Municipal Wastewater: A Rediscovered Resource for Sustainable Water Reuse

Gayathri Ram Mohan, Thomas F. Speth, Daniel Murray, and Jay L. Garland

Abstract Both population growth and movement put forth the need for increased regional water supplies across the globe. While significant progress has been made in the area of building new infrastructure to capture freshwater and divert it to urban and rural areas, there exists a considerable difference in the supply and demand of high-quality water. The cost and non-sustainability of diverting ever increasing volumes of water to stressed areas have become difficult to justify. Therefore, a key step in finding a solution to it is to identify alternate water resources. Given that approximately 45 million cubic meters of municipal wastewater is discharged every day in the United States, researchers and water industry planners have identified municipal wastewater as a viable source for water reuse. Given this potential source, an appraisal of the varying qualities and characteristics of municipal wastewater affecting water reuse is made. This is followed by a discussion on different sectors such as urban, agriculture, and industry that are potential consumers of reclaimed water. The conventional and advanced treatment technologies used to treat municipal wastewater to meet reuse standards are then evaluated; and a number of case studies demonstrating water reuse schemes in different parts of the world are described in brief.

Keywords Water stress • Wastewater reuse • Water quality • Municipal wastewater • Membrane bioreactors

---

G.R. Mohan (✉) • T.F. Speth • D. Murray • J.L. Garland
U.S. Environmental Protection Agency, Cincinnati, OH, USA
e-mail: Rammohan.Gayathri@epa.gov

T. Younos and C.A. Grady (eds.), *Potable Water*, The Handbook of Environmental Chemistry 30, DOI 10.1007/978-3-319-06563-2_6,

1 Introduction

In the years past, wastewater generated from water used for societal needs was labeled sewage and discharged into water bodies [1]. Later in the twentieth century, the deleterious consequences of direct discharge of wastewater on the environment and human health led to the development and implementation of various treatment technologies, mainly with respect to removal of biodegradable matter, nutrients, and pathogens [2, 3]. Today, the steadily increasing global population with particularly higher rates of growth in urban areas is an issue of growing concern [4, 5]. With many anthropogenic activities such as urbanization, industrialization, agriculture, and other land practices altering the water balance in nature, it is no surprise that the limited quantity of high-quality renewable water supply is distributed unevenly on a global scale [6].

Sustainable water use can be achieved by creating a balance between the rates of water withdrawn and that replenished. With the amount of water withdrawn for agriculture, industry, and municipal applications growing steadily, looking at alternate sources of water has become a necessity in many parts of the world. As a result of this immense pressure on the water industry to provide safe and sustainable drinking water to match consumption, the focus has turned to reusing municipal wastewater for various end purposes. To help with the discussion, the descriptions for various terminologies used in this chapter that are related to water reuse are described below.

Terminologies related to water reuse

Terminology	Description
Recycle	Diversion of effluent from a specific process back to the front end, typically used in industrial settings
Reclamation	The process of treating wastewater to standards for reuse
Reuse	Beneficial use of treated wastewater
Direct reuse	Transfer of untreated or treated wastewater from the point of its generation to the site of intended application, such as industrial, agricultural, or landscape purposes
Indirect reuse	Treated wastewater when used to augment surface or groundwater supplies by surface spreading or reused via mixing or dilution
Direct potable reuse	Direct incorporation of treated wastewater into a drinking water supply, either the plant headworks or distribution system
Indirect potable reuse	Incorporation of reclaimed water into the source water of one or more drinking water utilities.

1.1 Water Availability

Although global hydrological cycle ensures abundant supply of freshwater that is sufficient to sustain several times the world population, most of this is inaccessible for human use. A significant percent of the annual runoff reaches such remote locations in the world that pose physical and economic challenges to tap into. In 2006, the quantity of freshwater available on a global scale was 8,462 m^3/capita-year [7]. However, due to human demographics along with socioeconomic and cultural differences, water supply and usage patterns show significant variation in various parts of the world, leaving behind a small portion of the freshwater sources for human use [8–10]

With the current world population of seven billion that is expected to grow at least by 30 % in the next 30 years, more stress will be laid on the current water supply. Therefore, there will be call for measures such as robust water infrastructure and utilizing alternate renewable sources of water. Researchers have shown that hydraulic infrastructure such as dams, levees, and dikes built on water bodies tend to disrupt the balance in nature by affecting aquatic life. These effects are often followed by alteration in river's flow patterns, water temperature, DO levels, and nutrient content. Therefore, looking at alternate resources for sustainable water reuse, such as wastewater reuse, could be a suitable alternative goal to balance human and ecological goals.

Figure 1 shows various sectors and their usage of freshwater resources in the United States in 2009. Estimated projections have shown that by the end of 2025 about 61 % of the global population will be living in cities. As a result, the percent of annual water usage for household and industrial purposes in developing countries is expected to double. This will in turn lead to increased diversion of water supplies originally used for agricultural irrigation. Without subsequent changes to farming practices, this will most certainly affect the world's food supply. Also, the impact on the power industry could be significant in certain parts of the nation.

1.2 Water Stress

The pressure exerted on available water resources can be determined using water stress indices which is the ratio of a country's total water withdrawal to total renewable freshwater resources. A value of <10 % is considered low water stress, 10–20 % is where water availability is becoming limited and additional efforts are required to ensure sustained availability, and above 20 % is considered water stressed region where comprehensive management efforts are a necessity to balance supply and demand of available water resources [11].

The water stress plot of European countries (Fig. 2) shows the water stress index for the year 2000. The plot shows that many semiarid coastal areas and urbanized regions are affected by water stress. This trend is a result of uneven distribution, seasonal variations, and significant changes in global weather patterns. Various researchers have studied water stress around the globe and have used different parameters to contemplate the results. Various characteristics and the threshold values used to further characterize the water stress in different regions are as follows: (1) water stressed: $<1{,}700$ m^3/capita-year, (2) chronic water scarcity:

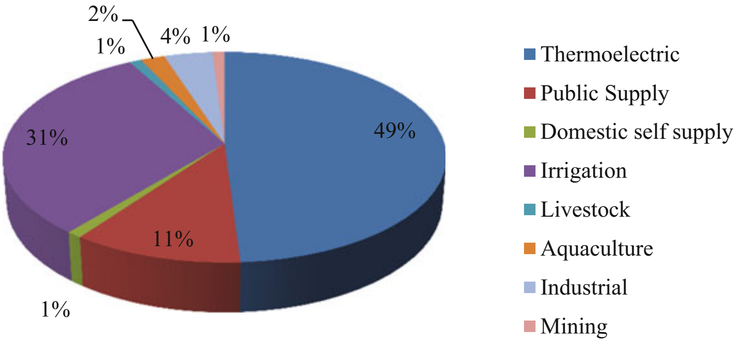

Fig. 1 Freshwater use in the United States (2009) [9]

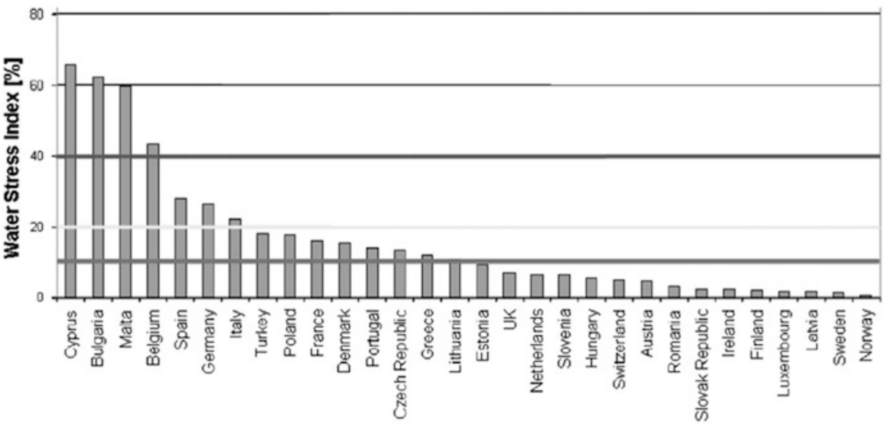

Fig. 2 Water stress index in European countries [11]

<1,000 m^3/capita-year, (3) absolute water stress: <500 m^3/capita-year, and (4) minimum survival level: <100 m^3/capita-year [7]. Researchers have shown that currently about 11 % of the total world population lives with less than 1,000 m^3/capita-year water, and the percentage population is expected to increase to 38 % by 2025.

