ECONOMIC AND SOCIAL COMMISSION FOR WESTERN ASIA

WASTE-WATER TREATMENT TECHNOLOGIES: A GENERAL REVIEW

United Nations

Distr.
GENERAL
E/ESCWA/SDPD/2003/6
11 September 2003
ORIGINAL: ENGLISH/ARABIC

ECONOMIC AND SOCIAL COMMISSION FOR WESTERN ASIA

WASTE-WATER TREATMENT TECHNOLOGIES: A GENERAL REVIEW

United Nations
New York, 2003

03-0695

Foreword

Waste-water treatment is becoming ever more critical due to diminishing water resources, increasing waste-water disposal costs, and stricter discharge regulations that have lowered permissible contaminant levels in waste streams. The treatment of waste-water for reuse and disposal is particularly important for ESCWA countries, since they occupy one of the most arid regions in the world.

The municipal sector consumes significant volumes of water, and consequently generates considerable amounts of waste-water discharge. Municipal waste-water is a combination of water and water-carried wastes originating from homes, commercial and industrial facilities, and institutions. The present study comprises a comprehensive survey of the various methods and technologies currently used in waste-water treatment, with emphasis on municipal waste-water.

The study also addresses the management of treated effluents, including approaches to their reuse and disposal. Case studies of selected ESCWA member countries are presented, highlighting their prevalent water usage, and hence their need for efficient waste-water treatment systems. By incorporating state-of-the-art methodologies into their waste-water treatment facilities, ESCWA member countries can significantly reduce water consumption and cut treatment and disposal costs. Studying the economics of different waste-water treatments is an essential pre-requisite to the identification of cost-effective solutions. This study devotes an entire chapter to comparison of the costs associated with the installation and operation of waste-water treatment facilities.

CONTENTS

Page

CONTENTS (*continued*)

Page

LIST OF TABLES

CONTENTS (*continued*)

Page

LIST OF FIGURES

CONTENTS (*continued*)

Page

LIST OF BOXES

LIST OF ANNEXES

ABBREVIATIONS AND ACRONYMS

AACE	American Association of Cost Engineers
$Al_2(SO_4)_3.14.3(H_2O)$	Alum
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
BOD	biochemical oxygen demand
$Ca(OH)_2$	lime
CH_4	methane
Cl_2, H_2O_2, O_3	chlorine
COD	chemical oxygen demand
DO	dissolved oxygen
EC	equipment cost
EC EDR	European Community Environmental Directive Requirements
ENR	Engineering News Record
EPA	Environmental Protection Agency
F/M	food to micro-organisms ratio
$Fe_2(SO_4)_3$	ferric sulfate
$FeCl_3.6H_2O$	ferric chloride
$FeSO_4.7H_2O$	ferrous sulfate
ft	foot
GAC	granular activated carbon
GCC	Gulf Cooperation Council
gfd	gallon per square foot per day
H_2S	hydrogen sulfide
ha	hectare
HRT	hydraulic retention time
IX	ion exchange
KOH	potassium hydroxide
MF	microfiltration
mgd	million of gallons per day
MLSS	mixed liquor suspended solids
MWTP	Municipal waste-water treatment plant
N	nitrogen
$Na_2S_2O_5$	sodium metabisulfite
Na_2SO_3	sodium sulfite
NaOH	sodium hydroxide
NF	nanofiltration
NGO	non-governmental organization
NPDES	national pollutant discharge elimination system
NTS	natural treatment system
O&M	operation and maintenance
OF	overflow
ORP	oxidation-reduction potential
P	phosphorus
P_2O_7	polyphosphate
PAC	powered activated carbon
PO_4^{-3}	orthophosphate
PVC	polyvinyl chloride
POTWs	publicly owned treatment works
RBC	rotating biological contactor
RI	rapid infiltration
RO	reverse osmosis
SBR	sequencing batch reactor
SCADA	Supervisory control and data acquisition
SO_2	sulfur dioxide

ABBREVIATIONS AND ACRONYMS (*continued*)

SR	slow rate
SRT	solids retention time
SS	suspended solids
TCC	total construction costs
TIC	total indirect cost
TOC	total organic carbon
TOD	total oxygen demand
TSS	total dissolved solids
UF	ultrafiltration
UNEP	United Nations Environment Programme
USAID	United States Agency for International Development
USEPA	United States Environmental Protection Agency
UV	ultraviolet
WaTER	Water Treatment Estimation Routine
WEF	Water Environment Federation
WWTP	Waste-water treatment plant

Introduction

Municipal waste-water is the combination of liquid or water-carried wastes originating in the sanitary conveniences of dwellings, commercial or industrial facilities and institutions, in addition to any groundwater, surface water and storm water that may be present.

Untreated waste-water generally contains high levels of organic material, numerous pathogenic micro-organisms, as well as nutrients and toxic compounds. It thus entails environmental and health hazards, and, consequently, must immediately be conveyed away from its generation sources and treated appropriately before final disposal. The ultimate goal of waste-water management is the protection of the environment in a manner commensurate with public health and socio-economic concerns.[1]

Due to the largely arid nature of the ESCWA member countries, waste-water treatment is of particular concern to them. The first chapter of this study identifies and briefly describes typical contaminants found in municipal waste-water. Chapter 2 extensively illustrates various waste-water treatment technologies. Technical details on treatment methods and applications and sludge disposal are presented. chapter 3 goes on to discuss the management of treated effluents and how they are reused and disposed of. Devices and techniques used for instrumentation and control in waste-water treatment facilities are covered in chapter 4. Chapter 5 is concerned with the economics of waste-water treatment, with details on installation and operation costs for several treatment methods. Case studies on selected ESCWA member countries (Egypt, Jordan, Kuwait, Lebanon and Yemen) are presented in chapter 6. The case studies outline the current status of each country with respect to its waste-water treatment efforts and look at its future plans for the development of waste-water treatment facilities. Finally, chapter 7 contains a number of recommendations, emphasizing in particular that more efforts are needed in the ESCWA region for the improvement of water reuse through an integrated, multi-disciplinary water management strategy.

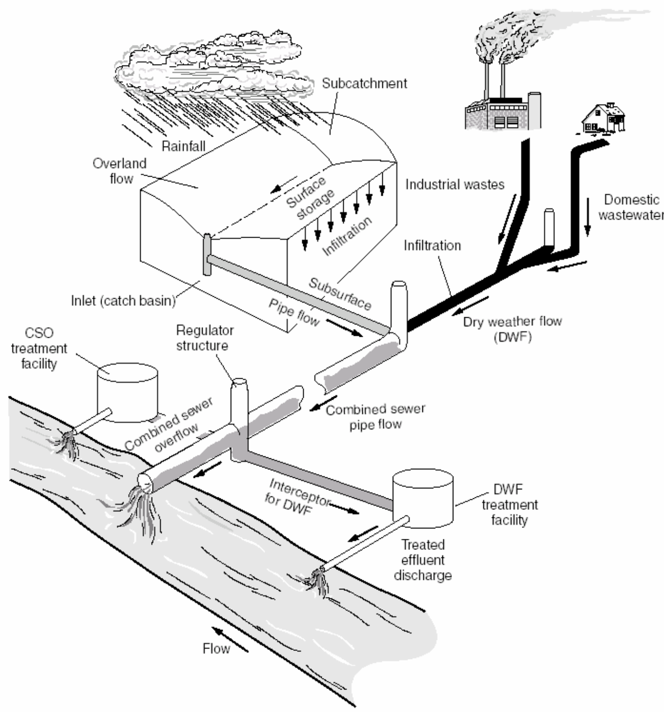
---

[1] Metcalf and Eddy, Inc., *Wastewater Engineering: Treatment, Disposal and Reuse*, third edition (New York: McGraw-Hill, 1991).

I. NATURE OF MUNICIPAL WASTE-WATER

An understanding of the nature of waste-water is fundamental for the design of appropriate waste-water treatment plants and the selection of effective treatment technologies. Waste-water originates predominantly from water usage by residences and commercial and industrial establishments, together with groundwater, surface water and storm water (see figure 1). Consequently, waste-water flow fluctuates with variations in water usage, which is affected by a multitude of factors including climate, community size, living standards, dependability and quality of water supply, water conservation requirements or practices, and the extent of meter services, in addition to the degree of industrialization, cost of water and supply pressure. Wide variations in waste-water flow rates may thus be expected to occur within a community (see table 1).

Figure 1. Sources of waste-water



Source: Metcalf and Eddy, Inc., *Wastewater Engineering, Treatment and Reuse*, fourth edition (New York: McGraw-Hill, 2003).

TABLE 1. VARIATIONS IN WASTE-WATER FLOW WITHIN A COMMUNITY

Community size (population)	Variation in waste-water flow (percentage of the average daily flow rate)
1 000	20-400
1 000-10 000	50-300
10 000-100 000	Up to 200

Source: Adapted from D.H.F. Liu and B.G. Lipták, *Wastewater Treatment* (Boca Raton: Lewis, 1999).

Waste-water quality may be defined by its physical, chemical, and biological characteristics. Physical parameters include colour, odour, temperature, and turbidity. Insoluble contents such as solids, oil and grease, also fall into this category. Solids may be further subdivided into suspended and dissolved solids as well as organic (volatile) and inorganic (fixed) fractions.

Chemical parameters associated with the organic content of waste-water include biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), and total oxygen demand (TOD). Inorganic chemical parameters include salinity, hardness, pH, acidity and alkalinity, as well as concentrations of ionized metals such as iron and manganese, and anionic entities such as chlorides, sulfates, sulfides, nitrates and phosphates. Bacteriological parameters include coliforms, fecal coliforms, specific pathogens, and viruses. Both constituents and concentrations vary with time and local conditions. Table 2 shows typical concentration ranges for various constituents in untreated domestic waste-water. Waste-water is classified as strong, medium or weak, depending on its contaminant concentration.

TABLE 2. TYPICAL COMPOSITION OF UNTREATED DOMESTIC WASTE-WATER

Contaminants	Unit	Concentration		
		Weak	Medium	Strong
Total solids (TS)	mg/L	350	720	1 200
Total dissolved solids (TDS)	mg/L	250	500	850
Fixed	mg/L	145	300	525
Volatile	mg/L	105	200	325
Suspended solids	mg/L	100	220	350
Fixed	mg/L	20	55	75
Volatile	mg/L	80	165	275
Settleable solids	mL/L	5	10	20
BOD_5, 20ºC	mg/L	110	220	400
TOC	mg/L	80	160	290
COD	mg/L	250	500	1 000
Nitrogen (total as N)	mg/L	20	40	85
Organic	mg/L	8	15	35
Free ammonia	mg/L	12	25	50
Nitrites	mg/L	0	0	0
Nitrates	mg/L	0	0	0
Phosphorus (total as P)	mg/L	4	8	15
Organic	mg/L	1	3	5
Inorganic	mg/L	3	5	10
Chlorides	mg/L	30	50	100
Sulfate	mg/L	20	30	50
Alkalinity (as $CaCO_3$)	mg/L	50	100	200
Grease	mg/L	50	100	150
Total coliforms	No/100 ml	10^6-10^7	10^7-10^8	10^7-10^9
Volatile organic compounds	μg/L	<100	100-400	>400

Source: Adapted from Metcalf and Eddy Inc., *Wastewater Engineering*, 3rd edition.

The effects of the discharge of untreated waste-water into the environment are manifold and depend on the types and concentrations of pollutants. Important contaminants in terms of their potential effects on receiving waters and treatment concerns are outlined in table 3.

TABLE 3. IMPORTANT CONTAMINANTS IN WASTE-WATER

Contaminants	Reason for importance
Suspended solids (SS) can lead to development of sludge deposits and anaerobic conditions when untreated waste-water is discharged to the aquatic environment.	
Biodegradable organics are principally made up of proteins, carbohydrates and fats. They are commonly measured in terms of BOD and COD. If discharged into inland rivers, streams or lakes, their biological stabilization can deplete natural oxygen resources and cause septic conditions that are detrimental to aquatic species.	
Pathogenic organisms found in waste-water can cause infectious diseases.	
Priority pollutants, including organic and inorganic compounds, may be highly toxic, carcinogenic, mutagenic or teratogenic.	
Refractory organics that tend to resist conventional waste-water treatment include surfactants, phenols and agricultural pesticides.	
Heavy metals usually added by commercial and industrial activities must be removed for reuse of the waste-water.	
Dissolved inorganic constituents such as calcium, sodium and sulfate are often initially added to domestic water supplies, and may have to be removed for waste-water reuse.	

Source: Adapted from Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

II. WASTE-WATER TREATMENT TECHNOLOGIES

Physical, chemical and biological methods are used to remove contaminants from waste-water. In order to achieve different levels of contaminant removal, individual waste-water treatment procedures are combined into a variety of systems, classified as primary, secondary, and tertiary waste-water treatment. More rigorous treatment of waste-water includes the removal of specific contaminants as well as the removal and control of nutrients. Natural systems are also used for the treatment of waste-water in land-based applications. Sludge resulting from waste-water treatment operations is treated by various methods in order to reduce its water and organic content and make it suitable for final disposal and reuse. This chapter describes the various conventional and advanced technologies in current use and explains how they are applied for the effective treatment of municipal waste-water.

A. WASTE-WATER TREATMENT METHODS

As mentioned earlier, waste-water treatment methods are broadly classifiable into physical, chemical and biological processes. Figure 2 lists the unit operations included within each category.

Figure 2. Waste-water treatment unit operations and processes

Physical unit operations	⇨	❑ Screening ❑ Comminution ❑ Flow equalization ❑ Sedimentation ❑ Flotation ❑ Granular-medium filtration
Chemical unit operations	⇨	❑ Chemical precipitation ❑ Adsorption ❑ Disinfection ❑ Dechlorination ❑ Other chemical applications
Biological unit operations	⇨	❑ Activated sludge process ❑ Aerated lagoon ❑ Trickling filters ❑ Rotating biological contactors ❑ Pond stabilization ❑ Anaerobic digestion ❑ Biological nutrient removal

1. *Physical unit operations*

Among the first treatment methods used were physical unit operations, in which physical forces are applied to remove contaminants. Today, they still form the basis of most process flow systems for waste-water treatment. This section briefly discusses the most commonly used physical unit operations.

(a) *Screening*

The screening of waste-water, one of the oldest treatment methods, removes gross pollutants from the waste stream to protect downstream equipment from damage, avoid interference with plant operations and prevent objectionable floating material from entering the primary settling tanks. Screening devices may consist of parallel bars, rods or wires, grating, wire mesh, or perforated plates, to intercept large floating or suspended material. The openings may be of any shape, but are generally circular or rectangular.[2] The material retained from the manual or mechanical cleaning of bar racks and screens is referred to as "screenings", and is either disposed of by burial or incineration, or returned into the waste flow after grinding.[2,3] The principal types of screening devices are listed in table 4.

TABLE 4. SCREEN TYPES

Screen category	Size of openings (millimeters)	Application	Types of screens
Coarse screens	≥ 6	Remove large solids, rags, and debris.	▪ Manually cleaned bar screens/trash racks ▪ Mechanically cleaned bar screens/trash racks o Chain or cable driven with front or back cleaning o Reciprocating rake screens o Catenary screens o Continuous self-cleaning screens
Fine screens	1.5-6	Reduce suspended solids to primary treatment levels	▪ Rotary-drum screens ▪ Rotary-drum screens with outward or inward flow ▪ Rotary-vertical-disk screens ▪ Inclined revolving disc screens ▪ Traveling water screens ▪ Endless band screen ▪ Vibrating screens
Very fine screens	0.2-1.5	Reduce suspended solids to primary treatment levels	
Microscreens	0.001-0.3	Upgrade secondary effluent to tertiary standards	

Sources: Adapted from Liu and Lipták, *Wastewater Treatment*, and Water Environment Federation (WEF) and American Society of Civil Engineers (ASCE), *Design of Municipal Wastewater Treatment plants (Volume 1)*, WEF Manual of Practice No. 8 and ASCE Manual and Report on Engineering Practice No. 76 (Vermont: Book Press Inc., 1992).

The coarse screen category includes manually or mechanically cleaned bar screens and trash racks. Bar screens consist of vertical or inclined steel bars distributed equally across a channel through which waste-water flows. They are used ahead of mechanical equipment including raw sewage pumps, grit chambers, and primary sedimentation tanks. Trash racks, for their part, are constructed of parallel rectangular or round steel bars with clear openings. They are usually followed by regular bar screens or comminutors. Criteria used in the design of coarse screens include bar size, spacing, and angle from the vertical, as well as channel width and waste-water approach velocity.[3]

Fine screens consist of various types of screen media, including slotted perforated plates, wire mesh, woven wire cloth and wedge-shaped wire. Due to their tiny openings, fine screens must be cleaned continuously by means of brushes, scrapers, or jets of water, steam, or air forced through the reverse side of the openings. The efficiency of a fine screen depends on the fineness of the openings as well as the sewage flow velocity through those openings.[4]

---

[2] Metcalf and Eddy, Inc., *Waste-water Engineering*, 3rd edition.

[3] Water Environment Federation (WEF) and American Society of Civil Engineers (ASCE), *Design of Municipal Wastewater Treatment Plants*.

[4] Liu and Lipták, *Wastewater Treatment*.

(b) *Comminution*

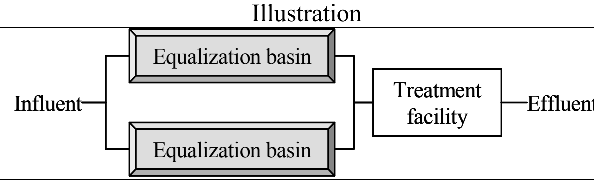
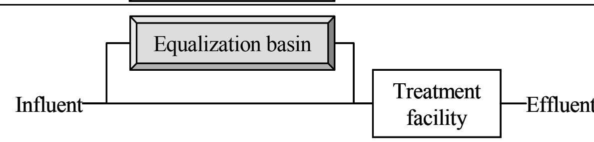
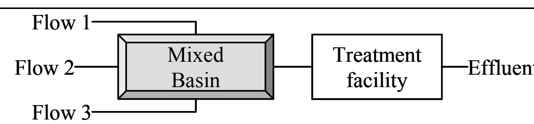
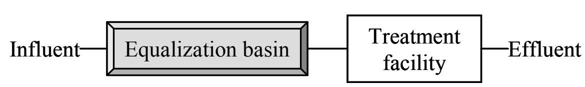
Comminutors are used to pulverize large floating material in the waste flow. They are installed where the handling of screenings would be impractical, generally between the grit chamber and the primary settling tanks. Their use reduces odours, flies and unsightliness. A comminutor may have either rotating or oscillating cutters. Rotating-cutter comminutors either engage a separate stationary screen alongside the cutters, or a combined screen and cutter rotating together. A different type of comminutor, known as a barminutor, involves a combination of a bar screen and rotating cutters.[5]

(c) *Flow equalization*

Flow equalization is a technique used to improve the effectiveness of secondary and advanced waste-water treatment processes by levelling out operation parameters such as flow, pollutant levels and temperature over a period of time. Variations are damped until a near-constant flow rate is achieved, minimizing the downstream effects of these parameters.

