, 2000; Sadr Ghayeni et al., 1996). The use of UF (pore size of 0.2 μm) could enhance the quality of the biologically treated sewage effluent with 100% removal of suspended solids (SS) and indicator bacteria (faecal coliforms and *E. coli*) (Arrojo et al., 2005). Nevertheless, MF and UF cannot provide a complete virus barrier, which is defined for practical purposes as 4 log reduction (LRV) or 99.99% removal (Pearce, 2007). Thus, reclamation of secondary effluent by a process involving MF/UF and RO is becoming economically attractive. At present, MF/UF systems are the popular choice for pretreatment of wastewater before it goes into the RO process and comprise 35–40% of all pretreatment system installations.

In industrial wastewater sectors, wide fluctuations in industrial effluent quality coupled with the requirement for process water of reliable and consistent quality tend to favour the application of membrane processes. The basic properties of membrane operations make them ideal for industrial production: they can provide permeate product water of uniform quality that can be processed to the degree required to facilitate the reuse of water; they are generally athermal and do not involve phase changes or chemical additives; they are simple in concept and operation; they are modular and easy to scale-up; and they are low in energy consumption with a remarkable potential for a more rational utilization of raw materials and recovery and reuse of by-products (Drioli and Fontananova, 2004).

Although traditionally, membrane technologies have been considered too expensive for wastewater reclamation in most industrial processes, this situation is changing with the new generation of membranes together with higher achievable fluxes and dramatic reduction in capital cost. For example, permeate production from an RO membrane has typically increased by more than a factor of 3 from 1980 to

2005. During the same period, the cost of an RO membrane has reduced by over 90%, and typically 30 times more permeate can be produced from the same unit RO system capital cost, compared to 1980 (Bennett, 2005). Moreover, less membrane area is needed, and systems can be designed to operate at lower net driving pressure to reduce component costs such as pumps, pipework and pressure vessels. Hence, the traditional membrane separation processes (RO, MF, UF, nanofiltration (NF), electrodialysis, dialysis, pervaporation, membrane air-stripping, etc.) already have been widely used in industrial wastewater reclamation and reuse. The increasing implementation of modern techniques (such as membrane bioreactor technology, membrane distillation and osmotic distillation, and integrated membrane hybrid systems) also enhances the competitiveness of reclaiming wastewater, compared with discharging effluent into the environment.

8.3 Opportunities for Membrane Processes in Biological Wastewater Reclamation and Reuse

8.3.1 Evolution of Wastewater Treatment Processes

Normally, high rate wastewater treatment processes utilize the exponential growth phase of bacterial cells, while low rate or extended aeration phase processes use the endogenous phase of bacterial cells. Therefore, in conventional processes, the growth phase could vary between the two extremes. The stable growth phase is difficult to attain in practice due to the varying quality and quantity of wastewater influent to the wastewater treatment processes (Ouano, 1981). Solids liquid separation is also a major disadvantage of suspended floc systems. Poor settling sludges are common and can make operation unsustainable (Cardew and Le, 1998).

Furthermore, conventional activated sludge (CAS) processes are restricted to a fairly low biomass concentration because of final settlement limitation. Consequently, the required reactor volumes are large (high capital cost), and the conversion rates are necessarily low (high operating cost). Some attempts have been made to increase the working biomass (e.g., biological aerated filters, biological fluidized beds, etc.) in order to develop highly efficient systems, especially with the use of membranes for biomass retention. The separation of activated sludge by membranes has been developed to a widespread technology. The complete retention of sludge in membrane systems allows operation at much higher biomass concentrations for a very high sludge age which generally means a reduction in the surplus sludge volume (Davies et al., 1998; Günder and Krauth, 1999).

Water Factory 21 (California, USA) was the first water reuse plant to have integrated membrane technology in its treatment chain (Levine et al., 1999). The evolution of water reclamation treatment trains utilizing alternative membrane processes is illustrated in Figure 8.1 by using the example of Water Factory 21 in Orange County (Côté et al., 1997). The wastewater was treated for groundwater recharge. Figure 8.1(a) shows a conventional high-rate activated sludge process to remove the bulk of SS and organic matter, followed by lime softening, sedimentation

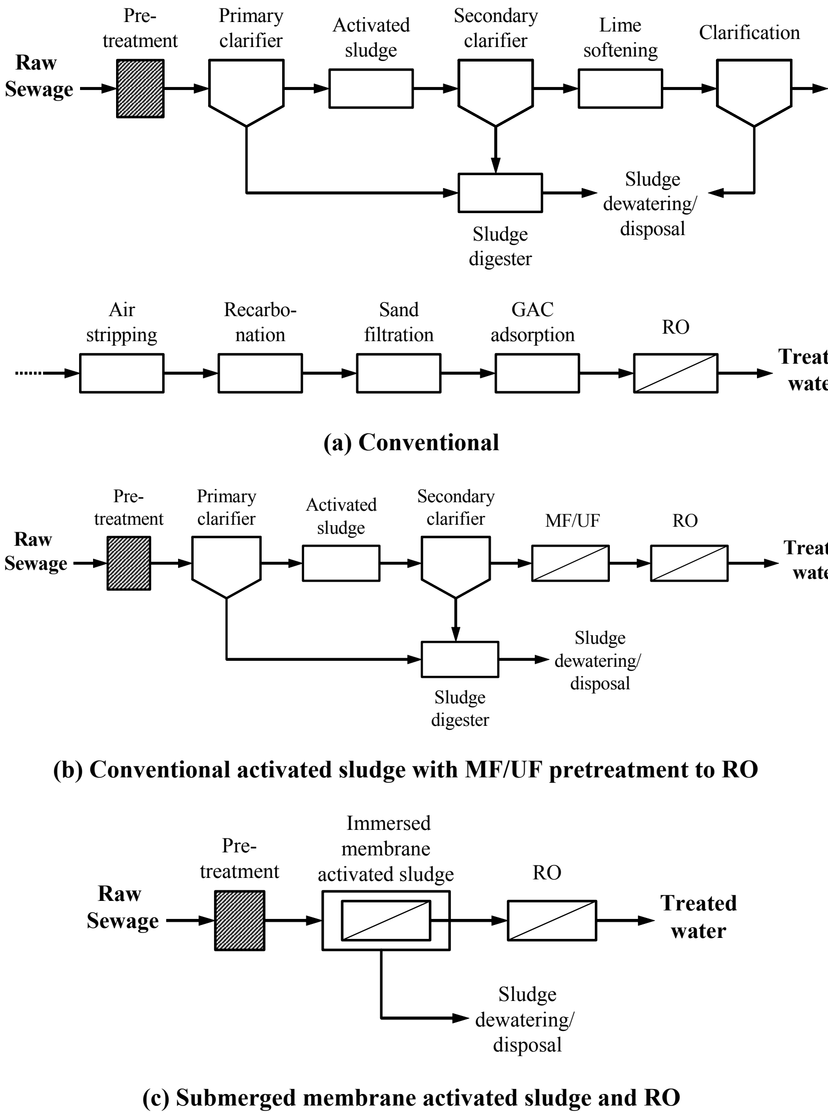

Figure 8.1 Evolution of water reclamation treatment processes (Redrawn from Côté et al., 1997).

and sand filtration to pre-treated effluent for RO. In this train, large volumes of primary, biological and chemical sludges were produced. A simplified process under evaluation at demonstration-scale at Water Factory 21 consisted in replacing the physical-chemical pretreatment to RO by MF or UF (Figure 8.1(b)). The production