Researchers have developed various tools to map the risk of water scarcity around the world especially due to the significant deterioration of the quality and quantity of water sources. Two metrics were developed at the Columbia University to study dry periods within a given year, called Normalized Deficit Index (NDI), and drought across years called Normalized Deficit Cumulative (NDC). Figure 3 shows the NDI- and NDC-based water risk assessment in the United States. NDI is calculated every year based on rainfall data in the particular area and the daily water needs; NDC is calculated as one number over the historical climate record. A value of NDI or NDC <1 (ratio) indicates that the magnitude of cumulative risk is less than average annual rainfall, while greater than 1 indicates that shortage during a run of bad years is greater than the average annual rainfall locally [12].

Figure 4 shows the water stress index map for 2011 developed by Maplecroft that was determined using the ratio of domestic, industrial, and agricultural water consumption against renewable supply of water from precipitation, rivers, and groundwater [13]. While the Middle East and North African countries are identified as being at "extreme risk," emerging economies such as India, China, and Korea have been categorized as "medium risk."

2 Water Reuse Applications

The ultimate goal of the water industry that encompasses drinking water, municipal wastewater, and industrial wastewater is to provide a sustained supply of safe drinking water while simultaneously protecting the environment. The main drivers for wastewater reuse vary from region to region and may range from issues such as lack of water, drought and famine, lack of sanitation, or due to socioeconomic reasons such as a population inclined towards greener management policies that include water reuse projects. Researchers have predicted that the number of water reuse projects and applications will steadily increase due to the drivers discussed above. By 2015 about 15,470 cfs water is estimated to be provided via reclaimed wastewater (Fig. 5) [14]. Table 1 shows the types of treatment and water reuse guidelines in the United States based on intended end usage. The three main sectors that have attracted most attention for application of water reuse are agriculture, industry, and direct and indirect municipal reuse.

Table 1 shows the types of treatment and water reuse standards based on intended end usage. The three main sectors that have attracted most attention for application of water reuse are agriculture, industry, and direct and indirect municipal reuse.

2.1 Agriculture

The agricultural sector accounts for 76 % of total water utilization in the world. The quantity of water needed to produce a balanced diet is 70 times more than the quantity used for regular household purposes. As a result of such high water usage, agriculture is also the sector that uses the highest percentage of recycled wastewater. Many countries reuse water in treated or untreated form to meet irrigation needs. The UN report released in 2003 showed that at least 50 countries worldwide are irrigating fertile lands using recycled polluted waters [7]. An advantage for farmers to irrigate with wastewater is the lack of necessity to supplement it with additional nutrients and the low costs associated with this practice. While such

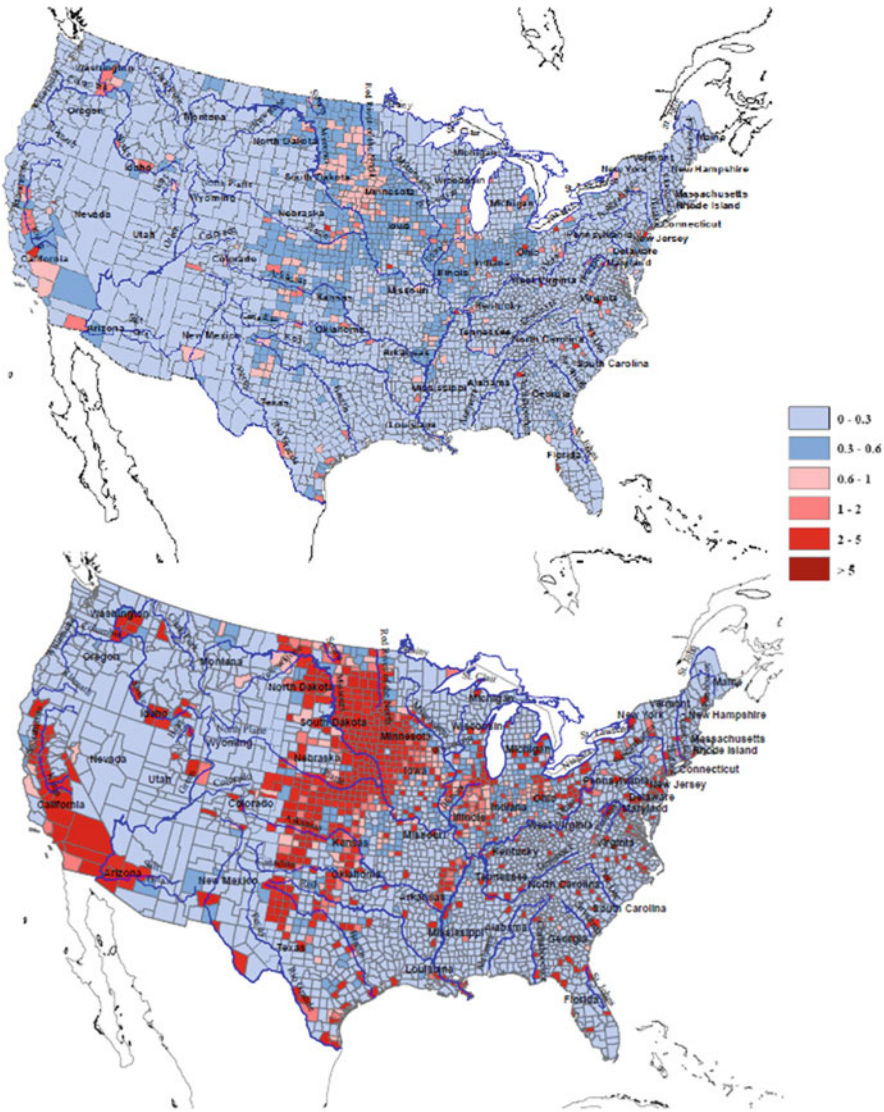

Fig. 3 Water stress in the United States defined by NDI (*above*) and NDC (*below*) developed by Columbia University [12]

practices are common in developing or underdeveloped countries, a similar practice in urban areas is referred to as "urban agriculture." In urban agriculture, wastewater is reused to irrigate land used to cultivate fruit, flowers, and vegetables. The demand for fresh produce along with availability of large quantities of wastewater results in such practices. Although this is a step closer to managing wastes while recovering resources from it, consequences such as diseases caused from consuming such