Flow equalization may be applied at a number of locations within a waste-water treatment plant, e.g. near the head end of the treatment works, prior to discharge into a water body, and prior to advanced waste treatment operations.[5] There are four basic flow equalization processes that are summarized in table 5.

TABLE 5. BASIC FLOW EQUALIZATION PROCESSES

<table>
<tr><th>Process</th><th>Description</th><th>Illustration</th></tr>
<tr><td>Alternating flow diversion</td><td>Two basins alternating between filling and discharging for successive time periods.</td><td>
</td></tr>
<tr><td>Intermittent flow diversion</td><td>An equalization basin to which a significant increase in flow is diverted. The diverted flow is then fed into the system at a controlled rate.</td><td>
</td></tr>
<tr><td>Completely mixed, combined flow</td><td>A basin that completely mixes multiple flows at the front end of the treatment process</td><td>
</td></tr>
<tr><td>Completely mixed, mixed flow</td><td>A large, completely mixed, holding basin located before the waste-water facility, levelling parameters in influent stream and providing a constant discharge.</td><td>
</td></tr>
</table>

Source: Adapted from Liu and Lipták, *Wastewater Treatment*.

(d) *Sedimentation*

Sedimentation, a fundamental and widely used unit operation in waste-water treatment, involves the gravitational settling of heavy particles suspended in a mixture. This process is used for the removal of grit, particulate matter in the primary settling basin, biological floc in the activated sludge settling basin, and chemical flow when the chemical coagulation process is used.

[5] Ibid.

Sedimentation takes place in a settling tank, also referred to as a clarifier. There are three main designs, namely, horizontal flow, solids contact and inclined surface.[6] In designing a sedimentation basin, it is important to bear in mind that the system must produce both a clarified effluent and a concentrated sludge. Four types of settling occur, depending on particle concentration: discrete, flocculent, hindered and compression. It is common for more than one type of settling to occur during a sedimentation operation.

(i) *Horizontal flow*

Horizontal-flow clarifiers may be rectangular, square or circular in shape (see figure 3). The flow in rectangular basins is rectilinear and parallel to the long axis of the basin, whereas in centre-feed circular basins, the water flows radially from the centre towards the outer edges. Both types of basins are designed to keep the velocity and flow distributions as uniform as possible in order to prevent currents and eddies from forming, and thereby keep the suspended material from settling. Basins are usually made of steel or reinforced concrete. The bottom surface slopes slightly to facilitate sludge removal. In rectangular tanks, the slope is towards the inlet end, while in circular and square tanks, the bottom is conical and slopes towards the centre of the basin.

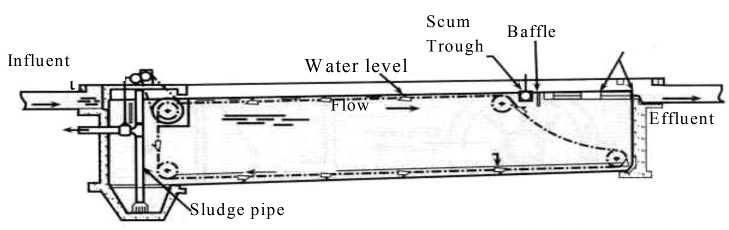
(ii) *Solid contact clarifiers*

Solid contact clarifiers bring incoming solids into contact with a suspended layer of sludge near the bottom that acts as a blanket. The incoming solids agglomerate and remain enmeshed within the sludge blanket, whereby the liquid is able to rise upwards while the solids are retained below.

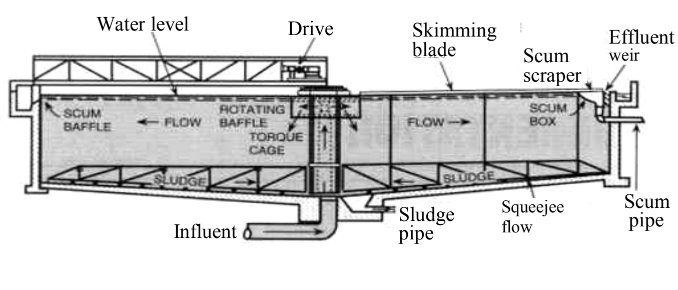
(iii) *Inclined surface basins*

Inclined surface basins, also known as high-rate settlers, use inclined trays to divide the depth into shallower sections, thus reducing particle settling times. They also provide a larger surface area, so that a smaller-sized clarifier can be used. Many overloaded horizontal flow clarifiers have been upgraded to inclined surface basins. Here, the flow is laminar, and there is no wind effect.

Figure 3. Settling basin with horizontal flow



(a) Parts of a rectangular basin



(b) Parts of circular tank

Source: Adapted from Liu and Lipták, *Wastewater Treatment*.

6 Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

(e) *Flotation*

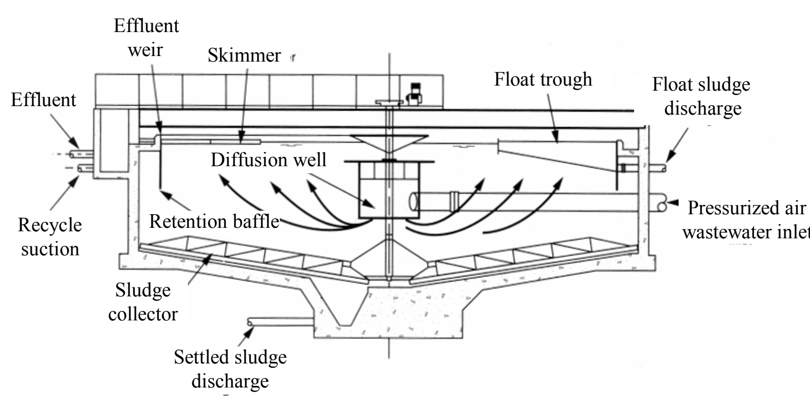
Flotation is a unit operation used to remove solid or liquid particles from a liquid phase by introducing a fine gas, usually air bubbles. The gas bubbles either adhere to the liquid or are trapped in the particle structure of the suspended solids, raising the buoyant force of the combined particle and gas bubbles. Particles that have a higher density than the liquid can thus be made to rise. In waste-water treatment, flotation is used mainly to remove suspended matter and to concentrate biological sludge. The chief advantage of flotation over sedimentation is that very small or light particles can be removed more completely and in a shorter time. Once the particles have been floated to the surface, they can be skimmed out. Flotation, as currently practised in municipal waste-water treatment, uses air exclusively as the floating agent. Furthermore, various chemical additives can be introduced to enhance the removal process.[7] The various flotation methods are described in table 6, while a typical flotation unit is illustrated in figure 4.

TABLE 6. FLOTATION METHODS

Process	Description
Dissolved-air flotation	The injection of air while waste-water is under the pressure of several atmospheres. After a short holding time, the pressure is restored to atmospheric level, allowing the air to be released as minute bubbles.
Air flotation	The introduction of gas into the liquid phase directly by means of a revolving impeller or through diffusers, at atmospheric pressure.
Vacuum flotation	The saturation of waste-water with air either directly in an aeration tank or by permitting air to enter on the suction side of a waste-water pump. A partial vacuum is applied, causing the dissolved air to come out of solution as minute bubbles which rise with the attached solids to the surface, where they form a scum blanket. The scum is removed by a skimming mechanism while the settled grit is raked to a central sump for removal.
Chemical additives	Chemicals further the flotation process by creating a surface that can easily adsorb or entrap air bubbles. Inorganic chemicals (aluminum and ferric salts and activated silica) and various organic polymers can be used for this purpose.

Source: Adapted from Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

Figure 4. Typical flotation unit



Source: Adapted from Liu and Lipták, *Wastewater Treatment*.

[7] Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

(f) *Granular medium filtration*

The filtration of effluents from waste-water treatment processes is a relatively recent practice, but has come to be widely used for the supplemental removal of suspended solids from waste-water effluents of biological and chemical treatment processes, in addition to the removal of chemically precipitated phosphorus. The complete filtration operation comprises two phases: filtration and cleaning or backwashing. The waste-water to be filtered is passed through a filter bed consisting of granular material (sand, anthracite and/or garnet), with or without added chemicals. Within the filter bed, suspended solids contained in the waste-water are removed by means of a complex process involving one or more removal mechanisms such as straining, interception, impaction, sedimentation, flocculation and adsorption. The phenomena that occur during the filtration phase are basically the same for all types of filters used for waste-water filtration. The cleaning/backwashing phase differs, depending on whether the filter operation is continuous or semi-continuous. In semi-continuous filtration, the filtering and cleaning operations occur sequentially, whereas in continuous filtration the filtering and cleaning operations occur simultaneously.[8] The operational characteristics of the various forms of granular medium filters commonly used for waste-water filtration are illustrated in annex figure 1 and reported in annex table 1 (see annex I).

2. *Chemical unit processes*

Chemical processes used in waste-water treatment are designed to bring about some form of change by means of chemical reactions. They are always used in conjunction with physical unit operations and biological processes. In general, chemical unit processes have an inherent disadvantage compared to physical operations in that they are additive processes. That is to say, there is usually a net increase in the dissolved constituents of the waste-water. This can be a significant factor if the waste-water is to be reused. This section discusses the main chemical unit processes, including chemical precipitation, adsorption, disinfection, dechlorination and other applications.

(a) *Chemical precipitation*

Chemical coagulation of raw waste-water before sedimentation promotes the flocculation of finely divided solids into more readily settleable flocs, thereby enhancing the efficiency of suspended solid, BOD_5 and phosphorus removal as compared to plain sedimentation without coagulation (see table 7). The degree of clarification obtained depends on the quantity of chemicals used and the care with which the process is controlled.[9]

TABLE 7. REMOVAL EFFICIENCY OF PLAIN SEDIMENTATION VS. CHEMICAL PRECIPITATION

Parameter	Percentage removal: Plain sedimentation	Percentage removal: Chemical precipitation
Total suspended solids (TSS)	40-90	60-90
BOD_5	25-40	40-70
COD		30-60
Phosphorus	5-10	70-90
Bacteria loadings	50-60	80-90

Source: WEF and ASCE, *Design of Municipal Wastewater Treatment Plants*.

Coagulant selection for enhanced sedimentation is based on performance, reliability and cost. Performance evaluation uses jar tests of the actual waste-water to determine dosages and effectiveness. Chemical coagulants that are commonly used in waste-water treatment include alum ($Al_2(SO_4)_3.14.3\ H_2O$),

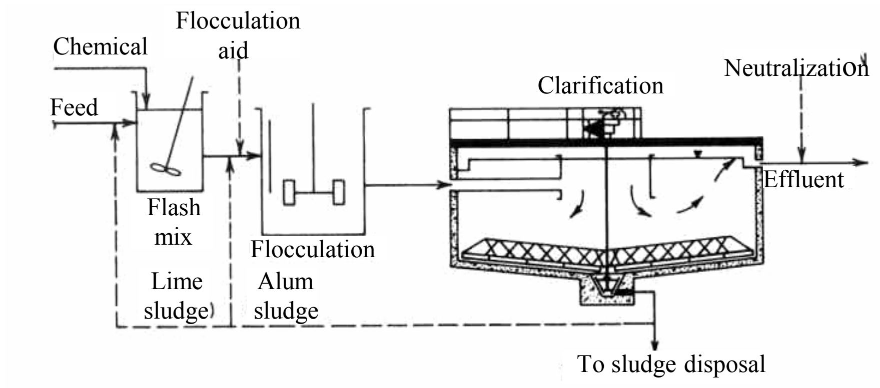
[8] Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

[9] Ibid.

ferric chloride ($FeCl_3.6H_2O$), ferric sulfate ($Fe_2(SO_4)_3$), ferrous sulfate ($FeSO_4.7H_2O$) and lime ($Ca(OH)_2$). Organic polyelectrolytes are sometimes used as flocculation aids.[10]

Suspended solids removal through chemical treatment involves a series of three unit operations: rapid mixing, flocculation and settling. First, the chemical is added and completely dispersed throughout the waste-water by rapid mixing for 20-30 seconds in a basin with a turbine mixer. Coagulated particles are then brought together via flocculation by mechanically inducing velocity gradients within the liquid. Flocculation takes 15 to 30 minutes in a basin containing turbine or paddle-type mixers.[11] The final step is clarification by gravity as discussed in section 0. A once-through chemical treatment system is illustrated in figure 5.

Figure 5. A once-through chemical treatment system



Source: Adapted from Liu and Lipták, *Wastewater Treatment*.

The advantages of coagulation include greater removal efficiency, the feasibility of using higher overflow rates, and more consistent performance. On the other hand, coagulation results in a larger mass of primary sludge that is often more difficult to thicken and dewater. It also entails higher operational costs and demands greater attention on the part of the operator.

(b) *Adsorption with activated carbon*

Adsorption is the process of collecting soluble substances within a solution on a suitable interface. In waste-water treatment, adsorption with activated carbon—a solid interface—usually follows normal biological treatment, and is aimed at removing a portion of the remaining dissolved organic matter. Particulate matter present in the water may also be removed. Activated carbon is produced by heating char to a high temperature and then activating it by exposure to an oxidizing gas at high temperature. The gas develops a porous structure in the char and thus creates a large internal surface area. The activated char can then be separated into various sizes with different adsorption capacities. The two most common types of activated carbon are granular activated carbon (GAC), which has a diameter greater than 0.1 mm, and powdered activated carbon (PAC), which has a diameter of less than 200 mesh.[12]

A fixed-bed column is often used to bring the waste-water into contact with GAC. The water is applied to the top of the column and withdrawn from the bottom, while the carbon is held in place. Backwashing and surface washing are applied to limit headloss build-up. A schematic of an activated carbon contactor is shown in figure 6. Expanded-bed and moving-bed carbon contactors have been developed to

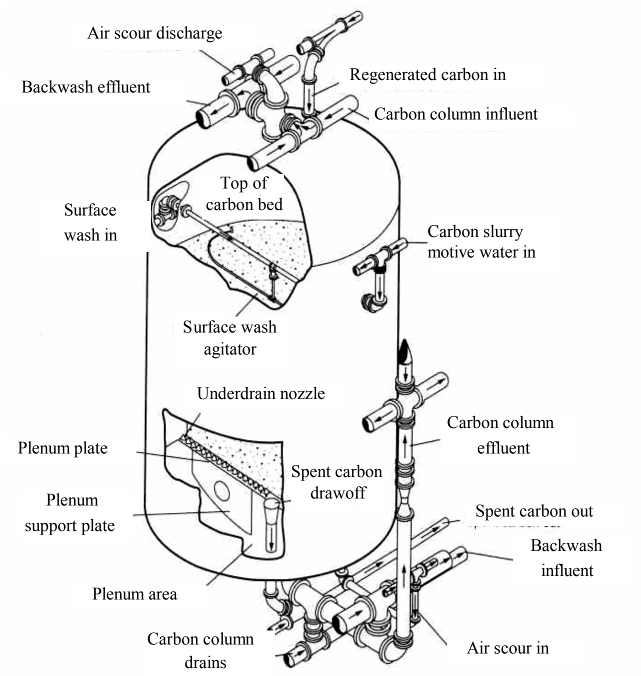
[10] WEF and ASCE, *Design of Municipal Wastewater Treatment Plants*.

[11] Liu and Lipták, *Wastewater Treatment*.

[12] Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

overcome the problem of headloss build-up. In the expanded-bed system, the influent is introduced at the bottom of the column and is allowed to expand. In the moving-bed system, spent carbon is continuously replaced with fresh carbon. Spent granular carbon can be regenerated by removal of the adsorbed organic matter from its surface through oxidation in a furnace. The capacity of the regenerated carbon is slightly less than that of the virgin carbon.

Figure 6. A typical granular activated carbon contactor



Source: Metcalf and Eddy, *Wastewater Engineering*, 3rd edition.

Waste-water treatment using PAC involves the addition of the powder directly to the biological treatment effluent or the physiochemical treatment process, as the case may be. PAC is usually added to waste-water in a contacting basin for a certain length of time. It is then allowed to settle to the bottom of the tank and removed. Removal of the powdered carbon may be facilitated by the addition of polyelectrolyte coagulants or filtration through granular-medium filters. A major problem with the use of powdered activated carbon is that the methodology for its regeneration is not well defined.

(c) *Disinfection*

Disinfection refers to the selective destruction of disease-causing micro-organisms. This process is of importance in waste-water treatment owing to the nature of waste-water, which harbours a number of human enteric organisms that are associated with various waterborne diseases. Commonly used means of disinfection include the following:

(i) Physical agents such as heat and light;

(ii) Mechanical means such as screening, sedimentation, filtration, and so on;

(iii) Radiation, mainly gamma rays;

(iv) Chemical agents including chlorine and its compounds, bromine, iodine, ozone, phenol and phenolic compounds, alcohols, heavy metals, dyes, soaps and synthetic detergents, quaternary ammonium compounds, hydrogen peroxide, and various alkalis and acids. The most common chemical disinfectants are the oxidizing chemicals, and of these, chlorine is the most widely used.[13]

TABLE 8. CHARACTERISTICS OF COMMON DISINFECTING AGENTS

Characteristic	Chlorine	Sodium hypochlorite	Calcium hypochlorite	Chlorine dioxide	Bromine chloride	Ozone	Ultraviolet light
Chemical formula	Cl_2	NaOCl	$Ca(OCl)_2$	ClO_2	BrCl	O_3	N/A
Form	Liquid, gas	Solution	Powder, pellets or 1 per cent solution	Gas	Liquid	Gas	UV energy
Toxicity to micro-organisms	High	High	High	High	High	High	High
Solubility	Slight	High	High	High	Slight	High	N/A
Stability	Stable	Slightly unstable	Relatively stable	Unstable, must be generated as used	Slightly unstable	Unstable, must be generated as used	Must be generated as used
Toxicity to higher forms of life	Highly toxic	Toxic	Toxic	Toxic	Toxic	Toxic	Toxic
Effect at ambient temperature	High	High	High	High	High	High	High
Penetration	High	High	High	High	High	High	Moderate
Corrosiveness	Highly corrosive	Corrosive	Corrosive	Highly corrosive	Corrosive	Highly corrosive	N/A
Deodorizing ability	High	Moderate	Moderate	High	Moderate	High	None
Availability/cost	Low cost	Moderately low cost	Moderately low cost	Moderately low cost	Moderately low cost	Moderately high cost	Moderately high cost

Sources: Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition, and Qasim, *Wastewater Treatment Plants*.

Disinfectants act through one or more of a number of mechanisms, including damaging the cell wall, altering cell permeability, altering the colloidal nature of the protoplasm and inhibiting enzyme activity. In applying disinfecting agents, several factors need to be considered: contact time, concentration and type of chemical agent, intensity and nature of physical agent, temperature, number of organisms, and nature of suspending liquid.[14] Table 8 shows the most commonly used disinfectants and their effectiveness.

(d) *Dechlorination*

Dechlorination is the removal of free and total combined chlorine residue from chlorinated waste-water effluent before its reuse or discharge to receiving waters. Chlorine compounds react with many organic compounds in the effluent to produce undesired toxic compounds that cause long-term adverse impacts on the water environment and potentially toxic effects on aquatic micro-organisms. Dechlorination may be brought about by the use of activated carbon, or by the addition of a reducing agent such as sulfur dioxide (SO_2), sodium sulfite (Na_2SO_3) or sodium metabisulfite ($Na_2S_2O_5$). It is important to note that dechlorination will not remove toxic by-products that have already been produced.[15]

[13] S.R. Qasim, *Wastewater Treatment Plants: Planning, Design, and Operation* (Lancaster, Pennsylvania: Technomic Publishing Company, 1999).

[14] Qasim, *Wastewater Treatment Plants* and Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

[15] Qasim, *Wastewater Treatment Plants*.

(e) *Other chemical applications*

In addition to the chemical processes described above, various other applications are occasionally encountered in waste-water treatment and disposal. Table 9 lists the most common applications and the chemicals used.

TABLE 9. OTHER CHEMICAL APPLICATIONS IN WASTE-WATER TREATMENT AND DISPOSAL

Application	Chemical used	Remarks
Treatment		
Grease removal	Cl_2	Added before preaeration
BOD reduction	Cl_2, O_3	Oxidation of organic substances
pH control	KOH, NaOH, $Ca(OH)_2$	
Ferrous sulfate oxidation	Cl_2	Production of ferric sulfate and ferric chloride
Filter - ponding control	Cl_2	Residual at filter nozzles
Filter - fly control	Cl_2	Residual at filter nozzles, used during fly season
Sludge-bulking control	Cl_2, H_2O_2, O_3	Temporary control measure
Digester supernatant oxidation	Cl_2	
Digester and Imhoff tank foaming control	Cl_2	
Ammonia oxidation	Cl_2	Conversion of ammonia to nitrogen gas
Odour control	Cl_2, H_2O_2, O_3	
Oxidation of refractory organic compounds	O_3	
Disposal		
Bacterial reduction	Cl_2, H_2O_2, O_3	Plant effluent, overflows, and stormwater
Odour control	Cl_2, H_2O_2, O_3	

Source: Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

3. *Biological unit processes*

Biological unit processes are used to convert the finely divided and dissolved organic matter in waste-water into flocculent settleable organic and inorganic solids. In these processes, micro-organisms, particularly bacteria, convert the colloidal and dissolved carbonaceous organic matter into various gases and into cell tissue which is then removed in sedimentation tanks. Biological processes are usually used in conjunction with physical and chemical processes, with the main objective of reducing the organic content (measured as BOD, TOC or COD) and nutrient content (notably nitrogen and phosphorus) of waste-water. Biological processes used for waste-water treatment may be classified under five major headings:

(a) Aerobic processes;
(b) Anoxic processes;
(c) Anaerobic processes;
(d) Combined processes;
(e) Pond processes.

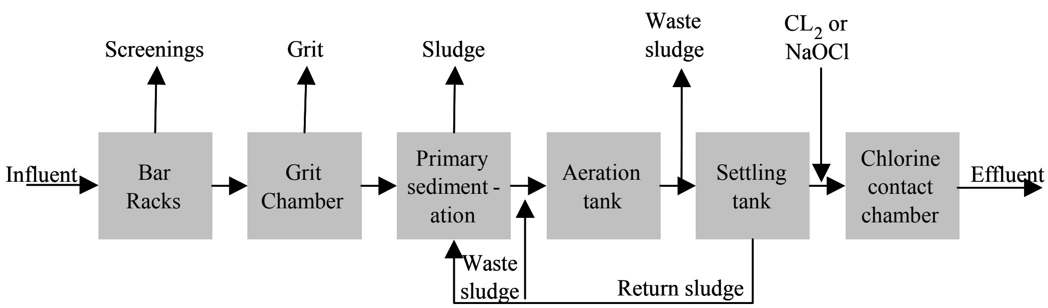
These processes are further subdivided, depending on whether the treatment takes place in a suspended-growth system an attached-growth system or a combination of both (see annex table 2). This section will be concerned with the most commonly used biological processes, including trickling filters, the activated sludge process, aerated lagoons, rotating biological contactors and stabilization ponds.

(a) *Activated-sludge process*

The activated-sludge process is an aerobic, continuous-flow system containing a mass of activated micro-organisms that are capable of stabilizing organic matter. The process consists of delivering clarified waste-water, after primary settling, into an aeration basin where it is mixed with an active mass of micro-organisms, mainly bacteria and protozoa, which aerobically degrade organic matter into carbon dioxide, water, new cells, and other end products. The bacteria involved in activated sludge systems are primarily

Gram-negative species, including carbon oxidizers, nitrogen oxidizers, floc formers and non-floc formers, and aerobes and facultative anaerobes. The protozoa, for their part, include flagellates, amoebas and ciliates. An aerobic environment is maintained in the basin by means of diffused or mechanical aeration, which also serves to keep the contents of the reactor (or mixed liquor) completely mixed. After a specific retention time, the mixed liquor passes into the secondary clarifier, where the sludge is allowed to settle and a clarified effluent is produced for discharge. The process recycles a portion of the settled sludge back to the aeration basin to maintain the required activated sludge concentration (see figure 7). The process also intentionally wastes a portion of the settled sludge to maintain the required solids retention time (SRT) for effective organic removal.

Figure 7. Typical flow diagram for an activated-sludge process



Control of the activated-sludge process is important to maintain a high treatment performance level under a wide range of operating conditions. The principal factors in process control are the following:

(a) Maintenance of dissolved oxygen levels in the aeration tanks;
(b) Regulation of the amount of returning activated sludge;
(c) Control of the waste activated sludge.

The main operational problem encountered in a system of this kind is sludge bulking, which can be caused by the absence of phosphorus, nitrogen and trace elements and wide fluctuations in pH, temperature and dissolved oxygen (DO). Bulky sludge has poor settleability and compactibility due to the excessive growth of filamentous micro-organisms. This problem can be controlled by chlorination of the return sludge.[16,17] Annex table 3 presents a description of conventional activated-sludge processes and various modifications (see annex figure 2).

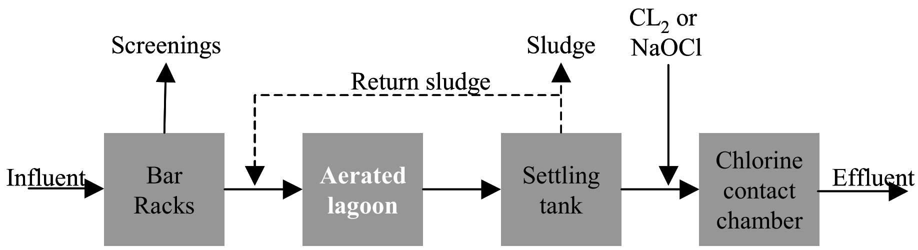
(b) *Aerated lagoons*

An aerated lagoon is a basin between 1 and 4 metres in depth in which waste-water is treated either on a flow-through basis or with solids recycling. The microbiology involved in this process is similar to that of the activated-sludge process. However, differences arise because the large surface area of a lagoon may cause more temperature effects than are ordinarily encountered in conventional activated-sludge processes. Waste-water is oxygenated by surface, turbine or diffused aeration. The turbulence created by aeration is used to keep the contents of the basin in suspension. Depending on the retention time, aerated lagoon effluent contains approximately one third to one half the incoming BOD value in the form of cellular mass. Most of these solids must be removed in a settling basin before final effluent discharge (see figure 8).

[16] Liu and Lipták, *Wastewater Treatment*.

[17] Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

Figure 8. Typical flow diagram for aerated lagoons

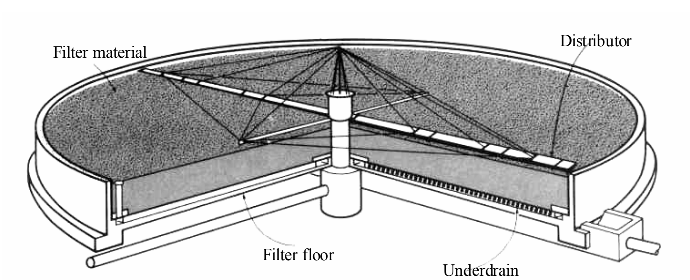


(c) *Trickling filters*

The trickling filter is the most commonly encountered aerobic attached-growth biological treatment process used for the removal of organic matter from waste-water. It consists of a bed of highly permeable medium to which organisms are attached, forming a biological slime layer, and through which waste-water is percolated. The filter medium usually consists of rock or plastic packing material. The organic material present in the waste-water is degraded by adsorption on to the biological slime layer. In the outer portion of that layer, it is degraded by aerobic micro-organisms. As the micro-organisms grow, the thickness of the slime layer increases and the oxygen is depleted before it has penetrated the full depth of the slime layer. An anaerobic environment is thus established near the surface of the filter medium. As the slime layer increases in thickness, the organic matter is degraded before it reaches the micro-organisms near the surface of the medium. Deprived of their external organic source of nourishment, these micro-organisms die and are washed off by the flowing liquid. A new slime layer grows in their place. This phenomenon is referred to as 'sloughing'.[18,19]

After passing through the filter, the treated liquid is collected in an underdrain system, together with any biological solids that have become detached from the medium (see figure 9). The collected liquid then passes to a settling tank where the solids are separated from the treated waste-water. A portion of the liquid collected in the underdrain system or the settled effluent is recycled to dilute the strength of the incoming waste-water and to maintain the biological slime layer in moist condition (see figure 10).

Figure 9. Cutaway view of a trickling filter

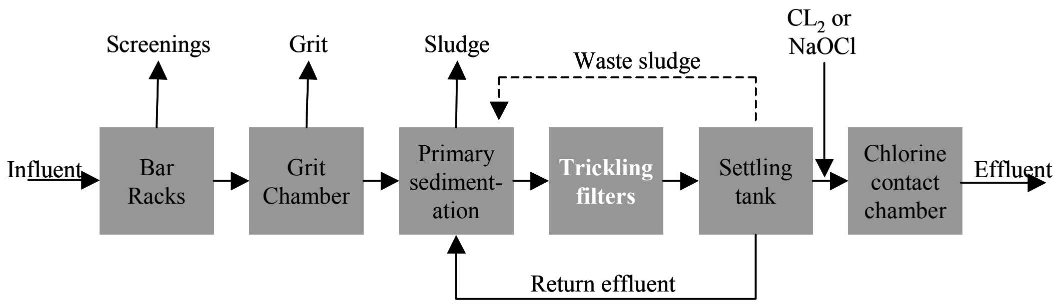


Source: Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

[18] Liu and Lipták, *Wastewater Treatment*.

[19] Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

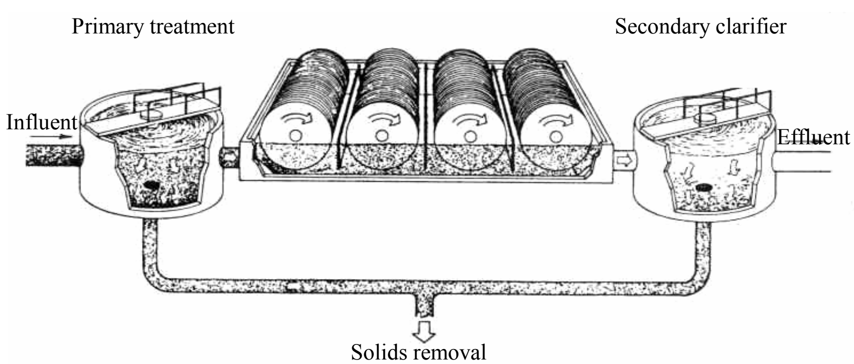
Figure 10. Typical flow diagram for trickling filters



(d) *Rotating biological contactors*

A rotating biological contractor (RBC) is an attached-growth biological process that consists of one or more basins in which large closely-spaced circular disks mounted on horizontal shafts rotate slowly through waste-water (see figure 11). The disks, which are made of high-density polystyrene or polyvinyl chloride (PVC), are partially submerged in the waste-water, so that a bacterial slime layer forms on their wetted surfaces. As the disks rotate, the bacteria are exposed alternately to waste-water, from which they adsorb organic matter, and to air, from which they absorb oxygen. The rotary movement also allows excess bacteria to be removed from the surfaces of the disks and maintains a suspension of sloughed biological solids. A final clarifier is needed to remove sloughed solids. Organic matter is degraded by means of mechanisms similar to those operating in the trickling filters process. Partially submerged RBCs are used for carbonaceous BOD removal, combined carbon oxidation and nitrification, and nitrification of secondary effluents. Completely submerged RBCs are used for denitrification.[20]

Figure 11. RBC system configuration

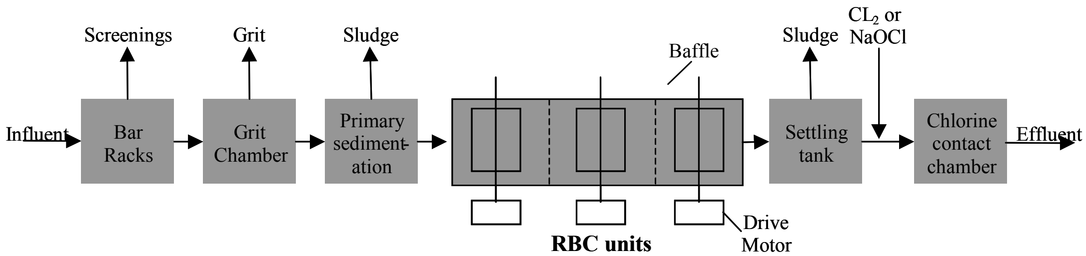


Source: Qasim, *Wastewater Treatment Plants*.

A typical arrangement of RBCs is shown in figure 12. In general, RBC systems are divided into a series of independent stages or compartments by means of baffles in a single basin or separate basins arranged in stages. Compartmentalization creates a plug-flow pattern, increasing overall removal efficiency. It also promotes a variety of conditions where different organisms can flourish to varying degrees. As the waste-water flows through the compartments, each subsequent stage receives influent with a lower organic content than the previous stage; the system thus enhances organic removal.

[20] Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

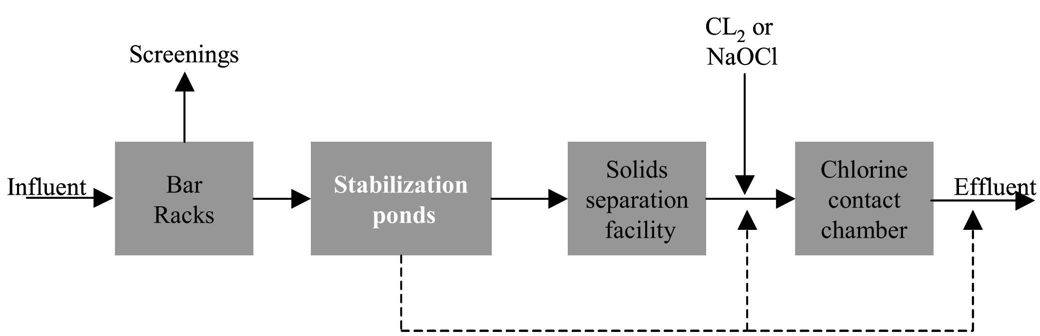
Figure 12. Typical flow diagram for RBC units



(e) *Stabilization ponds*

A stabilization pond is a relatively shallow body of waste-water contained in an earthen basin, using a completely mixed biological process without solids return. Mixing may be either natural (wind, heat or fermentation) or induced (mechanical or diffused aeration). Stabilization ponds are usually classified, on the basis of the nature of the biological activity that takes place in them, as aerobic, anaerobic, or aerobic-anaerobic (see table 10). Aerobic ponds are used primarily for the treatment of soluble organic wastes and effluents from waste-water treatment plants. Aerobic-anaerobic (facultative) ponds are the most common type and have been used to treat domestic waste-water and a wide variety of industrial wastes. Anaerobic ponds, for their part, are particularly effective in bringing about rapid stabilization of strong concentratons of organic wastes. Aerobic and facultative ponds are biologically complex. The bacterial population oxidizes organic matter, producing ammonia, carbon dioxide, sulfates, water and other end products, which are subsequently used by algae during daylight to produce oxygen. Bacteria then use this supplemental oxygen and the oxygen provided by wind action to break down the remaining organic matter. Waste-water retention time ranges between 30 and 120 days. This is a treatment process that is very commonly found in rural areas because of its low construction and operating costs. Figure 13 presents a typical flow diagram for stabilization ponds.[21]

Figure 13. Typical flow diagram for stabilization ponds



[21] Liu and Lipták, *Wastewater Treatment*.

TABLE 10. TYPES AND APPLICATIONS OF STABILIZATION PONDS

Type of pond	Common name	Characteristics	Application
Aerobic	Low-rate pond	Designed to maintain aerobic conditions throughout the liquid depth	Treatment of soluble organic wastes and secondary effluents
	High-rate pond	Designed to optimize the production of algal cell tissue and achieve high yields of harvestable proteins	Nutrient removal, treatment of soluble organic wastes, conversion of wastes
	Maturation pond	Similar to low-rate ponds but very lightly loaded	Used for polishing effluents from conventional secondary treatment processes such as trickling filter or activated sludge
Aerobic-anaerobic (supplemental aeration)	Facultative pond with aeration	Deeper than high-rate pond; aeration and photosynthesis provide oxygen for aerobic stabilization in upper layers. Lower layers are facultative. Bottom layer of solids undergoes anaerobic digestion.	Treatment of screened untreated or primary settled waste-water or industrial wastes.
Aerobic-anaerobic (oxygen from algae)	Facultative pond	As above, except without supplemental aeration. Photosynthesis and surface reaeration provide oxygen for upper layers.	Treatment of screened untreated or primary settled waste-water or industrial wastes.
Anaerobic	Anaerobic lagoon, anaerobic pretreatment pond	Anaerobic conditions prevail throughout; usually followed by aerobic or facultative ponds.	Treatment of municipal waste-water and industrial wastes.
Anaerobic followed by aerobic-anaerobic	Pond system	Combination of pond types described above. Aerobic-anaerobic ponds may be followed by an aerobic pond. Recirculation frequently used from aerobic to anaerobic ponds.	Complete treatment of municipal waste-water and industrial wastes with high bacterial removal.

Source: Adapted from Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

(f) *Completely mixed anaerobic digestion*

Anaerobic digestion involves the biological conversion of organic and inorganic matter in the absence of molecular oxygen to a variety of end-products including methane and carbon dioxide. A consortium of anaerobic organisms work together to degrade the organic sludges and wastes in three steps, consisting of hydrolysis of high-molecular-mass compounds, acidogenesis and methanogenesis.