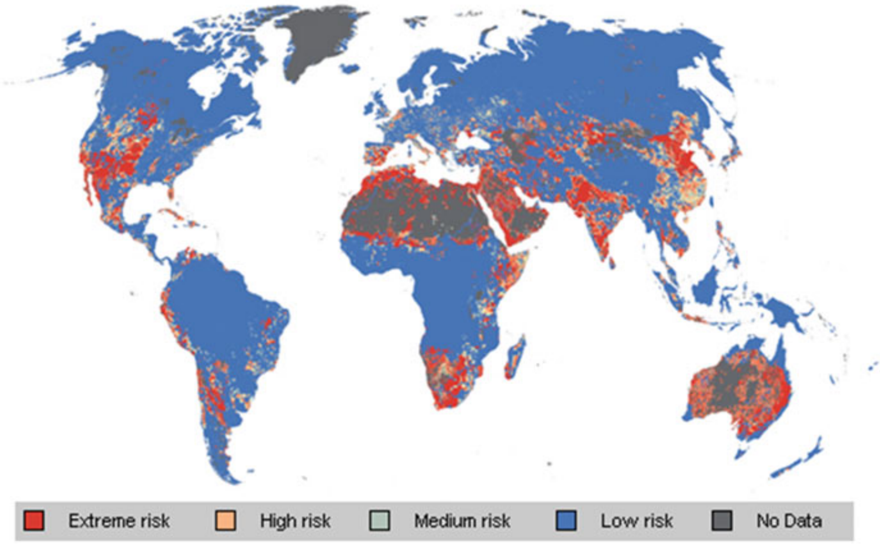

Fig. 4 Global water stress map [13]

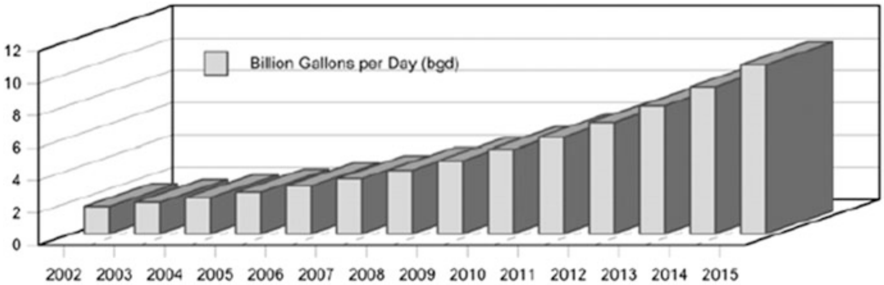

Fig. 5 Estimated growth of water reuse in the United States (2002–2015) [14] (one Billion gallons per day = 3.785 × 10^6 m^3 per day)

produce must not be neglected. To mitigate such exposure, affordable low-cost technologies have been implemented to treat the wastewater before reuse [10, 14, 16].

In Adelaide, Australia, approximately 30 million m^3/year of treated water from a sewage treatment plant is being used to irrigate horticulture crops. The wastewater is treated using dissolved air flotation and filtration processes [16]. In Mexico, about 90 % of the wastewater produced from advanced primary treatment, sand filtration, UV disinfection, and chlorination is reused for irrigation, particularly in the low rainfall areas that also have less fertile lands. Irrigating more than 9,000 ha of land with wastewater has not only improved the soil quality resulting in improved crop

Table 1 Wastewater reuse guidelines for various intended purposes [15]

Category of wastewater reuse	Treatment type	Treatment goals
Urban reuse		
Unrestricted Eg., Landscape irrigation, in-building uses like toilet flushing	Biological, filtration, disinfection	pH 6–9 BOD < 10 mg/L Turbidity < 2 NTU Residual chlorine—1 mg/L Fecal coliform—ND
Restricted Irrigation of golf courses or freeway medians	Biological, filtration, disinfection	pH 6–9 BOD < 30 mg/L TSS < 30 mg/L Residual chlorine—1 mg/L Fecal coliform < 200/100 mL
Agricultural reuse		
Food crops	Biological, filtration, disinfection	pH 6– BOD < 10 mg/L Turbidity < 2 NTU Residual chlorine—1 mg/L Fecal coliform—ND
Non food crops	Biological, disinfection	pH 6–9 BOD < 30 mg/L TSS < 30 mg/L Residual chlorine—1 mg/L Fecal coliform < 200/100 mL
Recreational reuse		
Unrestricted	Biological, filtration, disinfection	pH 6– BOD < 10 mg/L Turbidity < 2 NTU Residual chlorine—1 mg/L Fecal coliform—ND
Restricted	Biological, disinfection	pH 6–9 BOD < 30 mg/L TSS < 30 mg/L Residual chlorine—1 mg/L Fecal coliform < 200/100 mL
Groundwater recharge	Site specific	Site specific
Direct potable reuse	Safe drinking water regulations	Safe drinking water regulations

yield, but has also helped increase groundwater recharge in the Mezquital Valley [16].

2.2 Industry

Industrial effluents vary in quality and quantity based on the process they are subjected to and although reuse applications in industries are controlled by economic forces, generally private sector has its own well-defined rules and regulations for wastewater treatment to meet their specific needs [17]. Therefore, recycle of untreated wastewater is a common practice in industries as it saves them significant portion of associated water costs. While industries account for up to 18 % of direct reuse, their supply chains are more prone to water risk due to climate variability. In recent years, regulatory agencies have laid stringent rules, while also setting up generous incentive packages to promote reuse practice in industries. Some of the industries heavily involved in water reuse schemes are consequently the ones that have higher water usage such as bioethanol plants.

In power plants around the world, two main areas are well known for recycle of process water, namely, cooling towers and boiler feed. In the City of Phoenix, USA, where average annual rainfall is 175 mm/year, the cooling system makeup water is recycled within the station. Coco-Cola's Rainmaker beverage process water is collected and treated using conventional biological treatment, MBR filtration, reverse osmosis, ozonation, and UV disinfection before being reused. The Singapore Public Utilities authority has conducted research on suitability of recycled water treated using advanced technology for use in semiconductor industries. Because of the need for high purity water, the treatment train involves membrane filtration, reverse osmosis, and UV disinfection [16].

2.3 Municipal Sector

The areas at higher risk of water stress are concentrated in the cities due to their growing populations. Municipal wastewater reuse is a sustainable alternative for efficient waste management and resource recovery that helps reduce our dependence on freshwater resources. Municipal wastewater reuse applications include a wide range of treatment options from low treatment levels for applications involving low health risks such as vehicle wash or toilet flushing to others that require higher levels of treatment, for example, direct potable reuse. While direct potable reuse is a complicated and less practiced scheme, increasing scarcity of water supplies means that increasing attention has to be diverted to this area to supplement the available resources to meet population demands.

California has been a pioneer in practicing municipal wastewater reuse from the late 1900s in the United States. The Los Angeles County Sanitation District has used treated wastewater since 1962 to recharge groundwater through surface spreading basins [16]. Prior to recharge, the wastewater is disinfected and subjected to tertiary filtration. The State of California has also reported that the Whittier Narrows groundwater recharge meets the surface water quality standards. Windhoek, Namibia, where the nearest perennial river is at least 750 km from the city, was the world's first direct potable water reuse plant in 1968. The wastewater is subject to a dual membrane treatment process before reuse.

3 Municipal Wastewater Quality

A significant growth in population size, urbanization, and increase in the number of industries in the United States since the mid-1900s has contributed toward a significant increase in the quantity of wastewater discharged to municipal collection systems. Figure 6 shows the changes in municipal wastewater quality during various stages of its use. Technological advancement and the type of industries play a key role in determining the wastewater characteristics. Studies have shown that many unidentified new compounds are added each year to wastewater as a result of emerging industrialization.

3.1 Factors Affecting Water Reuse

The successful installation and operation of water reuse projects mainly depend on various social, economic, regulatory, and financial factors. With respect to technical factors, the treatment selection depends on the intended use of the reclaimed water. Extensive or intensive technologies may be applied depending on the compliance standards, costs associated with the treatment, and ease of operation and maintenance. The most challenging of all is the ability to achieve highly reliable operational, storage, and distribution networks [7].