The process takes place in an airtight reactor. Sludge is introduced continuously or intermittently and retained in the reactor for varying periods of time. After withdrawal from the reactor, whether continuous or intermittent, the stabilized sludge is reduced in organic and pathogen content and is non-putrescible. The two most widely used types of anaerobic digesters are standard-rate and high-rate. In the standard-rate digestion process, the contents of the digester are usually unheated and unmixed, and are retained for a period ranging from 30 to 60 days. In the high-rate digestion process, the contents of the digester are heated and mixed completely, and are retained, typically, for a period of 15 days or less. A combination of these two basic processes is known as the two-stage process, and is used to separate the digested solids from the supernatant liquor. However, additional digestion and gas production may occur.[22]

Aanerobic digesters are commonly used for the treatment of sludge and waste-waters with high organic content. The disadvantages and advantages of a system of this kind, as compared to aerobic treatment, stem directly from the slow growth rate of methanogenic bacteria. A slow growth rate requires a relatively long retention time in the digester for adequate waste stabilization to occur; however, that same slow growth means that only a small portion of the degradable organic matter is synthesized into new cells. Another advantage of this type of system is the production of methane gas, which can be used as a fuel source, if produced in sufficient quantities. Furthermore, the system produces a well-stabilized sludge, which can be safely disposed of in a sanitary landfill after drying or dewatering. On the other hand, the fact that high temperatures are required for adequate treatment is a major drawback.

(g) *Biological nutrient removal*

Nitrogen and phosphorus are the principal nutrients of concern in waste-water discharges. Discharges containing nitrogen and phosphorus may accelerate the eutrophication of lakes and reservoirs and stimulate the growth of algae and rooted aquatic plants in shallow streams. Significant concentrations of nitrogen may have other adverse effects as well: depletion of dissolved oxygen in receiving waters, toxicity to aquatic life, adverse impact on chlorine disinfection efficiency, creation of a public health hazard, and waste-water that is less suitable for reuse. Nitrogen and phosphorus can be removed by physical, chemical and biological methods. Biological removal of these nutrients is described below.

(i) *Nitrification-denitrification*

Nitrification is the first step in the removal of nitrogen by means of this process. Biological nitrification is the work of two bacterial genera: Nitrosomonas, which oxidize ammonia to the intermediate product nitrite, and Nitrobacter, which convert nitrite to nitrate. Nitrifying bacteria are sensitive organisms and are extremely susceptible to a wide variety of inhibitors such as high concentrations of ammonia and nitrous acid, low DO levels (< 1 mg/L), pH outside the optimal range (7.5-8.6), and so on. Nitrification can be achieved through both suspended-growth and attached-growth processes. In suspended-growth processes, nitrification is brought about either in the same reactor that is used for carbonaceous BOD removal, or in a separate suspended-growth reactor following a conventional activated sludge treatment process. Ammonia is oxidized to nitrate with either air or high-purity oxygen. Similarly, nitrification in an attached-growth system may be brought about either in the same attached-growth reactor that is used for carbonaceous BOD removal or in a separate reactor. Trickling filters, rotating biological contactors and packed towers can be used for nitrifying systems.

Denitrification involves the removal of nitrogen in the form of nitrate by conversion to nitrogen gas under anoxic conditions. In denitrifying systems, DO is a critical parameter. Its presence suppresses the enzyme system needed for denitrification. The optimal pH lies between 7 and 8. Denitrification can be achieved through both suspended- and attached-growth processes. Suspended-growth denitrification takes place in a plug-flow type of activated-sludge system. An external carbon source is usually necessary for micro-organism cell synthesis, since the nitrified effluent is low in carbonaceous matter. Some denitrification systems use the incoming waste-water for this purpose. A nitrogen-gas-stripped reactor should precede the denitrification clarifier because nitrogen gas hinders the settling of the mixed liquor. Attached-growth denitrification takes place in a column reactor containing stone or one of a number of synthetic media upon which the bacteria grow. Periodic backwashing and an external carbon source are necessary in a system of this kind.

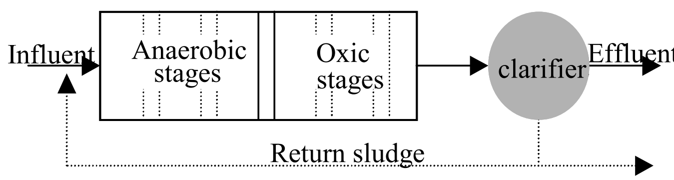
[22] Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

(ii) *Phosphorus removal*

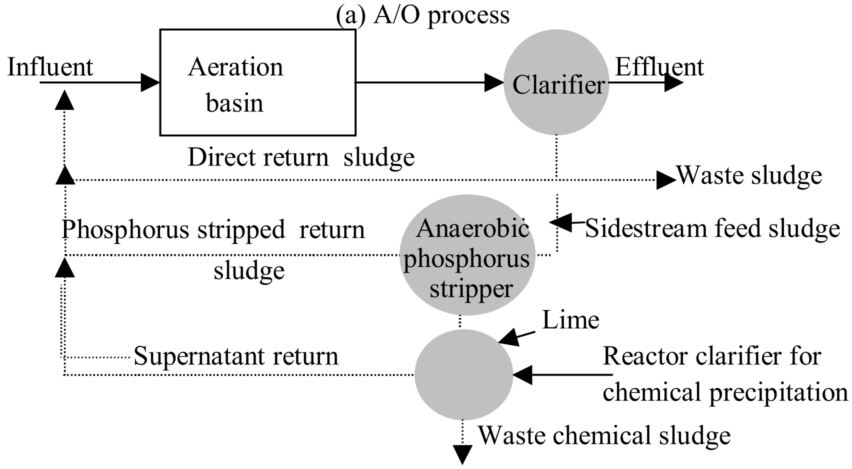
Phosphorus appears in water as orthophosphate (PO_4^{-3}), polyphosphate (P_2O_7), and organically bound phosphorus. Microbes utilize phosphorus during cell synthesis and energy transport. As a result, 10 to 30 per cent of all influent phosphorus is removed during secondary biological treatment. More phosphorus can be removed if one of a number of specially developed biological phosphorus removal processes is used. These processes are based on the exposure of microbes in an activated-sludge system to alternating anaerobic and aerobic conditions. This stresses the micro-organisms, so that their uptake of phosphorus exceeds normal levels. Typical biological processes used for phosphorus removal are the proprietary A/O process, the proprietary PhoStrip process, and the sequencing batch reactor (SBR) process (see figure 14).

The A/O process is a single-sludge suspended-growth system that combines aerobic and anaerobic sections in sequence. Settled sludge is returned to the influent end of the reactor and mixed with the incoming waste-water. In the PhoStrip process, a portion of the return activated sludge from the secondary biological treatment process is diverted to an anaerobic phosphorus stripping tank. There, phosphorus is released into the supernatant, which is subsequently treated with lime or some other coagulant. The phosphorus-poor activated sludge is returned to the aeration tank. The SBR system, as described in annex table 3, is also used to achieve a combination of carbon oxidation, nitrogen reduction and phosphorus removal.

Figure 14. Biological phosphorus removal systems



(a) A/O process



(b) PhoStrip process

Source: Adapted from Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

B. APPLICATION OF TREATMENT METHODS

In waste-water treatment plants, the unit operations and processes described in the previous section are grouped together in a variety of configurations to produce different levels of treatment, commonly referred to as preliminary, primary, secondary and tertiary or advanced treatment (see figure 15).

1. *Preliminary treatment*

Preliminary treatment prepares waste-water influent for further treatment by reducing or eliminating non-favourable waste-water characteristics that might otherwise impede operation or excessively increase maintenance of downstream processes and equipment. These characteristics include large solids and rags, abrasive grit, odours, and, in certain cases, unacceptably high peak hydraulic or organic loadings. Preliminary treatment processes consist of physical unit operations, namely screening and comminution for the removal of debris and rags, grit removal for the elimination of coarse suspended matter, and flotation for the removal of oil and grease. Other preliminary treatment operations include flow equalization, septage handling, and odour control methods.

2. *Primary treatment*

Primary treatment involves the partial removal of suspended solids and organic matter from the waste-water by means of physical operations such as screening and sedimentation. Preaeration or mechanical flocculation with chemical additions can be used to enhance primary treatment. Primary treatment acts as a precursor for secondary treatment. Its is aimed mainly at producing a liquid effluent suitable for downstream biological treatment and separating out solids as a sludge that can be conveniently and economically treated before ultimate disposal. The effluent from primary treatment contains a good deal of organic matter and is characterized by a relatively high BOD.

3. *Secondary treatment*

The purpose of secondary treatment is the removal of soluble and colloidal organics and suspended solids that have escaped the primary treatment. This is typically done through biological processes, namely treatment by activated sludge, fixed-film reactors, or lagoon systems and sedimentation.

4. *Tertiary/advanced waste-water treatment*

Tertiary treatment goes beyond the level of conventional secondary treatment to remove significant amounts of nitrogen, phosphorus, heavy metals, biodegradable organics, bacteria and viruses. In addition to biological nutrient removal processes, unit operations frequently used for this purpose include chemical coagulation, flocculation and sedimentation, followed by filtration and activated carbon. Less frequently used processes include ion exchange and reverse osmosis for specific ion removal or for dissolved solids reduction.

C. Natural treatment systems

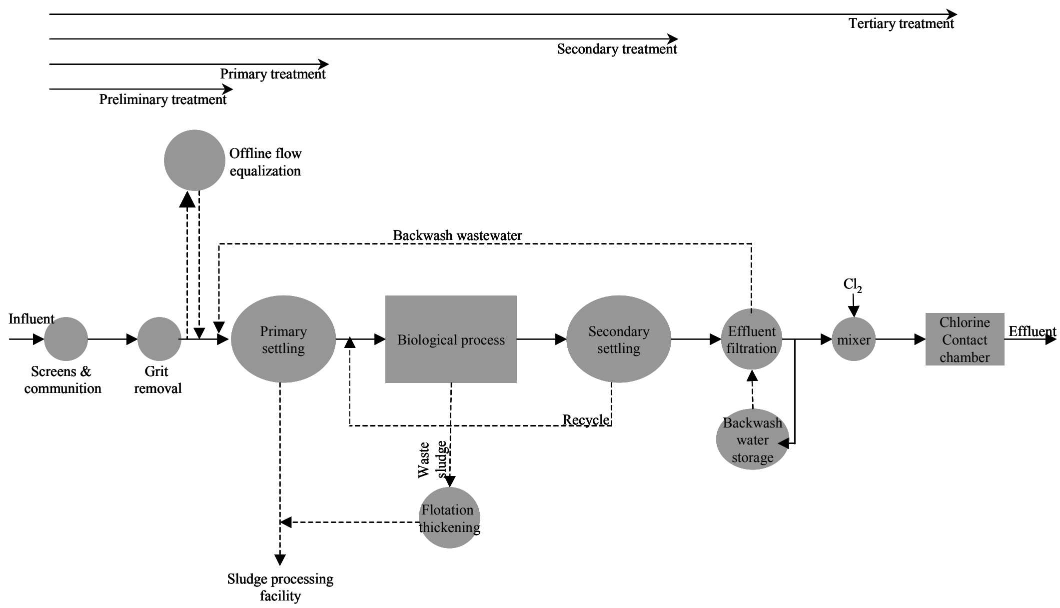
Natural systems for waste-water treatment are designed to take advantage of the physical, chemical, and biological processes that occur in the natural environment when water, soil, plants, micro-organisms and the atmosphere interact.[23] Natural treatment systems include land treatment, floating aquatic plants and constructed wetlands. All natural treatment systems are preceded by some form of mechanical pretreatment for the removal of gross solids. Where sufficient land suitable for the purpose is available, these systems can often be the most cost-effective option in terms of both construction and operation. They are frequently well suited for small communities and rural areas.[24]

---

[23] Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

[24] S.C. Reed, E.J. Middlebrooks and R.W. Crites, *Natural Systems for Waste Management and Treatment* (New York: McGraw-Hill, 1988); and Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

Figure 15. Various treatment levels in a waste-water treatment plant flow diagram



1. *Land treatment*

Land treatment is the controlled application of waste-water to the land at rates compatible with the natural physical, chemical and biological processes that occur on and in the soil. The three main types of land treatment systems used are slow rate (SR), overflow (OF), and rapid infiltration (RI) systems.

(a) *Slow rate*

SR systems are the predominant form of land treatment for municipal and industrial waste-water. This technology incorporates waste-water treatment, water reuse, crop utilization of nutrients and waste-water disposal. It involves the application of waste-water to vegetated land by means of various techniques, including sprinkling methods or surface techniques such as graded-border and furrow irrigation. Water is applied intermittently (every 4 to 10 days) to maintain aerobic conditions in the soil profile. The applied water is either consumed through evapotranspiration or percolated vertically and horizontally through the soil system. Any surface runoff is collected and reapplied to the system. Treatment occurs as the waste-water percolates through the soil profile (see table 11). In most cases, the percolate will enter the underlying groundwater, or it may be intercepted by natural surface waters or recovered by means of underdrains or recovery wells.[25, 26]

[25] Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

[26] Reed, Middlebrooks and Crites, *Natural Systems*.

TABLE 11. MECHANISMS OF WASTE-WATER CONSTITUENT REMOVAL BY SR SYSTEMS

Parameter	Removal mechanism
BOD	Soil adsorption and bacterial oxidation
SS	Filtration through the soil
Nitrogen	Crop uptake, denitrification, ammonia volatilization, soil storage
Phosphorus	Chemical immobilization (precipitation and adsorption), plant uptake
Metals	Soil adsorption, precipitation, ion exchange, complexation
Pathogens	Soil filtration, adsorption, desiccation, radiation, predation, exposure to other adverse environmental factors
Trace organics	Photodecomposition, volatilization, sorption, degradation

Source: Reed, Middlebrooks and Crites, *Natural Systems*.

SR systems can be classified into two types, Type 1 and Type 2, based on design objectives. Type 1 systems are designed with waste-water treatment itself, rather than crop production, as their main objective. Accordingly, in systems of this kind, the maximum possible amount of water is applied per unit land area. Type 2 SR systems, in contrast, are designed mainly with a view to water reuse for crop production, and consequently the amount of water applied in a system of this kind is just enough to satisfy the irrigation requirements of the crop being grown. SR systems have the highest treatment potential of all natural treatment systems.

(b) *Rapid infiltration*

Rapid infiltration (RI) is the most intensive of all land treatment methods. Relatively high hydraulic and organic loadings are applied intermittently to shallow infiltration or spreading basins (see figure 16). The RI process uses the soil matrix for physical, chemical, and biological treatment. Physical straining and filtering occur at the soil surface and within the soil matrix. Chemical precipitation, ion exchange and adsorption occur as the water percolates through the soil. Biological oxidation, assimilation and reduction occur within the top few feet of the soil. Vegetation is not applied in systems of this kind. The RI system is designed to meet several performance objectives including the following:

(a) Recharge of streams by interception of groundwater;
(b) Recovery of water by wells or underdrains, with subsequent reuse or discharge;
(c) Groundwater recharge;
(d) Temporary storage of renovated water in the local aquifer.[27, 28]

(c) *Overland flow*

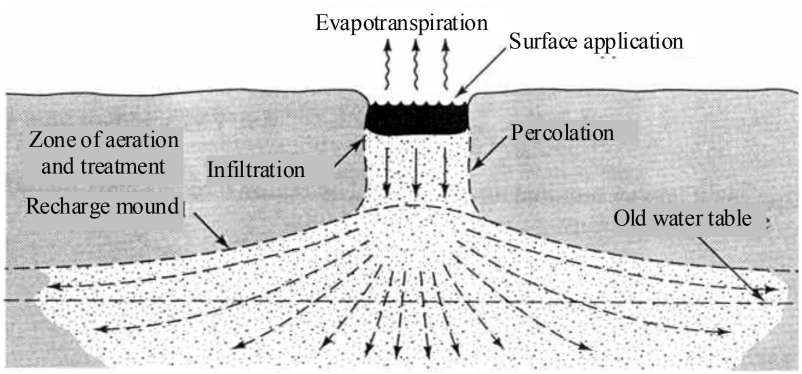
Overland flow (OF) is a treatment process in which waste-water is treated as it flows down a network of vegetated sloping terraces. Waste-water is applied intermittently to the top portion of each terrace and flows down the terrace to a runoff collection channel at the bottom of the slope (see figure 17). Application techniques include high-pressure sprinklers, low-pressure sprays, or surface methods such as gated pipes. OF is normally used with relatively impermeable surface soils, since, in contrast to SR and RI systems, infiltration through the soil is limited. The effluent waste-water undergoes a variety of physical, chemical and biological treatment mechanisms as it proceeds along surface runoff path. Overland flow systems can be

[27] R.L. Sanks and T. Asano, *Land Treatment and Disposal of Municipal and Industrial Wastewater* (Ann Arbor, Michigan: Ann Arbor Science, 1976).

[28] Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

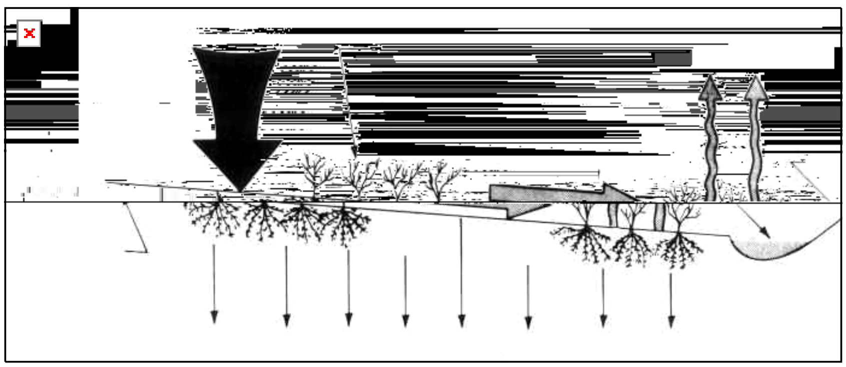
designed for secondary treatment, advanced secondary treatment or nutrient removal, depending on user requirements.[29, 30]

Figure 16. Rapid infiltration treatment system



Source: Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

Figure 17. Overland flow system



Source: Qasim, *Wastewater Treatment Plants*.

2. *Constructed wetlands*

Wetlands are inundated land areas with water depths typically less than 2 ft (0.6 m) that support the growth of emergent plants such as cattail, bulrush, reeds and sedges. The vegetation provides surfaces for the attachment of bacteria films, aids in the filtration and adsorption of waste-water constituents, transfers oxygen into the water column, and controls the growth of algae by restricting the penetration of sunlight. Two types of constructed wetlands have been developed for waste-water treatment, namely free water surface (FWS) systems, and subsurface flow systems (SFS).[29, 30]

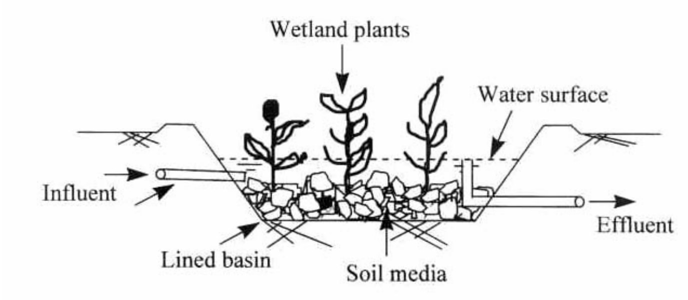
(d) *Free water surface systems*

FWS systems consist of parallel shallow basins ranging from 0.3 to 2 feet (0.1-0.6 metre) or channels with relatively impermeable bottom soil or subsurface barrier and emergent vegetation (see figure 18). As a rule, preclarified waste-water is applied continuously to be treated as it flows through the stems and roots of the emergent vegetation.