The microbial water quality indicators for water reuse for irrigation purposes are shown in Table 2. In the United States, individual states have varying rules and regulations with regard to water reuse, such as California Title 22 criteria (1978). The USEPA released the water reuse guidelines in 2012 that detailed the current status of water reuse projects in the United States; however, they did not recommend specific regulatory levels [9]. The World Health Organization (WHO)-related regulations are based on Health guidelines for the use of wastewater in agriculture and aquaculture (1989) [10].

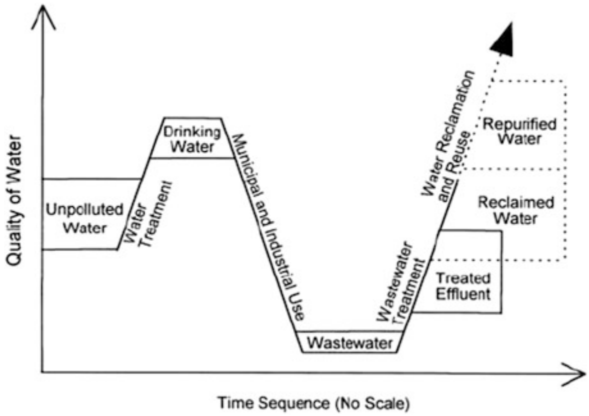

Fig. 6 Changes in water quality during various stages of municipal water usage [6, 15]

Table 2 Microbial indicators in wastewater treatment [9, 10]

Microorganisms	Indicators	Raw wastewater levels	Guidelines
Bacteria	Fecal, total coliform *Streptococcus faecalis* *E. Coli* *Vibrio cholera* *Shigella*	< 10^5 cells/1 L	WHO: 1,000 FC/100 mL FL, AZ, CA—2.2 FC/100 mL
Virus	*Hepatitis A* and *E Virus* *Enteroviruses* *Adenovirus* *Rotavirus*	10^5–10^6 cells/1 L	AZ, HI: <1 PFU/40 L
Helminths	Nematode eggs *Ascaris* *Trichuris* *Ancylostoma*	– <10^3 cells/1 L <10^2 cells/1 L <10^3 cells/1 L	WHO: < 1 Helminth egg/1,000 ml
Protozoa	*Giardia* *Cryptosporidium* *Entamoeba*	<10^5 cells/1 L <10^4 cells/1 L <10^2 cells/1 L	–

3.2 Wastewater Characteristics

3.2.1 Microorganisms in Wastewater

Two broad categories of microbes are found in wastewater: (1) beneficial decomposers that aid in the degradation of nutrients and organics present in wastewater and (2) disease-causing pathogens that are derived from infected human feces [18, 19]. While wastewater treatment is benefited by the presence of the former, the survival of the latter depends on various factors such as pH, salinity, temperature, and humidity. Parasites such as protozoa and helminthes may be released in the form of highly resistant spores, cysts, or oocytes that are to a great extent unaffected by environmental stress such as heat or freezing. Their physical state prevents disinfection via treatment such as chlorination or addition of chemical agents. However, due to their large size, sedimentation or filtration is very effective in removing these parasites. An effective treatment to destroy such pathogens is UV disinfection.

Bacterial levels in wastewater vary significantly due to regional and seasonal variations. Secondary biological treatment also helps remove pathogenic microorganisms from treated wastewater. Commonly used treatments include sedimentation, activated sludge, and disinfection. Indicator microorganisms are not themselves harmful to human health; however, they are used as a tool to determine the likelihood of health risks. Commonly monitored indicators in wastewater are fecal coliforms, total coliforms, and *E. Coli*. The variety and low concentration of pathogens in wastewater call for more advanced analytical laboratory testing protocols. While regulatory agencies require mandatory monitoring of basic indicators such as fecal and total coliforms, specific state regulations may call for more intense monitoring. For example, the states of Florida, Arizona, and California, require Giardia and Cryptosporidium monitoring.

3.2.2 Chemicals in Wastewater

Inorganics

Various inorganic constituents in wastewater include metals, salts, oxyhalides, nutrients, and nanomaterials whose concentrations vary greatly depending on the source of water and the type and degree of treatment received. The USEPA or the states set discharge standards for these chemicals in wastewater to avoid health risks. The Clean Water Act (CWA) requires that the concentration of toxic metals discharged in wastewater streams comply with the NPDES permit. EPA and WHO guidelines provide discharge standards for metalloids such as Boron, Aluminum, and Silicon. Due to higher costs for removal of salinity and management of brine, unless required in situations such as corrosion control or for potable water use, it is not a common practice. Oxyhalides such as bromate, chlorate, and perchlorate are priority pollutants whose bioaccumulative nature leads to high concentrations of the chemicals in certain plants. Sometimes due to the need for expensive treatment technologies such as ozonation, industries are advised to reduce oxyhalide formation during treatment.

Nutrients such as nitrogen and phosphorous are common in wastewater streams. The presence of excess nutrients in water bodies leads to eutrophication, a phenomenon associated with excessive growth of algae in contaminated water. Extensive research has been done in this area and various types of treatment options such as biological nitrogen or phosphate removal, struvite, calcium, or magnesium phosphate precipitation [17]. However, due to ease of operation and maintenance, industries and wastewater treatment plants are inclined toward biological nitrogen and phosphate removal.

The use of engineered nanotechnology is a rapidly growing area of research which has been extensively studied for wastewater treatment, resource recovery, and water quality monitoring. Various forms of usage include nanosorbents, nanocatalysts, bioactive particles, nanostructured membranes, and filtration; however, none of these applications are commercially ready at this time. Regarding the fate and transport of engineered nanoparticles, inconsistency in the results from experiments has raised questions concerning the risks to human health and environmental health. This applies to the distinct nanoparticles, along with agglomerated nanoparticles which are predominant in natural environments. Being reactive in nature, nanoparticles often form larger entities with other engineered nanoparticles, natural nanoparticles, and natural materials. Although not a concern at present, consequences from release and exposure of nanoparticles to the environment are an area of emerging concern.

Organics

Organic components of wastewater include household wastes, liquid wastes, humic substances, fecal matter, industrial wastes, fats, oils, and greases. Organics mainly cause odor problems due to their degradation and contribute to the colored appearance of wastewater. They also act as carbon source for microbial growth and sometimes lead to clogging issues as they promote filamentous growth in wastewater. Secondary biological treatment options are usually targeted to degrade the organic content of wastewater. Activated sludge, anaerobic treatment, and oxidation ponds are primarily employed to reduce the biological oxygen demand and the chemical oxygen demand of wastewater.

Contaminants of Emerging Concern

There are a multitude of chemicals that do not fit under typical categories of wastewater characteristics, but have negative consequences on human health and the environmental. Trace chemicals are considered pollutants when detected in wastewater above their background concentrations. Various categories of trace chemicals include:

1. Industrial chemicals
2. Pesticides, biocides
3. Natural chemicals
4. Pharmaceuticals
5. Personal care products
6. Household chemicals and
7. Transformation products

In 2009, USEPA's Office of Water published results from a nine POTW study that focused on a number of above-mentioned Contaminants of Emerging Concern (CECs) in wastewater. Due to the diverse nature of these compounds, no single treatment technology can be used to reduce their levels to meet the discharge standards. Therefore various pilot- and large-scale demonstrations have employed a sequence of biological treatment coupled with advanced tertiary treatment such as activated carbon adsorption or chemical oxidation to remove such trace chemicals from wastewater. Although the USEPA compiled a Candidate Contaminant List (CCL3) and a proposed an Unregulated Contaminants Monitoring Rule 3 (UCMR3) list for contaminants in drinking water [20], currently there are no stringent rules for CECs for potable water reuse, and so, individual states are permitted to set their own regulations.