[29] Sanks and Asano, *Land Treatment*.

[30] Reed, Middlebrooks and Crites, *Natural Systems*.

Figure 18. Free water surface system

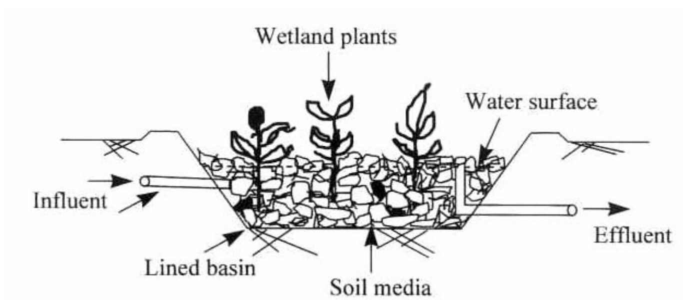


Source: Qasim, *Wastewater Treatment*.

(e) *Subsurface flow systems*

SFSs consist of beds or channels filled with gravel, sand, or other permeable media planted with emergent vegetation (see figure 19). Waste-water is treated as it flows horizontally through the media-plant filter. Systems of this kind are designed for secondary or advanced levels of treatment.

Figure 19. Subsurface flow system



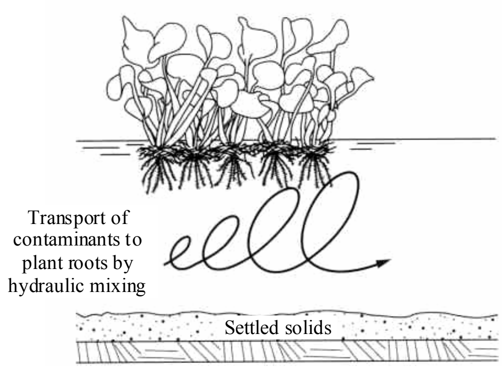
Source: Qasim, *Wastewater Treatment Plants*.

3. *Floating aquatic plants*

This system is similar to the FWS system except that the plants used are of the floating type, such as hyacinths and duckweeds (see figure 20). Water depths are greater than in the case of wetland systems, ranging from 1.6 to 6.0 feet (0.5-1.8 metres). The floating plants shield the water from sunlight and reduce the growth of algae. Systems of this kind have been effective in reducing BOD, nitrogen, metals and trace organics and in removing algae from lagoons and stabilization pond effluents. Supplementary aeration has been used with floating plant systems to increase treatment capacity and to maintain the aerobic conditions necessary for the biological control of mosquitoes.[31]

[31] Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

Figure 20. Floating aquatic plants system



Source: Metcalf and Eddy, *Wastewater Engineering*, 3rd edition.

Annex table 4 presents a comparison of major site characteristics, typical design features, and the expected quality of the treated waste-water from the principal types of natural systems.

D. Sludge treatment and disposal

Sewage sludge consists of the organic and inorganic solids that were present in the raw waste and were removed in the primary clarifier, in addition to organic solids generated in secondary/biological treatment and removed in the secondary clarifier or in a separate thickening process. The generated sludge is usually in the form of a liquid or semisolid, containing 0.25 to 12 per cent solids by weight, depending on the treatment operations and processes used.[32] Sludge handling, treatment and disposal are complex, owing to the offensive constituents present, which vary with the source of waste-water and the treatment processes applied. Sludge is treated by means of a variety of processes that can be used in various combinations. A generalized flow diagram showing the various unit sludge treatment operations and processes currently in use is presented in figure 21. Thickening, conditioning, dewatering and drying are primarily used to remove moisture from sludge, while digestion, composting, incineration, wet-air oxidation and vertical tube reactors are used to treat or stabilize the organic material in the sludge. This section examines various sludge treatment processes with emphasis on the most commonly used technologies.

1. *Thickening*

Thickening is the practice of increasing the solids content of sludge by the removal of a portion of its liquid content. A modest increase in solids content (from 3 to 6 per cent) can decrease total sludge volume significantly (by 50 per cent), entailing reduced size requirements for subsequent treatment units.[33] Sludge thickening methods are usually physical in nature: they include gravity settling, flotation, centrifugation and gravity belts. These technologies are briefly described in annex table 5 and illustrated in annex figure 3.

2. *Stabilization*

Sludges are stabilized to reduce their pathogen content, eliminate offensive odours, and reduce or eliminate the potential for putrefaction. Technologies used for sludge stabilization include lime stabilization, heat treatment, anaerobic digestion, aerobic digestion and composting.

---

[32] T.J. McGhee, *Water Supply and Sewerage* (New York: McGraw-Hill, 1991).

[33] McGhee, *Water Supply and Sewerage*.

Figure 21. Sludge processing and disposal flow diagram

SLUDGE FROM TREATMENT PROCESSES

⇩

PRELIMINARY OPERATIONS

- ❑ Sludge grinding
- ❑ Sludge storage
- ❑ Sludge bending
- ❑ Sludge degritting

⇩

THICKENING

- ❑ Rotary drum thickening
- ❑ Centrifugation
- ❑ Gravity thickening
- ❑ Gravity belt thickening
- ❑ Flotation thickening

⇩

STABILIZATION

- ❑ Chlorine oxidation
- ❑ Anaerobic digestion
- ❑ Lime stabilization
- ❑ Aerobic digestion
- ❑ Heat treatment
- ❑ Composting

⇩

CONDITIONING

- ❑ Elutriation
- ❑ Chemical conditioning
- ❑ Heat treatment

⇩

DISINFECTION

- ❑ Pasteurization
- ❑ Long-term storage

⇩

DEWATERING

- ❑ Vacuum filter
- ❑ Centrifuge
- ❑ Pressure filter
- ❑ Drying bed
- ❑ Horizontal belt filter
- ❑ Lagoon

⇩

DRYING

- ❑ Multiple effect evaporator
- ❑ Rotary drying
- ❑ Flash drying
- ❑ Multiple hearth drying
- ❑ Spray drying

⇩

THERMAL REDUCTION

- ❑ Multiple hearth incineration
- ❑ Flash combustion
- ❑ Fluidized bed incineration
- ❑ Co-incineration with solid wastes
- ❑ Vertical deep well reactor

⇩

ULTIMATE DISPOSAL

- ❑ Landfill
- ❑ Reclamation
- ❑ Land application
- ❑ Reuse

(a) *Lime stabilization*

In this process, lime is added to untreated sludge to raise the pH to 12 or higher. The high pH environment inhibits the survival of micro-organisms, and thus eliminates the risk of sludge putrefaction and odour creation. Hydrated lime ($Ca(OH)_2$) and quicklime (CaO) are most commonly used for lime stabilization. Lime is added either prior to dewatering (lime pre-treatment) or after dewatering (lime post-treatment).

(b) *Heat treatment*

This process involves the treatment of sludge by heating in a pressure vessel to temperatures of up to 500ºF (260ºC) at pressures of up to 2,760 kN/m^2 for approximately 30 seconds. The exposure of sludge to such conditions results in the hydrolysis of proteinaceous compounds, leading to cell destruction and the release of soluble organic compounds and nitrogen. This process also serves for conditioning, as the thermal activity releases bound water and results in the coagulation of solids.

(c) *Anaerobic sludge digestion*

This process involves the anaerobic reduction of organic matter in the sludge by biological activity. The methane produced can be recovered and reused for heating and incineration. Four types of anaerobic digesters are commonly used for sludge stabilization: standard-rate, standard high-rate, two-stage and separate. These digesters are outlined in table 12 and illustrated in figure 22.

TABLE 12. COMMON ANAEROBIC DIGESTERS

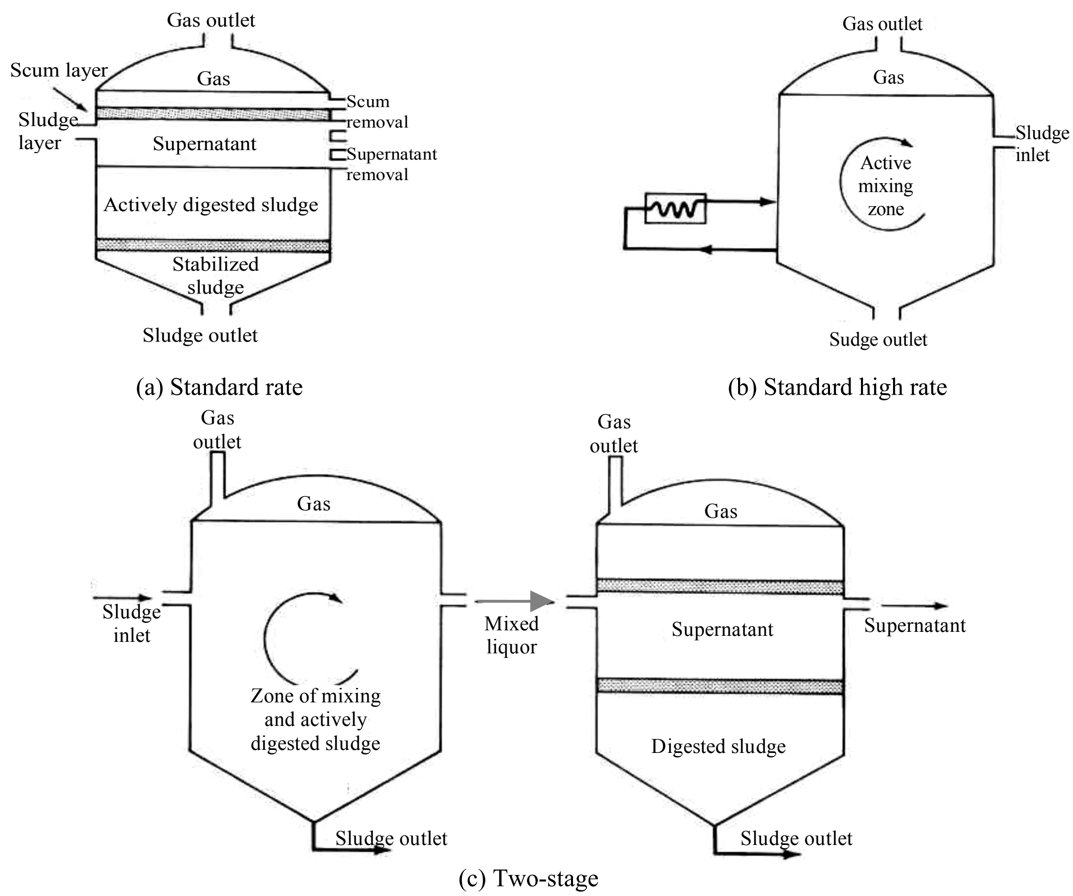
Type of digester	Description
Standard rate	This is a single-stage process in which digestion, sludge thickening and supernatant formation take place simultaneously. The untreated sludge is added to the active digestion zone, where it is heated by an external source. Mesophilic conditions are maintained within the reactor. The resulting gas rises to the surface, carrying oils and grease with it (see figure 22, a).
Standard high-rate	This process is a modification of the standard rate process. The solids loading is much greater, and the sludge is mixed by gas recirculation, pumping or mechanical mixing (see figure 22, b).
Two-stage	This method features two tanks. The first serves for digestion and is fitted with heating and mixing facilities, while the second is used for the storage and concentration of digested sludge and for the formation of a clear supernatant (see figure 22, c).
Separate	This process, which is relatively new, involves the separate digestion of primary and biological sludges.
Thermophilic	Thermophilic digestion occurs between 120 and 135 ºF (49 and 57 ºC). This process is characterized by a rapid digestion rate, increased bacterial destruction and improved sludge dewatering. However, the process is characterized by higher energy requirements, produces poorer quality supernatant and generates odours.

Source: Adapted from Liu and Lipták, *Wastewater Treatment*.

(d) *Aerobic sludge digestion*

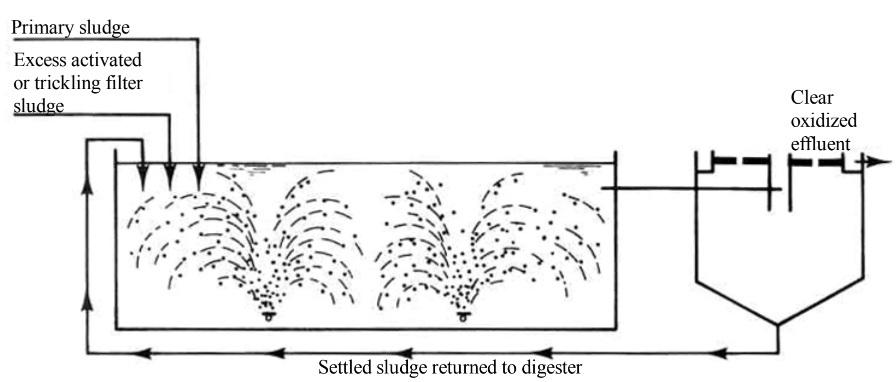
Aerobic sludge digestion is similar to the activated-sludge process. It involves the direct oxidation of biodegradable matter and microbial cellular material in open tanks for an extended period of time. Aeration occurs either naturally or by means of mechanical aerators and diffusers (see figure 23). This process is preferably used only for the treatment of waste activated sludge, a mixture of waste activated or trickling filter sludge with primary sludge, or waste sludge from extended aeration plants or activated-sludge treatment plants designed without primary settling. As compared to anaerobic processes, aerobic digestion affords both advantages and disadvantages (see table 13).

Figure 22. Typical anaerobic sludge digesters



Source: Qasim, *Wastewater Treatment Plants*.

Figure 23. Schematic of aerobic sludge digestion



Source: Qasim, *Wastewater Treatment Plants*.

TABLE 13. ADVANTAGES AND DISADVANTAGES OF AEROBIC SLUDGE DIGESTION

Advantages	Disadvantages
- Volatile solids reduction approximately the same as anaerobic digestion - Supernatant liquor with lower BOD concentrations - Production of an odourless, humus-like, biologically stable end-product - Recovery of most of the basic fertilizer values in the sludge - Operation relatively easier - Lower capital cost	- Higher power cost associated with supplying oxygen - Produces a digested sludge with poor mechanical dewatering characteristics - The process is significantly affected by temperature, location, and type of tank - High operating cost

Source: Qasim, *Wastewater Treatment Plants*.

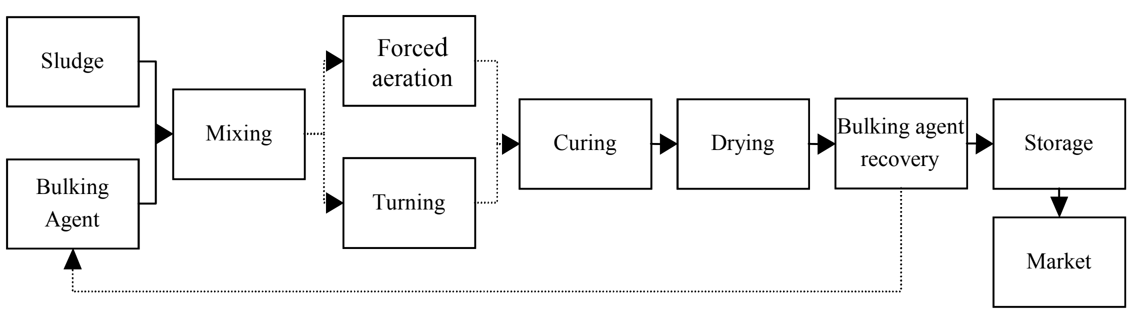
(e) *Composting*

Composting is used for both sludge stabilization and final disposal. During composting, organic material undergoes biological degradation, resulting in a 20 to 30 per cent reduction of volatile solids. Enteric micro-organisms are also destroyed due to the rise in temperature of the compost. Composting includes the following operations:

(i) Mixing dewatered sludge with a bulking agent;
(ii) Aerating the compost pile by mechanical turning or the addition of air;
(iii) Recovery of the bulking agent;
(iv) Further curing and storage;
(v) Final disposal.

The resulting end product is stable and may be used as a soil conditioner in agricultural applications. Aerobic composting is more commonly used than anaerobic composting. The three major types of aerobic composting systems are the static aerated pile, windrow and in-vessel systems (see table 14).

Figure 24. Composting process flow diagram



Source: Adapted from Liu and Lipták, *Wastewater Treatment*.

TABLE 14. AEROBIC COMPOSTING SYSTEMS

Type	Description
Aerated static pile	Consists of an aeration grid over which a mixture of dewatered sludge and bulking agent is placed. The sludge and the bulking agent are mixed by means of a rotary drum or front-end loaders. The cured compost is screened for recovery of the bulking agent.
Windrow	Windrows are similar to static piles in terms of mixing and screening operations. However, no mechanical aeration is used. Aerobic conditions are maintained by periodic mixing of the compost.
In-vessel	Composting takes place in a closed container. Air flow, temperature and oxygen concentration are mechanically maintained.

Source: Adapted from Liu and Liptáak, *Wastewater Treatment*.

3. *Conditioning*

Conditioning involves the chemical and or physical treatment of sludge to enhance its dewatering characteristics. The two most commonly applied conditioning methods are the addition of chemicals and heat treatment. Other conditioning processes include freezing, irradiation and elutriation.[34]

(a) *Chemical conditioning*

Chemical conditioning is associated principally with mechanical sludge dewatering systems. It reduces the moisture content of incoming sludge from 90-99 per cent to 65-85 per cent by causing solids to coagulate, so that the absorbed water is released. Both organic and inorganic chemicals are used for this purpose. The two most commonly used inorganic conditioners are ferric chloride and lime. Upon being added, ferric chloride forms positively charged soluble iron complexes that neutralize the negatively charged sludge solids, causing them to aggregate. Ferric chloride also reacts with the bicarbonate alkalinity in the sludge to form hydroxides that cause flocculation. Lime, for its part, is ordinarily used with ferric iron salts. It reacts in the sludge to produce calcium carbonate, thus creating a granular structure that increases sludge porosity and reduces sludge compressibility.

Organic polymers are also widely used in sludge conditioning. Organic polyelectrolytes dissolve in water to form solutions of varying viscosity. The electrolytes adhere to the surface of the sludge particles, causing desorption of bound surface water, charge neutralization, and agglomerization by bridging between particles.[34]

(b) *Thermal conditioning*

Thermal conditioning involves heating the sludge to a temperature of 248-464 ºF in a reactor at a pressure of 1,720-2,760 kN/m^2 for 15-40 minutes. The applied heat coagulates the solids, breaks down the gel structure and reduces affinity for water, resulting in a sterilized, deodorized, dewatered sludge. The supernatant from the heat treatment unit has a high BOD and may require special treatment before redirection into the mainstream waste-water treatment process.[35]

[34] Qasim, *Wastewater Treatment Plants*.