4 Municipal Wastewater Treatment Technologies

Following preliminary screening to remove rags, floatables, and grits using equipment such as rotary screens, wastewater is subjected to following treatments:

1. Solid–liquid separation or primary treatment
2. Secondary biological treatment
3. Tertiary or advanced treatment

Table 3 shows a list of various wastewater treatment technologies. Suspended particles greater than 3 μm can be removed via coarse filtration, a solid/liquid removal process. Other solid removal processes used commonly in wastewater treatment are coagulation, flocculation, and sedimentation. Addition of chemical agents to cause precipitation or flocculation followed by gravity settling are commonly employed techniques for removal of colloidal matter and suspended solids.

Secondary wastewater treatment comprises of biological treatment that targets removal of organic matter and sometimes nutrients as well. In aerobic treatment, microorganisms oxidize organic matter into CO_2 and H_2O in an aeration basin. Although aerobic treatment is more stable and common in industrial wastewater treatment, anaerobic digestion has several advantages such as production of a valuable biofuel-biogas, lower quantity of sludge production, and lower costs due to lack of aeration [22, 23]. However, anaerobic systems are more prone to instability than aerobic systems and typically require a post-aeration step to meet discharge standards. While aerobic and anaerobic systems are artificially designed and operated in a controlled environment, other natural systems such as oxidation ponds are also employed in certain areas where space and sunlight are not limiting factors.

The selection of the secondary wastewater treatment is heavily dictated by the economics of the process. Table 4 shows the cost prices for different conventional treatment technologies used in the past for various plant capacities [24].

Table 3 Municipal and industrial wastewater treatment technologies [21]

Process	Description
Primary-solids separation	
Coagulation	Addition of coagulants such as alum to remove colloidal and suspended particles
Flocculation	Passive or active agglomeration of colloidal matter induced by addition of a clarifying agent
Filtration	Passage of water through a granular medium such as sand to remove suspended matter
Sedimentation	Gravity settling of flocs, precipitates, or particulate matter
Secondary biological treatment	
Aerobic-activated sludge	Breakdown of organic matter in wastewater by subjecting to aeration. Converts organics to CO_2 and H_2O
Anaerobic treatment	Multistep digestion of organics in an oxygen-deprived environment, leading to production of methane and CO_2
Natural treatment systems	Spacious, shallow oxidation ponds with abundance sunlight penetration are natural wastewater treatment systems. Algal growth consumes nutrients present in wastewater
Membrane bioreactors	Used as a replacement to conventional biological treatment. Allows uniform biofilm growth on a solid surface with high surface area. High reaction rates, stability, and compact size are key advantages
Tertiary treatment	
Activated carbon	Physical adsorption of contaminants on surface of granular activated carbon. GAC will also exhibit biological activity
Air stripping	Passage of forced air through wastewater for removal of ammonia and VOCs
Ion exchange	Ion exchange resins are used in flow through reactors to treat wastewater
Advanced treatment/disinfection	
Chlorine disinfection	Inactivation or elimination of pathogens from treated wastewater by addition of chlorine
UV	Exposure of biologically treated effluent to UV helps destroy microbial cells and disinfect the treated water
AOP—Ozone, H_2O_2, TiO_2/UV	Advanced oxidation process involves use of a chemical agent and an auxiliary energy source to degrade recalcitrant residual organics and disinfect secondary effluent

Table 4 Cost analysis for secondary wastewater treatment [24]

	Costs (cents/m^3)			
Biological Treatment Process	4 mcm	14 mcm	40 mcm	90 mcm
Trickling filter	16.6	10.1	7.4	6.3
Activated sludge (AS)	20.3	12.1	8.6	7.2
AS + nitrification	23	13.7	9.7	8.2
AS + nitrification – denitrification	31.6	19.3	14.2	12.3

Membrane bioreactors (MBRs) are an exception to other add-on technologies that supplement the secondary biological treatment [15]. MBRs are considered emerging treatment technologies because they are typically designed to replace secondary biological treatment. MBRs produce high-quality effluent and display higher performance efficiency as a result of higher reaction rates [25, 26]. In the late 1990s, MBRs were commissioned for small decentralized treatment in Europe. Recently, however, their use in wastewater treatment has been progressively increasing due to their compact size and higher stability.

Tertiary treatment involves technologies such as membrane processes ranging from commonly used sand filtration to more expensive treatment using microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. Depending on the size of the contaminant to be removed (from suspended solids to simple molecules), different membrane schemes may be employed. Membrane filtration is most commonly used as a pre- or a posttreatment step for removal of coarse particles (i.e., microfiltration and ultrafiltration) [27]. Some water reuse schemes also employ a dual membrane treatment concept such as microfiltration followed by reverse osmosis in order to attain high purity water for potable reuse. Microfiltration is often used to prevent the fouling the expensive high-pressure reverse osmosis membranes. Other commonly used tertiary treatments include GAC adsorption, ion exchange, and air stripping [28].

5 Case Studies

As a result of global water scarcity, many developing and developed nations have embraced various water reuse practices. In this section, a number of case studies are discussed to give a real-world perspective to the current status of water reuse applications.

5.1 USA

5.1.1 Phoenix, Arizona

The cities of Glendale, Mesa, Phoenix, Scottsdale, and Tempe form the Sub-Regional Operating Group (SROG) in Arizona. Municipal wastewater from the SROG cities is treated via nitrification–denitrification scheme at the 91st Avenue wastewater treatment plant (WWTP). Out of the 158,000 ac-ft/year of wastewater processed annually, 60 % is reused for various purposes such as cooling water makeup in nuclear and power stations, irrigation water, and constructed wetlands.

The 91st Avenue WWTP was originally built in 1958 as a 7.7 cfs plant near the Salt River in Phoenix. It has progressively expanded over the years to a 356 cfs plant that was built using a unified plant concept [9]. Such a plan allows uncoupling of a single unit process that needs repair or maintenance from rest of the unit processes, thus leaving the total treatment train unaffected at all times. The plant has been constructed with provision for additional advanced tertiary treatment on the effluent (i.e., reverse osmosis membrane treatment) that will allow reuse of the treated wastewater.

5.1.2 Frito-Lay, Arizona

Since the 1970s, Frito-Lay, a key brand within PepsiCo, has taken environmentally cautious decisions in order to reduce their footprint. A near net-zero plant in the southeast region of the United States operates entirely on renewable energy and reclaimed water. It utilizes solar energy cells, generates steam from a renewable biomass boiler, and discharges zero landfill waste [9]. Their Process Water Recovery Treatment Plant (PWRTP) recycles up to 75 % of Frito-Lay's facility process water, reducing their freshwater demand by about 0.4 million cubic meters annually.

The treatment train used at Frito-Lay's plant is shown in Fig. 7. In order for the reuse water to meet EPA's drinking water standards, the oily wastewater is subjected to primary screening, pH adjustment, clarification, activated sludge with biological nitrogen removal (BNR), membrane bioreactor process (MBR), granular activated carbon adsorption (GAC), UV disinfection, low-pressure reverse osmosis, and chlorine disinfection. Resource recovery occurs at various stages in this plant:

1. The solids collected from screening are dewatered and centrifuged and eventually sold as animal feed.
2. Starch is recovered at different stages and reused in the process to reduce associated costs.
3. The treated water is reused for moving and washing potatoes and corn, for cleaning equipment, and for other production needs.

5.1.3 City of San Diego, California

California and Florida are pioneers in employing water reuse schemes in the United States. Figure 8 shows the water reuse patterns in the two states. While a significant portion of treated water is reused for agricultural purposes in California, the major consumer of reclaimed water is the landscaping sector in Florida. The water quality standards differ greatly based on the intended use which dictates the degree of treatment.