[35] Qasim, *Wastewater treatment plants* and Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

4. *Dewatering*

A number of techniques are used for dewatering, which is a physical unit operation aimed at reducing the moisture content of sludge. The selection of the appropriate sludge-dewatering technique depends on the characteristics of the sludge to be dewatered, available space, and moisture content requirements of the sludge cake for ultimate disposal. When land is available and sludge quantity is small, natural dewatering systems such as drying beds and drying lagoons are most attractive. Mechanical dewatering methods include vacuum filter, centrifuge, filter press and belt filter press systems.

(a) *Sludge drying beds*

Sludge drying beds are typically used to dewater digested sludge. After drying, the sludge is either disposed of in a landfill or used as a soil conditioner. The various types of drying beds in current use are described in table 15.

TABLE 15. TYPES OF SLUDGE DRYING BEDS

Sludge drying beds	Description
Conventional sand drying beds	Typical sand beds consist of a layer of coarse sand supported on a graded gravel bed with perforated pipe underdrains. Sludge is placed on the bed and allowed to dry. Drying occurs by evaporation and drainage. The sludge cake is removed manually.
Paved drying beds	These are similar to conventional beds in terms of their underdraining system. Two types are commonly used: a drainage type and a decanting type. The drainage type involves agitation to facilitate dewatering and uses a front-end loader for sludge removal. The decanting type uses low-cost impermeable paved beds that rely on supernatant decanting and mixing of the drying sludge for enhanced evaporation.
Wedge-wire beds	These consist of beds constructed from artificial media such as stainless steel wedge-wire or high-density polyurethane. The drainage process is controlled by an outlet valve, enhancing the dewatering process.
Vacuum-assisted	In this system, dewatering and drying is accelerated by the application of vacuum to the underside of porous filter plates.

Source: Qasim, *Wastewater Treatment Plants* and Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

(b) *Drying lagoons*

Sludge-drying lagoons, which are suitable only for the treatment of digested sludge, consist of shallow earthen basins enclosed by earthen dykes. The sludge is first placed within the basin and allowed to dry. The supernatant is decanted from the surface and returned to the plant while the liquid is allowed to evaporate. Mechanical equipment is then used to remove the sludge cake.[36]

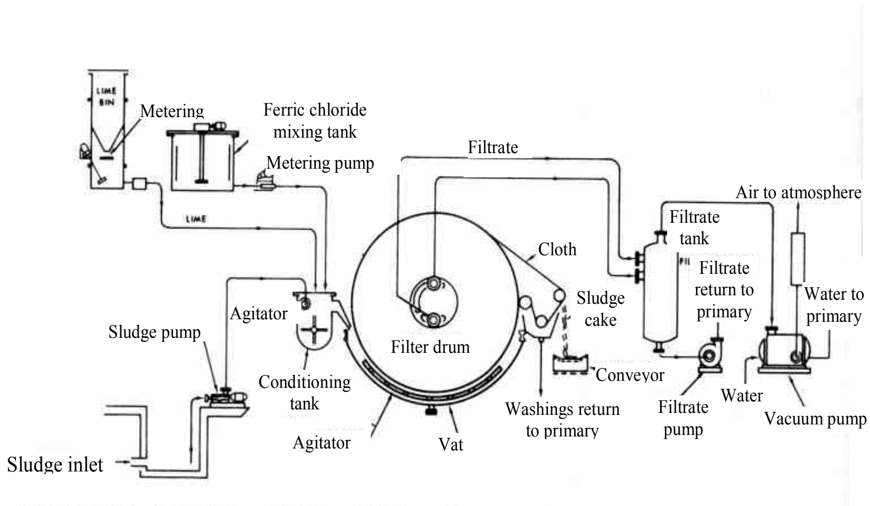
(c) *Vacuum filtration*

The vacuum filtration process consists of a horizontal cylindrical drum that is partially submerged in a tank of conditioned sludge. The surface of the drum is covered with a porous medium (cloth belts or coiled springs) and is divided into sections around its circumference. As the drum rotates, the sections function in sequence as three distinct zones: cake formation, cake dewatering and cake discharge (see figure 25). An internal vacuum that is maintained inside the drum draws the sludge to the filter medium.[37]

[36] Liu and Lipták, *Wastewater Treatment*.

[37] Qasim, *Wastewater Treatment Plants*.

Figure 25. Schematic of a vacuum filter system



Source: Adapted from Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

(d) *Belt filter press*

Belt filter presses use single or double moving belts to dewater sludge continuously. The filtration process involves four basic stages (see table 16 and figure 26):

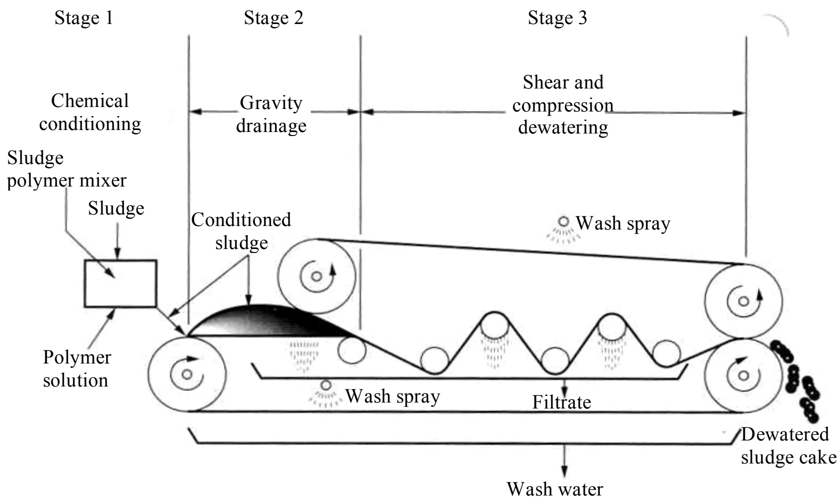
(i) Polymer conditioning zone;
(ii) Gravity drainage zone for excess water;
(iii) Low pressure zone;
(iv) High pressure zone.

TABLE 16. OPERATIONAL STAGES WITHIN A BELT FILTER PRESS

Filtration stage	Description
Polymer conditioning zone	Consists of a tank located close to the press, a rotating drum attached to the press, or an in-line injector
Gravity drainage zone	Consists of a flat or slightly inclined belt. Sludge is thickened by the gravity drainage of free water. This section may be vacuum-assisted.
Low pressure zone	This is the area where the upper and lower belts come together with the sludge in between. It prepares the sludge by forming a firm sludge cake that is able to withstand the shear forces within the high-pressure zone.
High pressure zone	In this stage, forces are exerted on the sludge by the movement of the upper and lower belts relative to each other, as they go over and under a series of rollers with decreasing diameters. The resulting sludge cake is removed by scraper blades.

Source: Qasim, *Wastewater Treatment Plants*.

Figure 26. Belt filter press



Source: Adapted from Metcalf and Eddy, Inc., *Wastewater Engineering*.

(e) *Filter presses*

In a filter press, dewatering is brought about by the use of high pressure to force the water out of the sludge. Advantages of the filter press are high sludge cake concentration, filtrate clarity and high solids capture. On the other hand, the system is characterized by high mechanical complexity, high chemical costs, high labour costs and limited cloth life. The two most widely used filter presses are the fixed-volume and the variable-volume recessed-plate types.

The fixed-volume filter press consists of a series of rectangular plates that are supported face to face in a vertical position, with a filter cloth hung over each plate. The conditioned sludge is pumped into the space between the plates and subjected to high pressure for 1 to 3 hours, so that the liquid is forced through the cloth and plate outlet ports. The plates are then separated and the sludge is removed. The variable-volume recessed-plate filter press is similar to the fixed-volume type except that a rubber diaphragm is placed between the plates to help reduce cake volume during compression.[38]

5. *Drying*

The purpose of sludge drying is to reduce the water content to less than 10 per cent by evaporation, making the sludge suitable for incineration or processing into fertilizer. Drying is performed mechanically by the application of auxiliary heat. Mechanical processes used for this purpose are described briefly in table 17 and illustrated in figure 27.

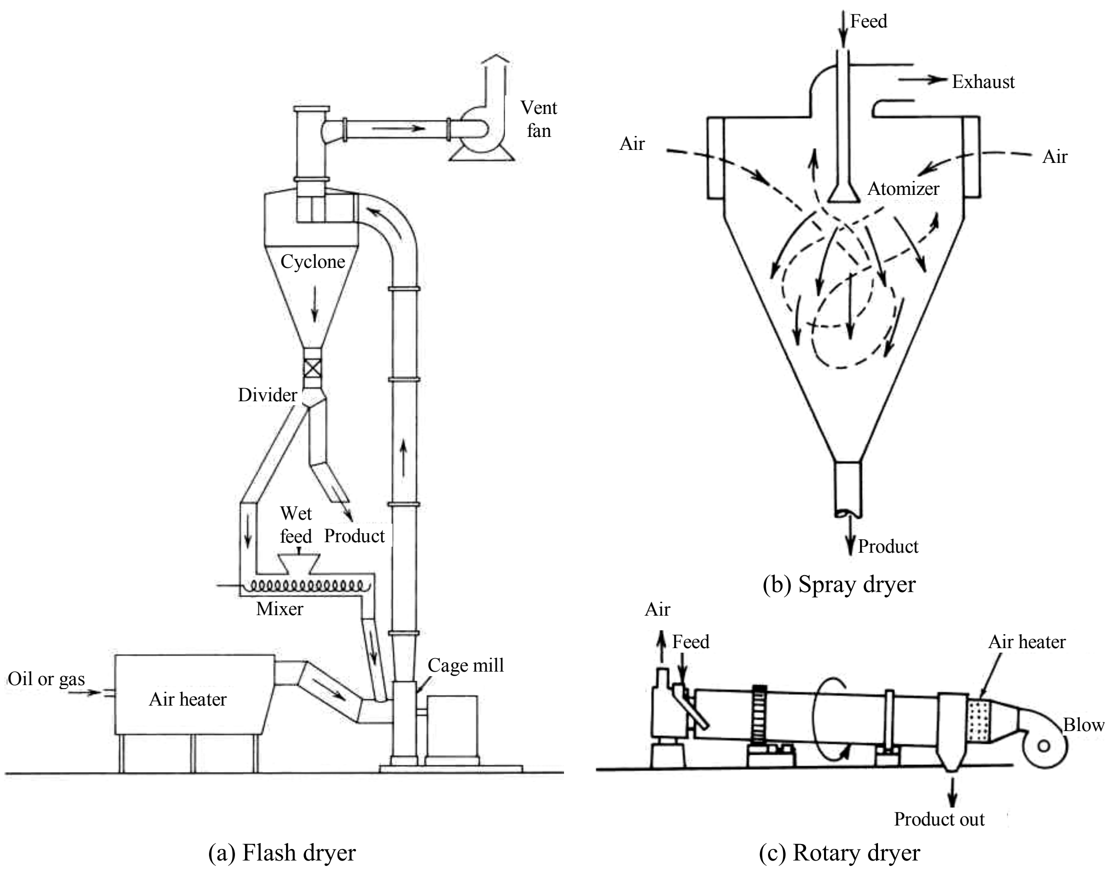
[38] Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

TABLE 17. MECHANICAL SLUDGE DRYING METHODS

Dryer type	Description
Flash dryer	Sludge is pulverized in a cage mill or by means of an atomized suspension technique in the presence of hot air.
Spray dryer	Liquid sludge is fed into a high-speed centrifuge bowl. Centrifugal forces atomize the sludge into fine particles and spray them into the top of a drying chamber.
Rotary dryer	Involves direct or indirect heating. Direct-heat dryers bring the sludge into physical contact with hot gases, while in indirect-heat dryers, the central cell containing the sludge material is surrounded with steam.
Multiple-hearth dryer	Heated air and products of combustion are passed over finely pulverized sludge that is raked continuously to expose fresh surfaces.

Source: Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

Figure 27. Sludge dryer technologies



Source: Adapted from Liu and Lipták, *Wastewater Treatment*.

6. *Thermal reduction*

The thermal reduction of sludge involves two main processes:

(a) Total or partial conversion of organic solids to oxidized end products, primarily carbon dioxide and water, either by incineration or by wet-air oxidation;

(b) Partial oxidation and volatilization of organic solids, either by pyrolysis[39] or by starved air combustion,[40] to end-products with energy contents, including gases, oil, tar and charcoal.[41] The main objective of this conversion process is the reduction of the volume of solids, as required for final disposal.

The principal thermal reduction methods are described in table 18 and illustrated in figure 28.

TABLE 18. SLUDGE INCINERATION METHODS

Type of incinerator	Description
Multiple-hearth furnace	A steel shell the interior of which is divided into a series of hearths. The sludge is fed through the furnace roof by a screw-feeder or a belt and flapgate. Rotating rabble arms and rabble teeth push the sludge across the hearth to drop holes, where it falls to the subsequent hearths and continues downward until sterile phosphate-laden ash is discharged at the bottom.
Wet air oxidation	A reactor held at high temperature (200-300 ºC) and high pressure (5-20 kN/m^2). Sludge and sufficient air pumped into the reactor are oxidized in a liquid phase. The liquid and solid residues are separated by settling or filtration.
Fluidized-bed incinerator	A vertical, cylindrical, refractory-lined steel shell that contains a sand bed and fluidizing air orifices to produce and sustain combustion. Sludge is mixed quickly within the fluidized bed by its turbulent action, resulting in evaporation of the water and combustion of the sludge solids.

Source: Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

7. *Sludge disposal and reuse*

There was a time when sludge was commonly disposed of in sanitary landfills and lagoons. However, the beneficial uses of sludge are attracting more attention nowadays. Treated and digested sludge may be used as a soil amendment and conditioner. Sludge may also be treated chemically for use as landfill cover or for landscaping or land reclamation projects.

E. NEW DIRECTIONS AND CONCERNS[42]

Increasingly, advanced computational methods in fluid dynamics are being used for the design of new treatment systems and the optimization of existing ones, in order to eliminate sources of inefficiencies. For example, improved UV disinfection systems, sedimentation tanks and chlorine contact tanks are being designed using computational fluid dynamics. In addition, these computational methods can be used to improve the performance of ongoing operations when integrated into the process control system.

Energy management, too, is becoming an essential aspect of the design and operation of waste-water treatment facilities. Some operations, such as aeration in biological treatment, consume large quantities of energy, and consequently the selection of energy-efficient equipment and the design of energy recovery schemes are assuming progressively greater importance.

---

[39] Pyrolysis, also known as destructive distillation, involves heating of organic matter in an oxygen-free atmosphere (Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

[40] Starved air combustion combines some of the features of both complete combustion and pyrolysis (Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

[41] Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

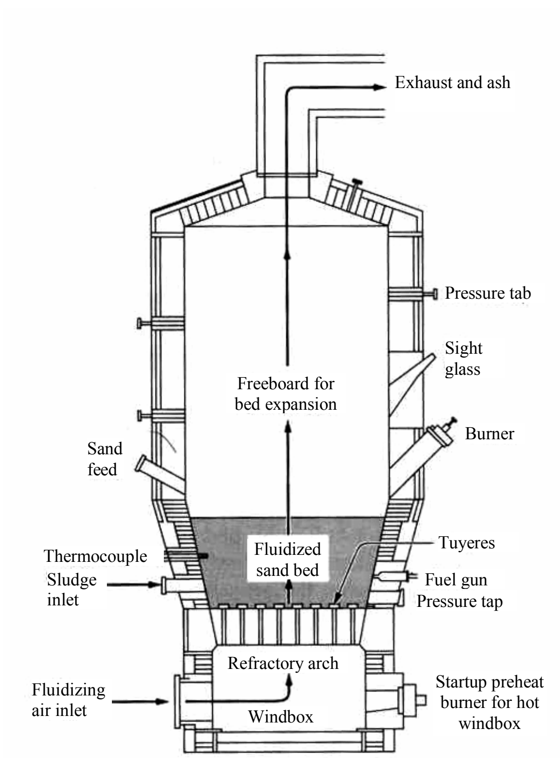
[42] Metcalf and Eddy, Inc., *Wastewater Engineering*, 4th edition.

As discharge regulations now require lower or even undetectable chorine residues in treated effluents, dechlorination units are being installed, or alternative disinfection methods are being used. Ultraviolet radiation is gaining ground as an alternative to chlorination, owing mainly due to the improvements that have been made to these systems during the past ten years and their declining capital and operating costs.

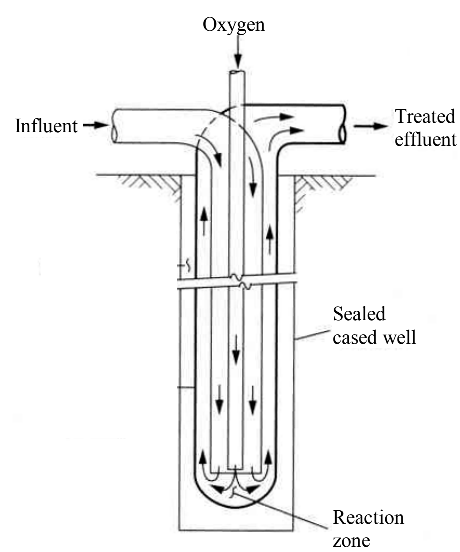
In many countries, the waste-water treatment infrastructure is now old and undersized. There is growing awareness of the need to repair, expand and upgrade existing facilities. Future studies and design efforts will address these ageing issues and look for ways to improve the performance and increase the capacity of existing facilities.

Technological changes in industry mean that industrial effluents are also changing. Industrial waste-water now contains larger quantities of heavy metals and new synthetic organic compounds. New treatment technologies may be required if these compounds are to be removed effectively. In addition, there is a growing trend in the direction of facilities designed for even higher levels of treatment and more compact size. New technologies now in use include vortex separators, high rate clarification, membrane bioreactors and membrane filtration. A trend towards the development of proprietary treatment processes in response to the privatization of treatment facilities is also observable.

Figure 28. Sludge incineration technologies

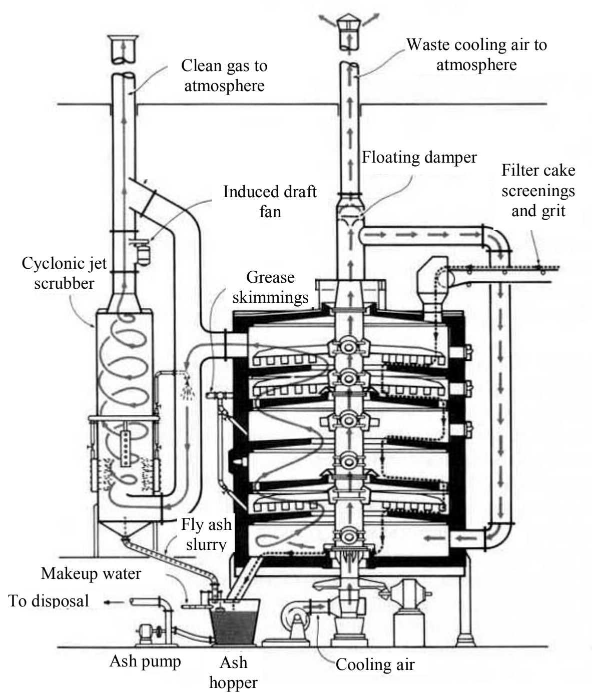


(a) Fluidized bed



(b) Wet air oxidation

Figure 28 (*continued*)



(c) Multiple hearth

Source: Adapted from Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition, and Liu and Lipták, *Wastewater Treatment*.

III. MANAGEMENT OF TREATED EFFLUENT

After treatment, waste-water is either reused or discharged into the environment. Highly treated waste-water effluent from municipal waste-water treatment plants can be reused as a reliable source of water for agricultural irrigation, landscape irrigation, industrial recycling and reuse, groundwater recharge, recreational uses, non-potable urban reuse or even potable reuse. If not reused, treated waste-water is commonly discharged into a water body and diluted. Environmental regulations, guidelines and policies ensure acceptable discharge of waste-water effluent.

A. EFFLUENT RECLAMATION AND REUSE

Effluent reclamation and reuse has received much attention lately, owing to growing demand for water and unsustainable rates of consumption of natural water resources. A major concern in reuse applications is the quality of the reclaimed water, which is the main factor dictating the selection of the waste-water treatment process sequence. This section describes the various effluent reuse applications with emphasis on effluent quality issues.

1. *Irrigation*

Treated waste-water effluent can be used for the irrigation of crops or landscaped areas. The main consideration associated with this effluent application method is the quality of the treated water and its suitability for plant growth. Some constituents in reclaimed water that are of particular significance in terms of agricultural irrigation include elevated concentrations of dissolved solids, toxic chemicals, residual chlorine and nutrients. Another highly important consideration is public health and safety hazards resulting from the potential presence of bacterial pathogens, intestinal parasites, protozoa and viruses. Concerns vary with the intended irrigation use and the degree of human contact. Potential constraints associated with the use of reclaimed waste-water for irrigation include the marketability of crops and public acceptance, surface and groundwater pollution in the absence of adequate management, and high user costs, notably the cost of pumping effluent to irrigated land.[43]

2. *Industrial use*

Reclaimed water is ideal for industries using processes that do not require water of potable quality. Industrial uses of reclaimed water include evaporative cooling water, boiler-feed water, process water, and irrigation and maintenance of the grounds and landscape around the plant. Each type of reuse is associated with a number of constraints on its applicability; the use of reclaimed water in cooling towers, for example, creates problems of scaling, corrosion, biological growth, fouling and foaming. These problems are also encountered when fresh water is used, but less frequently. Reclaimed water used as boiler feed water must be softened and demineralized, while process water quality is dependent on the requirements of the manufacturing process involved.[44]

3. *Recreational uses*

Reclaimed water is widely used for recreational purposes, including landscape maintenance, aesthetic impoundments, recreational lakes for swimming, fishing, and boating, ornamental fountains, snow making and fish farming.[44] The required treatment level for reclaimed water is dictated by the intended use: the greater the potential for human contact, the higher the treatment level required. For example, non-restricted recreational water use requires the treatment of secondary effluent by coagulation, filtration, and disinfection to achieve a total coliform count of fewer than 3 per 100 millilitres.[45]

---

[43] Qasim, *Wastewater Treatment Plants*.

[44] D.R. Rowe and I.H. Abdel-Magid, *Handbook of Wastewater Reclamation and Reuse* (Boca Raton: Lewis, 1995).

[45] Qasim, *Wastewater Treatment Plants*.

4. *Groundwater recharge*

Groundwater recharge using reclaimed waste-water serves to mitigate water table decline, protect groundwater in coastal aquifers against salt-water intrusion, and store reclaimed water for future use. Groundwater recharge methods include surface spreading in basins and by direct injection into aquifers. Surface spreading utilizes flooding, ridge and furrow, constructed wetlands, and infiltration basins. This application method improves the quality of the reclaimed water considerably as it percolates successively through soil, unsaturated zone and aquifer. Direct injection involves the pumping of reclaimed water directly into an aquifer. Drawbacks of this method include high effluent treatment cost and the high cost of the necessary injecting facilities. The major disadvantage of groundwater recharge using reclaimed water is the increased risk of groundwater contamination.[46,47]

5. *Potable reuse*

The issue of the use of reclaimed water for drinking purposes has been approached with extreme caution because of public rejection and because of health, safety and aesthetic concerns. Although extensive research is being conducted in this field, many constraints remain, notably the determination of appropriate quality criteria for such water. At the present time, the option of direct potable use of reclaimed municipal waste-water is limited to extreme situations.

B. EFFLUENT DISPOSAL

Treated waste-water effluent, if not reused, is disposed of either on land or into water bodies. Discharge into water bodies is the most common disposal practice. It takes advantage of the self-purification capacity of natural waters to further treat the effluent. However, waste-water effluent discharge must be based on sound engineering practice if the receiving environment is not to be adversely affected. Excessive quantities of organic material may cause rapid bacterial growth and depletion of the dissolved oxygen resources of the water body. In addition, changes in pH or concentrations of some organic and inorganic compounds may be toxic to particular life forms. Accordingly, outfall structures must be designed for adequate dispersal of the effluent in the receiving waters in order to avoid localized pollution. Depending on the characteristics of the receiving waters, many factors are considered for proper mixing and dispersal of effluent. These factors include flow velocity, depth stratification due to salinity and temperature, shape, reversal of current and wind circulation.[48] The temperature and salinity of the effluent should also be taken into consideration. The disposal area should be downstream from any location where water is to be withdrawn for human consumption. This section addresses major considerations that need to be taken into account when treated waste-water effluent is discharged into water bodies, including rivers and streams, lakes, and seas and oceans. Specific mathematical models devised to assess the effect of effluent discharge on receiving bodies and to aid in the design of outfalls will not be discussed here.

1. *Discharge into rivers and streams*

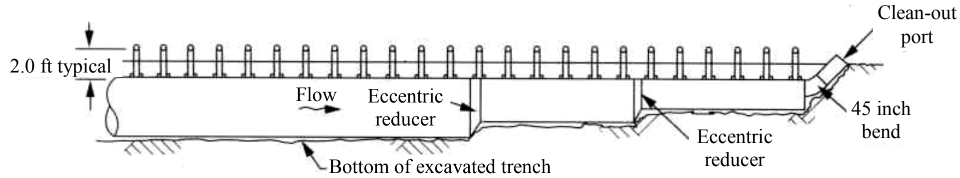
Waste-water effluent discharge into rivers should be such as to ensure rapid vertical mixing of the effluent over the full river depth and avoid foaming problems. This can be achieved by using a multiport diffuser that extends across the width of the river. A diffuser is a structure that discharges the effluent through a series of holes or ports along a pipe extending into the river (see figure 29).

[46] Rowe and Abdel-Magid, *Handbook*.

[47] Qasim, *Wastewater Treatment Plants*.

[48] R.L. Droste, *Theory and Practice of Water and Wastewater Treatment* (New York: John Wiley and Sons, 1996).

Figure 29. Typical river diffuser outfall



Source: Adapted from Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

2. *Discharge into lakes*

Being larger and deeper than rivers, lakes are subject to temperature stratification and less pronounced natural mixing via currents. Consequently, the lower strata in a lake are usually subject to conditions of low temperature and low dissolved oxygen, which slow down the decomposition of organic matter. Consequently, it is essential to ensure that appropriate mixing occurs when waste-water effluent is discharged into a lake in order to prevent the formation of an anaerobic stratum. In shallow lakes, effluents are adequately dispersed by wind-induced currents that ensure appropriate mixing.

3. *Discharge into seas and oceans*

Oceans are extensively used for waste-water disposal because of their great assimilation capacity. Waste-water is of lower density than seawater, and consequently, upon discharge, the effluent forms a rapidly rising water plume which entrains large amounts of ambient water, enhancing waste-water dilution. If the water is not stratified, the plume will rise to the surface, where the waste-water will be diluted by ambient currents. A marine outfall should be designed to ensure sufficient dilution of the effluent before it reaches the surface of the water or is carried inshore by ambient currents.[49] The outfall carries the waste-water to an offshore discharge point through a pipe laid on or buried in the ocean floor. The discharge may be through a single-port or a multiport outfall structure that is similar to a river outfall (see figure 30).

C. EFFLUENT GUIDELINES AND STANDARDS

A significant element in waste-water disposal is the potential environmental impact associated with it. Environmental standards are developed to ensure that the impacts of treated waste-water discharges into ambient waters are acceptable. Standards play a fundamental role in the determination of the level of waste-water treatment required and in the selection of the discharge location and outfall structures.

Regulations and procedures vary from one country to another and are continuously reviewed and updated to reflect growing concern for the protection of ambient waters. The United States Environmental Protection Agency (USEPA) developed the National Pollutant Discharge Elimination System (NPDES) permit programme in 1972 to control water pollution by regulating point sources that discharge pollutants into waters. Accordingly, industrial, municipal, and other facilities are required to obtain permits if their discharges go directly into surface waters. Under this programme, secondary treatment standards were established by USEPA for publicly owned treatment works (POTWs), governing the performance of secondary waste-water treatment plants. These technology-based regulations, which apply to all municipal waste-water treatment plants, represent the minimum level of effluent quality attainable by secondary treatment in terms of BOD_5 and TSS removal.[50] Table 19 lists the NPDES limitations for secondary waste-water treatment plants and the European Community Environmental Directive Requirements (EC EDR) for discharges from urban waste-water treatment plants.

---

[49] Metcalf and Eddy, Inc, *Wastewater Engineering*, 3rd edition.

[50] United States Environmental Protection Agency, *National Pollutant Discharge Elimination System: Secondary Treatment Standards* (2002). http://cfpub.epa.gov/npdes/techbasedpermitting/sectreat.cfm.

TABLE 19. USEPA, NPDES AND EC EDR FOR DISCHARGES FROM WASTE-WATER TREATMENT PLANTS

	NPDES[a/]			EC EDRWD[b/]	
Parameter	30-day average concentration	7-day average concentration	Percentage of removal[c/]	Concentration (mg/L)	Percenatge of removal[c/]
BOD_5	30 mg/L	45 mg/L	85	25	70-90
TSS	30 mg/L	45 mg/L	85	35-60	70-90
PH	6-9	-	-	-	-
COD	-	-	-	125	75
Total nitrogen[d/]	-	-	-	10-15	70-80
Total phosphorus[d/]				1-2	80

Sources: USEPA, *National Pollutant Discharge Elimination System*, and L. Somlyódy and P. Shanahan, *Municipal Wastewater Treatment in Central and Eastern Europe: Present Situation and Cost-Effective Development Strategies* (Washington, D.C.: The World Bank Group, 1998).

a/ National Pollutant Discharge Elimination System for secondary waste-water treatment plants.
b/ European Community Environmental Directive Requirements for waste-water discharges.
c/ Removals in relation to influent load.
d/ Limited to sensitive areas subject to eutrophication.

D. NEW DIRECTIONS AND CONCERNS[51]

A worldwide trend toward acceptance of the concept of reuse is currently observable, as water shortages have intensified. This has led to an increase in the use of dual water systems[52] and satellite reclamation systems.[53] At the same time, however, potential microbial and chemical water contamination, especially from new trace contaminants, has become a growing source of concern, and consequently direct potable reuse of reclaimed water is likely to remain impracticable.

In response to these increasing concerns, new technologies offering significantly higher removal rates are being designed and implemented. These technologies include pressure-driven membranes, carbon adsorption, advanced oxidation, ion exchange and air stripping systems. Membrane technologies, which were formerly restricted to water desalination applications, are now being tested for the production of high-quality water for indirect potable reuse, and are expected to become the predominant treatment technologies in the near future.

In the field of sludge reclamation and reuse technologies, increased attention is being devoted to the production of sludge that is clean, has less volume and can be safely reused. Developments in this area have been slower than in the field of waste-water treatment, but a number of new technologies have emerged, including high-solids centrifuges, egg-shaped digesters and powerful heat dryers. Other developments include temperature-phased anaerobic digestion and auto-thermal aerobic digestion processes, which destroy volatile solids more effectively and yield enhanced production of class A biosolids.[54]

Sludge landfilling and incineration continue to decrease due to stricter regulations and increased public awareness. The current trend is in the direction of more reuse opportunities through the production of class A biosolids. Volume reduction with a view to decreased disposal requirements is also an ongoing concern.

[51] Metcalf and Eddy, Inc., *Wastewater Engineering Treatment*, 4th edition.

[52] Dual water systems involve the supply of potable water and non-potable water through two separate distribution networks.

[53] In satellite reclamation systems, waste-water flows are withdrawn from the collection system, treated, and then reused locally in order to minimize transportation and treatment costs.

[54] Class A biosolids are biosolids in which pathogen concentrations have been reduced to below detectable levels.

IV. INSTRUMENTATION AND CONTROL IN WASTE-WATER TREATMENT FACILITIES

Waste-water treatment processes are characterized by continuous disturbances and variations that cannot be detected by manual measurements with the precision and within the time span necessary for maintaining proper operation of the facility. Typical process disturbances include process inputs and conditions such as variable flow rates, chemical and biological composition, temperature and density[55]. Instrumentation and automatic control allow continuous monitoring of process variables, rapid transfer of data to the operator or manager, and immediate automatic execution of corrective measures when needed. The use of instrumentation and automatic control is growing nowadays, owing to the multitude of benefits that they confer in terms of process improvement, equipment performance, and convenience to personnel (see table 20).

TABLE 20. BENEFITS OF INSTRUMENTATION AND CONTROL SYSTEMS IN WASTE-WATER TREATMENT

Purpose	Benefit
Process	Improved process performance and better process results Efficient use of energy Efficient use of chemicals Process changes detected in a timely manner Automatic execution of corrective measures Greater ability to control complex processes
Equipment	Immediate malfunction alert signal Diagnosis of problems in a remotely located equipment item before malfunction occurs Status at all times Automatic execution of corrective measures and automatic response to potentially disastrous situations Increase in running time
Personnel	Timely and accurate process information Safer operation Efficient use of labour Capability to solve analytical problems quickly Minimized potential for human error Feasibility of an overview of plant operation Decrease in manual paperwork More complete records that may allow an overview of plant operation and plant behavior, and design of future expansion Increased security

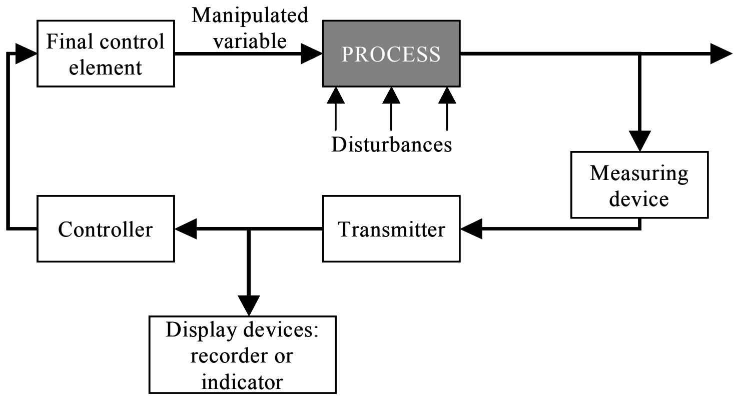
Source: Qasim, *Wastewater Treatment Plants*.

Figure 30 illustrates a typical control system, which generally comprises the following components:

(a) Measurement device;
(b) Signal transmitting device;
(c) Data display or readout;
(d) Control system;
(e) Computer and central control room.

[55] H.D. Gilman et al., *Instrumentation in Wastewater Treatment Facilities*. Manual of Practice No. 21 (Alexandria, Virginia: Water Environment Federation, 1993).

Figure 30. Typical control system components



Source: Qasim, *Wastewater Treatment Plants*.

A. MEASURING DEVICES

Measuring devices, referred to as sensors, include instruments that sense, measure or compute the process variables. These variables fall into three categories: physical (flow, pressure, level, temperature, etc.), chemical (pH, oxidation-reduction potential, turbidity, specific conductance, dissolved oxygen, chlorine residual, and so on) and biological (oxygen consumption rate, TOC reduction rate, sludge growth rate, etc.). Sensor devices can measure variables directly, indirectly or by inferential means. Moreover, measurements may be performed on-line or off-line, continuously or intermittently.[56,57] Some commonly used on-line process measurement devices and their applications are summarized in annex I.

B. SIGNAL-TRANSMITTING DEVICES

The function of a signal-transmitting device is to transmit a process variable signal from a sensor to a readout device or controller. The signal may be transmitted *mechanically*, by means of the movement of a pen, indicator, float or cable, *pneumatically* by means of a detector or an amplifier, or *electronically* by means of voltage and current, pulse duration, or tone. In voltage and current transmission, signals are transmitted by milliamp direct current or by voltage signals. In pulse duration or time-pulse transmission, the length of time the voltage is transmitted is in proportion to the measured data. In tone transmission, standard telephone lines are normally used to transmit signals.

Radio/microwave transmission has recently been developed and put into practice. This transmission method is particularly advantageous where the gathering points are scattered over a large area and where telephone lines are either not available or prohibitively expensive. Electronic and radio/microwave control systems are becoming more attractive for a number of reasons.[57] Electronic signals can operate over great distances without causing time lags, they can be made compatible with a digital computer, and they can handle multiple signal inputs. Furthermore, electrical hazards have been eliminated by intrinsic safety techniques. Electronic devices are often comparatively small in size and relatively inexpensive, and they can be maintenance-free.

C. DATA DISPLAY READOUT

Readout devices display the transmitted operation in a configuration that is usable by the operator. The most common types of readout devices are indicators, recorders, and totalizers on panels or computer

[56] Qasim, *Wastewater Treatment Plants*.

[57] Gilman et al., *Instrumentation*.

screens. The data display is placed either locally, close to the equipment site, or at a central operating room for the whole facility.

D. Control systems

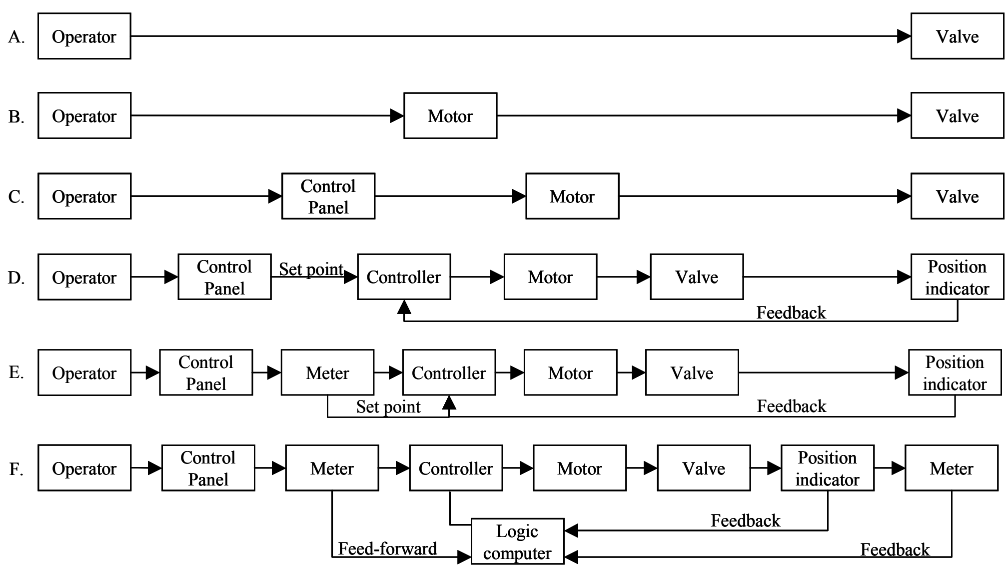
Time control systems used in waste-water engineering fall into three categories:

(a) Digital control;
(b) Analog control;
(c) Automatic control.