San Diego, the 8th largest city in the United States, receives only 25 cm of annual rainfall and therefore depends on the water imported from the Colorado River and California Water projects to meet its demands. The increasing costs of imported water have created the need for locally controlled water resources. While the city has reduced its imported water dependency by recycling water for irrigation and industrial purposes, the seasonal variation and need for special infrastructure have limited its use of recycled water. Since 2004, the city has embarked a water reuse

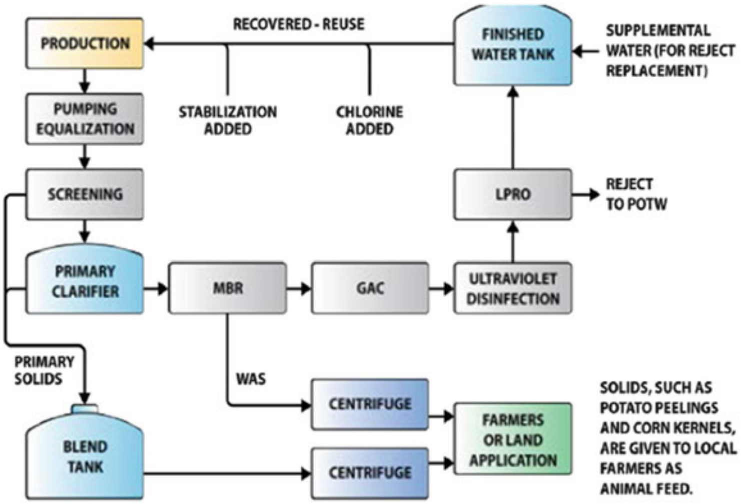

Fig. 7 Process flow diagram for Frito-Lay's Process Water Recovery Treatment Plant (PWRTP) [9]

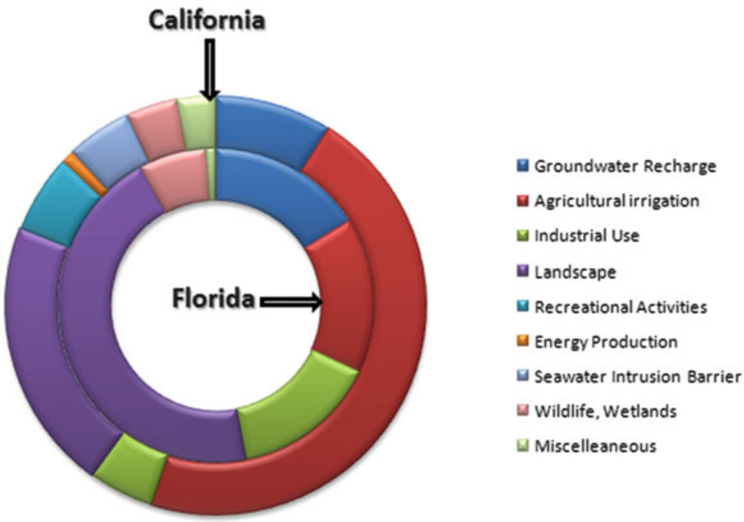

Fig. 8 Water reuse pattern in California and Florida [9]

program that was divided into three phases. During the initiation phase, a great deal of emphasis was laid on augmenting the reservoir storage capacity. The second phase will entail a demonstration of water purification at a 1.6 cfs facility. Finally, in the third phase, a fully functional large-scale plant will be constructed and operated. Figure 9 shows the plan for second and third phase of this plant [9].

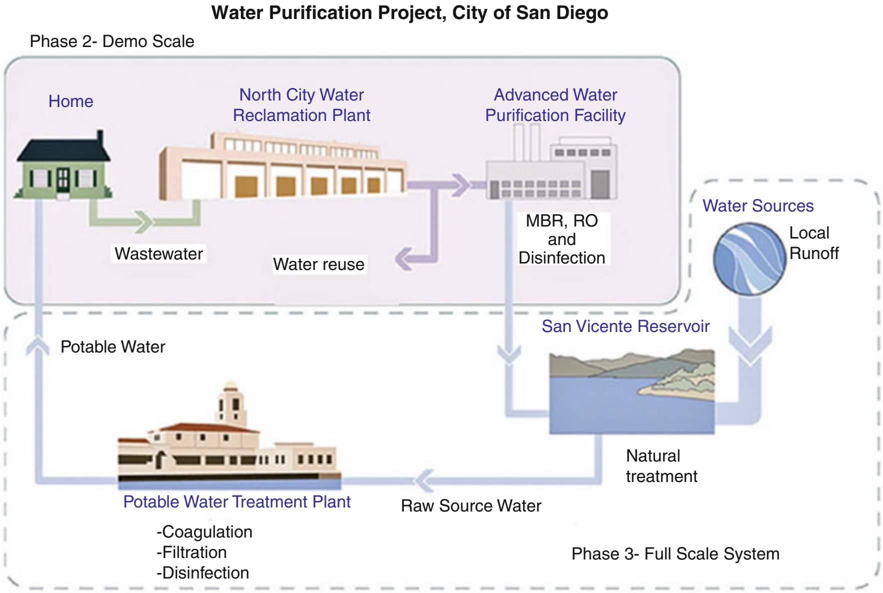

Fig. 9 Phase 2 and Phase 3 of the demonstration plant in San Diego, California [9]

The treatment sequence used in this facility included microfiltration and ultrafiltration membrane, reverse osmosis, and advanced oxidation process using UV and H_2O_2. The demo plant will be operated for a year and during this time, the water quality parameters such as nutrient levels, disinfection byproducts, trace chemicals, and other contaminants regulated by the State of California will be monitored to determine the efficiency of treatment. This demonstration project is the stepping stone to spreading awareness among public and a mode to continue regulatory involvement and public outreach that will eventually pave way to installation of the large-scale plant that can supply up to 23.2 cfs of purified water for indirect or direct potable reuse.

5.1.4 Leo J. Vander Lans Water Treatment Facility, California

In Southern California, the Water Replenishment District replenishes groundwater basins in the central and west coast using spreading basins and sea intrusion barriers. A 0.3 m^3/s Leo J. Vans water treatment facility receives treated tertiary effluent from Los Angeles County Sanitation District and Long Beach water reclamation plant. The treatment sequence used at this facility is shown in Fig. 10. A microfiltration equipped with a backwash is followed by reverse osmosis and UV disinfection. The expanded plant is expected to have a 92 % water recovery rate and the treated water will be used for indirect potable purposes (Table 5).

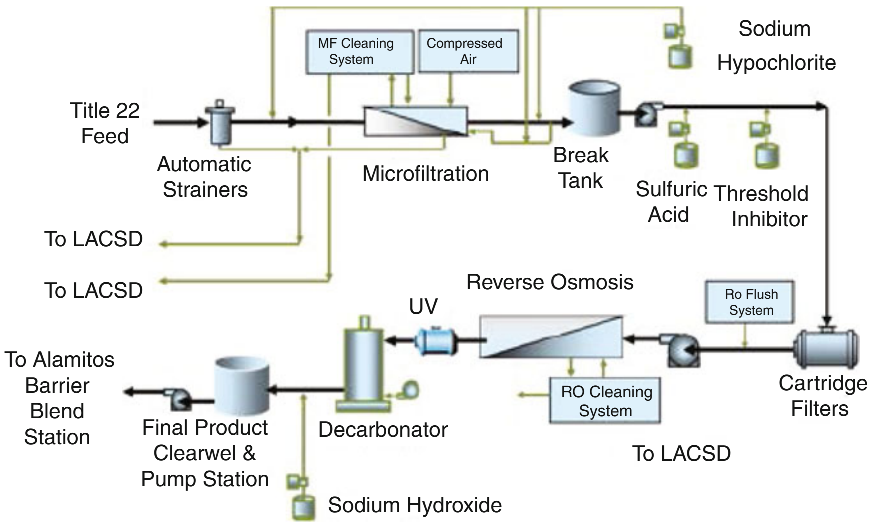

Fig. 10 Process flow diagram of LVLWTF [9]

Table 5 Water quality parameters in the Leo J. Vander Lans Water treatment Facility (LVLWTF), California [9]

		Influent		Product
Parameter	Units	LBWRP	LCWRP	LVLWTF
pH	pH units	7.9	7.9	8.12
Turbidity	NTU	0.48	0.5	0.07
Ammonia-N	mg/L	1.5	2.0	0.22
Nitrate-N	mg/L	6	5.3	1.74
Total N	mg/L	9	9.3	2.05
Total dissolved solids	mg/L	703	787	83
Total organic carbon	mg/L	6.7	7.5	0.44

5.1.5 Miami South District Plant, Florida

With three major water treatment plants serving the county's 90 % of water supply, Miami Dade water and sewer department is the largest utility in Florida. Due to various factors such as rapidly growing population and environmental stress due to drought conditions, much pressure has been laid on the utility to restore the Everglades, while not overexploiting the groundwater reserve. Therefore, to address this, the tertiary effluent form the South District wastewater plant will be treated in the South District Water Reclamation plant in order to provide water for potable reuse. Treated water will be used to recharge the Biscayne aquifer that provides the main drinking water supply in the county. Similar to other water reuse projects, this reclamation plant includes the following unit processes to treat the wastewater: microfiltration, reverse osmosis, and UV-H_2O_2. The ammonia levels will be maintained by ion exchange treatment post RO and the brine from the process will be discharged into a deep well [9]. This treatment scheme ensures availability of locally controlled, sustainable source of water treated using previously available infrastructure.

5.1.6 Reedy Creek, Florida

Walt Disney resort's municipal services are provided by the Reedy Creek District in Florida. Over the course of 20 years, the Reedy Creek Improvement District (RCID) has practiced water reuse beginning with water reuse for irrigation purposes to 100 % reuse for various other purposes such as wash down of sidewalks, cooling water makeup, vehicle wash, etc. About 7.7–9.3 cfs of treated water is currently reused for non-potable purposes. The treatment scheme used at RCID includes a five-stage Bardenpho process for C and N removal, followed by filtration and hypochlorite disinfection [9]. This facility meets the zero-discharge standards set under an FDEP permit and has met all USEPA standards for primary and secondary drinking water.

5.2 China

Scarcity of water in the world's most populated countries arises as a result of steeply growing population and urbanization. The uneven distribution of water resources in the country with abundant water supply is an issue of great concern. Added to the serious water shortage in many large cities, polluted surface water renders many sources unfit for potable purposes.

Currently, although water reuse is limited to industrial applications in China, a couple of reclamation facilities have demonstrated the immense potential for China's future water supply via advanced wastewater treatment. Table 6 shows the water quality standards for reuse of water in different sectors such as urban, surface water recharge, or for aesthetic purposes.

The Beijing Olympic Park water reuse scheme is an exemplary demonstration of the potential behind installation of advanced wastewater treatment (Fig. 11) [9]. During the 2008 Olympics, a 0.92 m^3/s Qinghe water reclamation plant was built with the Zeeweed ultrafiltration MBR process followed by activated carbon filter for wastewater treatment. About 75 % of the reclaimed water was used for vehicle wash, road wash, toilet flushing, and other non-potable purposes in Haidian and Chaoyang districts.

Table 6 Water quality standards in Beijing, China [29]

Parameters	Units	Scenic impoundments		Urban reuse			Surface water
		Restricted	Unrestricted	Toilet flushing	Irrigation	Washing	
BOD	mg/L	6	6	10	20	10	4
Total dissolved solids	mg/L	–	–	1,500	1,000	1,000	–
Turbidity	NTU	–	5	5	20	5	–
Total phosphate	mg/L	0.5	0.5	–	–	–	0.05
Total nitrogen	mg/L	15	15	–	–	–	1
Fecal coliform	cfu/100 mL	10,000	500	3	3	3	1,000

Fig. 11 Wastewater treatment in Beijing Olympic Park (GE Water Treatment Technologies) [9, 29]

5.3 India

With poor sanitary conditions and limited access to safe potable water, India is exploring alternate options to provide safe and sustained supply of drinking water to its rapidly growing population. At the capital city of India, Delhi, the estimated water demand to serve the current population of 15 million is about 48 m^3/s.

The Okhla sewage treatment plant in Delhi has a capacity of 7.2 m^3/s and was developed in 5 phases with activated sludge process used to treat the wastewater (Fig. 12). The reclaimed water is currently being used to supply cooling tower makeup water to Badarpur Thermal Power station, for horticulture at the Central Public Works department, for irrigation to the Minor Irrigation department, and as discharge into the Agra canal.

5.4 Australia

Located in western Sydney and developed by the Sydney Water as a part of the New South Wales Metropolitan water plan, St Mary's advanced water recycling plant was started to provide alternate source for high-quality drinking water provided by the Warragamba Dam and to reduce the nutrient load in downstream river. The tertiary effluent received in this plant is further treated by ultrafiltration, reverse osmosis, decarbonation, and chlorine disinfection. A chemical monitoring program was started to test the treated water for toxicological chemicals such as disinfection by-products or endocrine disruptors. Since the reverse osmosis process was key barrier to trace chemicals, the chemical monitoring program was focused on this

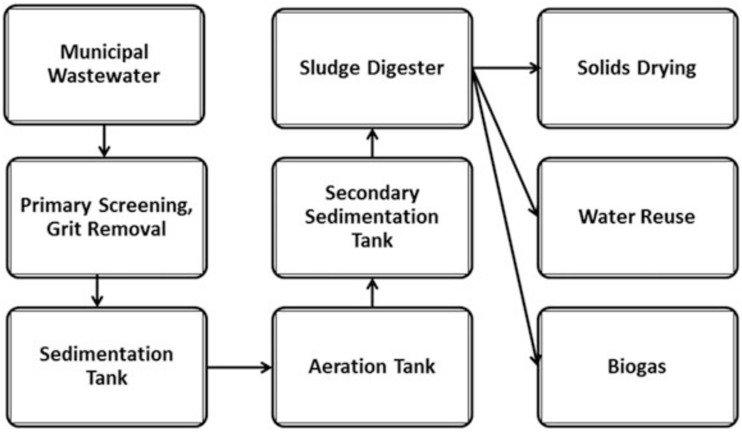

Fig. 12 Wastewater treatment scheme in the Okhla plant in New Delhi, India [9]

technology. Following the successful demonstration, a full-scale plant was constructed in June 2010 adjacent to the existing one.

5.5 *Europe*

The stringent regulations for effluent discharge laid by regulatory authorities combined with water shortage have led European countries to investigate alternate resources [30]. Water reuse is becoming increasingly popular in Northern European countries, especially in the coastal areas and in the Western and Southern islands of Europe. France, Spain, and Italy are some of the pioneers in integrated water resource management. Table 7 shows various EU-funded projects demonstrated in various continents around the world.

The serious water shortage in Belgium has been a key driver leading to 100 % reuse of renewable water resources in the country [10]. In the Wulpen WWTP, about 2.5 million m^3/year of wastewater is treated via microfiltration and reverse osmosis and stored in an aquifer and used to augment the drinking water supply.

The early zero discharge systems in Europe were constructed in the coastal areas and on smaller islands such as Mt Saint Michael in France. On Noirmoutier Island in France, reclaimed wastewater is used to supply 100 % of agricultural irrigation demand. Water reuse helps increase available resources that are currently imported and also help prevent contamination of sensitive coastal areas. Techno-economic assessments of various water management scenarios showed the use of reclaimed water for irrigation and landscaping as the most economical way to overcome water shortage in the island [10].

With a water exploitation index exceeding 45 %, Cyprus is one of the most water stressed regions in Europe. With the rapidly expanding domestic and tourist sectors,

Table 7 EU funded projects for water reuse [31]

EU funded projects	Description
CORETECH	Integrated sanitary, environmental and agricultural engineering for cost-effective treatment of wastewater, and reuse of treated water for agricultural purposes
NAORA	Simultaneous treatment of wastewater to reduce pollution and manage water scarcity by providing additional means of water for agricultural irrigation in the province of Settat
SWITCH	Challenge existing paradigms and create sustainable integrated urban water management
AQUAREC	Introduction of wastewater reuse as a major component to sustainable water management practices. Technologies to monitor and mitigate risks posed by chemicals and pathogens in wastewater were also investigated
EUROMBRA	Optimization of advanced wastewater treatment in European countries using MBR technology
PROMEMBRANE	Improvement of membrane technologies to protect water in the Mediterranean region

ensuring availability of sustained water supply to agricultural sector has been a challenge in the country [9]. Well known for their impressive water infrastructure projects, Cyprus's policy of "Not a drop of water to the sea" was initiated with an objective to increase utilization of runoff water. About 90 % of treated water is reused primarily for non-potable purposes such as irrigation of agricultural land, parks, and gardens, leaving a minor fraction for groundwater recharge.

6 Conclusions

Advanced treatment processes are pivotal in treating municipal wastewater to meet water quality standards to protect human health and the environment. Various socioeconomic drivers such as the monetary value of reclaimed water that is used to supplement water resources and availability of high purity water play a significant role in pushing for change and adoption of water reuse. In developed countries, incentives provided by Government agencies seem to attract application of expensive advanced wastewater treatment technologies for reuse purposes. In developing countries, the possibility to reuse nutrients from wastewater to improve the quality of soil in fertile lands is a driving force for reuse.

In this chapter we have briefly discussed water availability on a global and regional scale and the excessive pressure laid on fixed quantities of water available for human use by the ever growing population and other anthropogenic activities. Treating municipal wastewater for water reuse not only helps in handling large quantities of wastewater, but also provides a renewable resource for water supply. Various primary, secondary, and advanced treatment technologies used to treat wastewater have been discussed. Finally, case studies representing current status of water reuse applications from different parts of the world have been covered to give a real-world perspective of the various components of water reuse schemes described n this chapter.

The implementation of treating wastewater for reuse applications mainly depends on public acceptance. Success has occurred when Government agencies help spread awareness among public. Singapore's NEWater projects are successful examples of a nation can implement water reuse. Space constraints and lack of infrastructure to collect and store rainwater were drivers behind installation of advanced treatment technologies such as membrane processes and UV disinfection that treat reclaimed water to safe potable water standards. Currently about 30 % of Singapore's water needs are met by reusing reclaimed water.

Although the deciding factor varies due to geographical and socioeconomic differences, there is no denying that municipal wastewater is indeed a sustainable, alternative resource for water reuse. With continued regulatory guidance, public outreach, and technological advancement, water reuse projects will become increasingly popular in the future.

Disclaimer The views expressed in this chapter are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency (EPA). The chapter has been reviewed in accordance with EPA policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

References

1. Levine AD, Asano T (2004) Peer reviewed: recovering sustainable water from wastewater. Environ Sci Technol 38(11):201A–208A
2. Stenekes N et al (2006) Risk and governance in water recycling public acceptance revisited. Sci Technol Human Values 31(2):107–134
3. Agyin-Birikorang S, O'Connor G, Pullammanappallil P, Mohan GR (2013) Recovery of essential plant nutrients from. J Sustain Bioenergy Syst 3:149
4. Otterpohl R, Grottker M, Lange J (1997) Sustainable water and waste management in urban areas. Water Sci Technol 35(9):121–133
5. Bakir H (2001) Sustainable wastewater management for small communities in the Middle East and North Africa. J Environ Manage 61(4):319–328
6. Asano T (2002) Water from wastewater- the dependable water resource. Water Sci Technol 45 (8):24
7. Cisneros BEJ, Jiménez B, Asano T (2008) Water reuse: an international survey of current practice, issues and needs. IWA publishing, London
8. Postel SL (2000) Entering an era of water scarcity: the challenges ahead. Ecol Appl 10(4):941–948
9. USEPA (2012) Guidelines for water reuse
10. Lazarova V et al (2001) Role of water reuse for enhancing integrated water management in Europe and Mediterranean countries. Water Sci Technol 43(10):25–33
11. Bixio D et al (2006) Wastewater reuse in Europe. Desalination 187(1):89–101
12. Shi D, Devineni N, Lall U, Piñero E (2013) America's Water Risk: Water Stress and Climate Variability
13. Maplecroft. Available from: http://maplecroft.com/about/news/water_stress_index.html.

14. Wade Miller G (2006) Integrated concepts in water reuse: managing global water needs. Desalination 187(1):65–75
15. Mujeriego R, Asano T (1999) The role of advanced treatment in wastewater reclamation and reuse. Water Sci Technol 40(4):1–9
16. Anderson J (2003) The environmental benefits of water recycling and reuse. Water Supply 3 (4):1–10
17. Mohan GR, Gadekar S, Pullammanappallil P (2011) Development of a Process Model for Recovery of Nutrients from Wastewater by Precipitation as Struvite. Florida Water Resour J
18. Moe C, et al (2007) Waterborne transmission of infectious agents. In: Hurst CJ et al (eds) Manual of environmental microbiology, 3 edn, pp 222–248
19. Ashbolt NJ (2004) Risk analysis of drinking water microbial contamination versus disinfection by-products (DBPs). Toxicology 198(1):255–262
20. Rammohan G, Nadagouda MN (2013) Green photocatalysis for degradation of organic contaminants: a review. Curr Org Chem 17(20):2338–2348
21. Tchobanoglous G, Burton FL (2003) Wastewater engineering. Management 7:1–4
22. Mohan GR et al (2013) Comparison of two stage mesophilic and thermophilic anaerobic digestion of OFMSW. In: George W (ed) Materials challenges in alternative and renewable energy II: ceramic transactions. Wiley-American Ceramic Society, Hoboken, NJ, pp 47–58
23. Tian Z, Mohan GR, Ingram L, Pullammanappallil P (2013) Anaerobic digestion for treatment of stillage from cellulosic bioethanol production. Bioresour Technol 144:387–395
24. Haruvy N (1997) Agricultural reuse of wastewater: nation-wide cost-benefit analysis. Agr Ecosyst Environ 66(2):113–119
25. Judd S (2010) The MBR book: principles and applications of membrane bioreactors for water and wastewater treatment. Elsevier, London
26. Sutton PM (2003) Membrane bioreactors for industrial wastewater treatment: the state-of-the-art based on full scale commercial applications. In: Proceedings of the Water Environment Federation, pp 23–32
27. Speth TF, Summers RS, Gusses AM (1998) Nanofiltration foulants from a treated surface water. Environ Sci Technol 32(22):3612–3617
28. Speth TF, Miltner RJ (1998) Technical note: adsorption capacity of GAC for synthetic organics. J Am Water Works Assoc 90(4):171–174
29. Ernst M et al (2007) An integrated wastewater treatment and reuse concept for the Olympic Park 2008, Beijing. Desalination 202(1):293–301
30. Angelakis A, Bontoux L, Lazarova V (2003) Challenges and prospectives for water recycling and reuse in EU countries. Water Supply 3(4):59–68
31. Lopez A (2013) The MEDIWAT Project. In: Final Conference and Stakeholders Event