Digital control systems have two positions (on/off, open/close, alarm/normal). The transmitted signal, which originates from a position, limit, float or pressure switch, indicates a status change. Analog control systems, in contrast, transmit data as a range of values measuring flow rate, concentration and level. Analog data may be reused and transmitted unchanged, converted to digital form, or transmitted as a combination of the two.

Automatic control systems may be discrete or continuous. In discrete control, the status of equipment and status changes (digital measurement) are correlated with a preset value or programme of events. The operation may be initiated manually by the operator, using a push button, or automatically by an internal process-generated event. Continuous control, on the other hand, requires analog measurement for its input and manipulates a final control element as its output. The control element may be feedback and feed-forward control loops and control systems or controllers. The devices automatically regulate the control variable.[58] Control loops and control systems may be set up in a variety of configurations, as demonstrated in figure 31.

Figure 31. Examples of control systems



Note: A. Manual control; B. Facilitated manual control; C. Remote manual control; D. Automatic feedback control; E. Automatic feed-forward control; and F. Automatic feed-forward-feedback computer control.

[58] Qasim, *Wastewater Treatment Plants*.

E. Data acquisition systems

Data acquisition systems effectively accumulate, format, record, and display data transmitted from sensors. Modern data acquisition systems, commonly referred to as Supervisory Control and Data Acquisition (SCADA) systems, can provide accurate, impartial documentation of process measurements and operator actions. In addition to data accumulation and processing, SCADA systems can produce the necessary process corrections such as chemical solutions, air supply, pump scheduling, and so on.

Data acquisition systems are located in a central control room, displaying treatment information, important events and alarms in a centralized location. Automatic or manual actuation of final control elements is also performed at the central control room, with the result that fewer personnel are required to operate a large treatment facility.

F. Artificial intelligence

New technological advances have made it feasible to use artificial intelligence for the monitoring and control of operations in a waste-water treatment plant. Three systems have been developed for that purpose, namely, expert systems, fuzzy control systems, and neural networks. Expert systems were the first to be developed, followed by fuzzy control systems. Neural networks are relatively new and have not yet been extensively developed for use in waste-water management.[59] Table 21 describes the three systems and their applications.[60]

Table 21. Artificial intelligence systems

Artificial intelligence system	Description
Expert System	▪ Involves mathematical models that incorporate concepts and facts used by experienced operators for decision-making ▪ Consists of an interactive interface allowing operators to meet their information needs ▪ May be regarded as rudimentary compared to the complexity of the treatment operations ▪ Experts may disagree on proposed rules
Fuzzy Control System	▪ Consists of a reasoning system that incorporates qualitative and/or quantitative models of processes and mixtures of automatic control and expert systems techniques. - Uses expert systems to control plant operations - Expresses experts' operating methods with IF-THEN control rules ▪ Executes data and performs feedback control of the process ▪ Allows smooth control of processes, reduces operator workload, reduces chemical use, reduces energy demand and improves overall system performance
Neural Networks System	▪ Provides the computer system with learning capabilities ▪ System is supplied with a set of input data and a set of expected results or output data, and then learns by adapting its internal recognition formulations ▪ Once trained, the system is capable of solving problems by comparing the inputs to its previous experience and plant historical data ▪ Potential disadvantage that no warning may be given if the process reaches a state that has not occurred previously

Source: Qasim, *Wastewater Treatment Plants*, and Gilman et al., *Instrumentation*.

[59] Qasim, *Wastewater Treatment Plantsn* and T.M. Garrett Jr., "Instrumentation, Control and Automation Progress in the United States in the Last 24 Years," *Water Science and Technology*, 37 (1998), 21-25.

[60] Gilman et al., *Instrumentation*.

G. Application in the waste-water treatment plant

There are many factors that determine the need for instrumentation and control elements in waste-water systems. These factors include the size of the facility, hours of manned operation, complexity of the process, reliability requirements, and availability of instrumentation maintenance personnel. Ultimately, most of the resultant decisions are made on an economic basis. The decision to use instrumentation, automation, and control in waste-water treatment systems should be made early in the conceptual design phase of a facility, as it influences the design of the entire system; the size and configuration of existing vessels, tanks, channels, pipes and mechanical equipment will frequently have to be substantially altered to accommodate good instrumentation and control practices.[61] There is a wide range of variables that can be monitored within each treatment unit used at the facility. Annex table 6 outlines the functions that can be monitored for various treatment processes.

H. New directions

As new and more sophisticated instrumentation is developed, waste-water characterization is likely to improve in the years to come. With devices that can measure values of micrograms and even nanograms per liter, contaminants that are present only in trace amounts will be accurately detected. This means that a broader range of compounds will be monitored, and that stricter limits imposed on waste-water discharges will be met.

Improved characterization of waste-water, made possible by more sensitive detection methods and advanced analytical techniques, will also yield more knowledge about the behavior of waste-water constituents and their relationship to process performance. This is especially true for biological treatment processes, where microbiological techniques, including RNA and DNA typing, help optimize process performance. As process modeling becomes more accurate, the design and operation of waste-water treatment facilities will be greatly enhanced.[62]

---

[61] Gilman et al., *Instrumentation*.

[62] Metcalf and Eddy, Inc., *Wastewater Engineering*, 4th edition.

V. ECONOMICS OF WASTE-WATER TREATMENT

The selection and design of waste-water treatment facilities is greatly dependent on the costs associated with treatment processes, including capital investment, operation and maintenance, land requirements, sludge handling and disposal, and monitoring costs. This chapter examines cost estimation methodologies for various water treatment technologies and provides illustrative examples of cost estimates as reported in the literature.

A. THE WATER TREATMENT COST ESTIMATION PROCESS

The process of evaluating and selecting appropriate water treatment technology usually begins with a technical feasibility study that depends on the nature of the application. Cost-effectiveness evaluation is undertaken only after existing and future conditions have been estimated, waste-water volume and characteristics forecast, and process alternatives for waste-water treatment, effluent and sludge management identified and compared in terms of their effectiveness.

According to S. R. Qasim, 'a cost-effective [waste-water treatment] solution is one that will minimize total costs of the resources over the life of the treatment facility.[63] Resources are the capital, operation and maintenance costs, but also social and environmental costs. Benefits from sludge and effluent reuse must also be included in the feasibility study.

Water treatment cost estimation requires a thorough knowledge of the mechanical elements involved. In addition, experience and sound judgment are necessary, since there are a number of parameters that cannot easily be quantified. When the costs associated with two or more processes appear to be equal, sensitivity analysis with respect to estimate inaccuracies must be performed to break the tie.

In this section, the cost estimation process is described in general terms, and the cost elements usually included in an estimate are indicated.

1. *Levels of cost estimate*[64]

According to the American Association of Cost Engineers (AACE), the following three levels of cost estimate are needed throughout the design process: order-of-magnitude, preliminary and definitive. Other authorities have defined a fourth level of estimate, termed the conceptual level estimate, which comes between the order-of-magnitude and preliminary estimates.

Historical data from similar projects usually provides a good order-of-magnitude estimate. The processes used in both projects must be similar, while differences in capacity can be resolved through proper factorization. In general, a conceptual cost estimate is needed when alterations to an existing plant are under consideration. A preliminary definition of the scope of work must be identified, including the major process and work elements required.

The preliminary design cost estimate determines the financial feasibility of the project and provides a cost baseline. At this stage, major facilities and equipment must be identified and sized, usually according to manufacturers' specifications. It is a genuinely multidisciplinary effort, and all design engineers must take part in the process, which is known as the design-to-cost process.

---

[63] Qasim, *Wastewater Treatment Plants*.

[64] American Water Works Association (AWWA) and ASCE, *Water Treatment Plant Design* (New York: McGraw-Hill, 1990).

When the design document is finalized, a definitive level estimate can be produced. This estimate is not expected to vary from the preliminary design estimate by more than 15 per cent; if it does, the reason for the deviation must be determined. The definitive level estimate is commonly used as a contract price for construction contractors. Vendor quotations for all equipment used must be confirmed at this stage. Great care must be taken to ensure that all cost items have been included.

2. *Contingencies*

In almost all projects, contingencies may be expected to occur. Table 22 lists the levels of accuracy and recommended contingency for each level of cost estimate. Of course, high contingencies are allowed for estimates with low degrees of confidence. As the design process progresses, the known project cost will increase, but contingencies will decrease, so that the total project cost will remain unchanged.

TABLE 22. LEVELS OF COST ESTIMATES
(*Percentage*)

Type of cost estimate	Level of accuracy	Recommended contingency
Order-of-magnitude	+ 50 to – 30	20 to 30
Conceptual	+ 40 to – 20	20 to 15
Preliminary design	+ 30 to – 15	15 to 10
Definitive	+ 15 to – 5	10 to 5

Source: AWWA and ASCE, *Water Treatment Plant Design*.

3. *Estimation of capital costs*

In addition to the cost of the treatment unit and its ancillary equipment, the capital costs of investment include piping, instrumentation and controls, pumps, installation, engineering, delivery and contingencies. Historical cost data are commonly used for capital cost estimates. These data are most useful when they incorporate enough detail to allow cost estimates for different plant sections separately. A breakdown according to a standardized format, such as that given by the Construction Specification Institute, for example, helps produce more accurate conceptual and preliminary cost estimates.

For the purpose of conceptual or preliminary design estimates, or when historical data are not available, cost estimation factors can be used. The cost of the major process equipment must be known, primarily from vendors' quotations. Examples of cost factors from two sources are listed in table 23 and table 24. According to table 23, the total project cost is approximately 525 per cent of the equipment cost, including miscellaneous items.

Another rule of thumb, known as the six-tenths rule, is used to compare the costs of two plants using the same process but with different capacities, according to the following equation:[65]

$$\text{Cost}_{\text{new plant}} = \text{Cost}_{\text{existing plant}} \times (\text{Capacity}_{\text{new plant}} / \text{Capacity}_{\text{existing plant}})^{0.6}$$

[65] AWWA and ASCE, *Water Treatment Plant Design*.

TABLE 23. STANDARD CAPITAL COST ALGORITHM

Factor	*Capital cost*
Total construction costs (TCC)	
Equipment cost (EC)	Technology-specific cost
Installation	25 to 55 per cent of EC
Piping	31 to 66 per cent of EC
Instrumentation and controls	6 to 30 per cent of EC
Total indirect cost (TIC)	
Engineering	15 per cent of TCC
Contingency	15 per cent of TCC
Total capital cost	TCC + TIC

Source: USEPA, *Detailed Costing Document for the Centralized Waste Treatment Industry*, EPA 821-R-98-016 (1998). http://www.epa.gov/ostwater/guide/cwt.

TABLE 24. PERCENTAGE OF TOTAL FACILITY COST BASED ON HISTORICAL COST DATA
(*Percentage*)

Equipment cost	100.0
Equipment installation	50.0
Process mechanical piping	65.0
Instrumentation and control	20.0
Electrical	10.0
Buildings	20.0
Yard improvements	10.0
Service facilities	70.0
Engineering and supervision	35.0
Project management and overhead	40.0
Total percentage of equipment cost	420.0
Subtotal percent of project cost for above	80.0
Additional project cost elements	
Miscellaneous and unidentified equipment	10.0
Miscellaneous and unidentified process mechanical	5.0
Miscellaneous and unidentified electrical/I&C	5.0
Percentage of total project cost	100.0

Source: AWWA and ASCE, *Water Treatment Plant Design*.

4. *Land requirements*

The land requirements include the total area needed for the equipment plus peripherals (pumps, controls, access areas, and so on). Land requirements for each new equipment item are based on equipment dimensions. Additionally, a 20-foot perimeter around each unit can be assumed. Land requirement equations have been developed for each technology. The land requirements are further multiplied by the corresponding land costs to obtain facility-specific land cost estimates.[66]

5. *Preparation of the O&M budget*

The annual O&M costs include the costs of maintenance, taxes and insurance, labour, energy, treatment chemicals (if used) and residuals management (if needed). Table 25 presents annual O&M costs

[66] USEPA, *Detailed Costing Document*.

for various systems derived by the USEPA from vendors' information or from engineering literature. Major cost elements of the O&M budget are briefly outlined in the following sections.

TABLE 25. STANDARD OPERATION AND MAINTENANCE COST FACTOR BREAKDOWN

Factor	O&M 1998 USD/year
Maintenance	4 per cent of total capital cost
Taxes and insurance	2 per cent of total capital cost
Labour	$30,300 to $31,200 per man-year
Electricity	$0.08 per kilowatt-hour
Chemicals:	
Lime (calcium hydroxide)	$57 per ton
Polymer	$3.38 per pound
Sodium hydroxide (100% solution)	$0.28 per pound
Sodium hydroxide (50% solution)	$0.14 per pound
Sodium hypochlorite	$0.64 per pound
Sulfuric acid	$1.34 per pound
Ferrous sulfate	$0.09 per pound
Hydrated lime	$0.04 per pound
Sodium sulfide	$0.30 per pound
Residuals management	Technology-specific cost

Source: USEPA, *Detailed Costing Document*.

(a) *Labour budget*

Initial staffing cost includes recruitment cost. A continuing staffing cost is also added to the budget to account for employee turnover. The number of staff required and corresponding labour rates must be established. Staff requirements depend on the level of automation, the number of processes and the degree of plant spreadout. Table 26 presents an estimate of staff requirements for two 50 mgd and two 5 mgd conventional water treatment plants that differ in respect of their levels of automation. As will be seen from this table, a large-capacity facility that is fully automated will require a significantly smaller number of operators.

Training cost is highest at initial startup, but is expected to continue during the lifetime of the facility, in order to stay ahead of a constantly evolving technology.

TABLE 26. ESTIMATE OF STAFF REQUIREMENTS FOR 50 AND 5 MGD WATER TREATMENT PLANTS

	50 mgd water treatment plant		5 mgd water treatment plant	
Position	Semiautomatic	Fully automatic	Semiautomatic	Fully automatic
Plant manager	1	1	1	1
Operations supervisor	1	1	0	0
Maintenance supervisor	1	1	0	0
Operator	15	5	5	1
Mechanical technician	3	3	1	1
Electronics technician	2	2	1*	1*
Instrument technician	2	3	0	1
Laboratory technician	2	2	1	1
Buildings maintenance	1	1	1**	1**
Grounds maintenance	1	1	0	0

Source: AWWA and ASCE, *Water Treatment Plant Design*.

* Position split between electrical and instrumentation duties.

** Position split between janitorial and groundskeeping duties.

(b) *Chemical budget*

All chemicals must be listed, and quantities for specific operational requirements must be estimated. Price quotes are then obtained from several vendors. A strictly maintained inventory is essential in order to regulate the use of chemicals, particularly those with a limited shelf life, and to avoid possible losses.

It is also important to take the cost of providing adequate storage facilities into consideration, since suitable storage conditions will not merely preserve but actually extend the shelf life of chemicals. Adequate measures must be taken for the disposal of expired chemicals and other chemical wastes, and the associated costs must be taken into account.

(c) *Utilities budget*

The utilities budget includes the cost of power, gas, sewer and telephone, the most significant of these being power. Possible ways of reducing power costs should be considered, such as operating at off-peak rates, if available, and the use of energy-efficient electrical equipment.

It is important to note that actual energy consumption may be much higher than the amount calculated for theoretical conditions. Distillation processes, for example, may require temperatures as much as 20°C higher than those indicated by theory in order to accelerate heat transfer in systems with small heat transfer areas, resulting in increased energy consumption.[67]

(d) *Equipment maintenance budget*

This budget will inevitably increase as the waste-water treatment plant ages. It includes replacement costs for equipment, consumables and maintenance tools. When costly equipment is involved, replacement frequencies and cost must be envisaged in full detail, as otherwise the feasibility of the entire project may be jeopardized. In reverse osmosis, for example, membrane fouling rates affect membrane replacement costs and consequently must be estimated with a high degree of accuracy.[68]

6. *Other cost considerations*

It is essential not to overlook unique project conditions that are not usually reflected in historical data, as these conditions may entail substantial additional costs. The most pertinent of these are geotechnical and site constraints.[69] If, for example, the plant is located far from its primary water source, the cost of material transportation may be substantial. In some cases, soil conditions may be less than ideal for construction, with the result that additional foundation support is required.

7. *Methods of financial analysis*

Common methods of financial analysis can be applied once the original capital and operating costs and interest rates are established, including for example, the payback period, the internal rate of return, and the net present value.[70] Box 1 illustrates how the payback period method was applied to determine the viability of using RO for treating rinse water in an electroplating facility.

---

[67] G.A. Pittner, "The Economics of Desalination Processes," Chapter 3 in *Reverse Osmosis: Membrane Technology, Water Chemistry, and Industrial Applications*, edited by Z. Amjad (New York: Van Nostrand Reinhold, 1993).

[68] Ibid.

[69] AWWA and ASCE, *Water Treatment Plant Design*.

[70] Pittner, "Economics of Desalination".

Box 1. Reverse osmosis economics for an electroplating facility

An electroplating facility is considering the use of reverse osmosis (RO) for the treatment of rinse water. Benefits are expected through the reuse of rinse water and metals recovered. Table 27 summarizes the results obtained through the payback period method. It can be seen from this table that payback periods depend both on feed flow and concentration. RO treatment of nickel rinse water seems to be economically feasible, with short payback periods, while it is less economical for chromium.

TABLE 27. PAYBACK PERIODS FOR NICKEL, CADMIUM AND CHROMIUM RINSE WATERS

Rinse water	Membrane	Feed concentration (mg/l)	Payback period (years)		
			5 m^3/h	5 m^3/d	15 m^3/d
Nickel	Tubular cellulose acetate	2 035	1.3	2.1	1.7
Cadmium	Spiral wrap polyamide	588	3.0	4.8	3.9
Cadmium	Spiral wrap polyamide	223	5.9	9.4	8.0
Chromium	Spiral wrap thin film composite	1 840	7	No net savings	9.9

Source: J.J. Schoeman et al., "Evaluation of reverse osmosis for electroplating effluent treatment", *Water Science and Technology*, 25, 10 (1992): pp. 79-93

8. *Water treatment cost estimation tools*

A number of computer tools have been developed to assist the designer in estimating water treatment system cost. These tools are helpful in arriving at first-level estimates, but should be used with caution, since they incorporate many simplifying assumptions. In this section, two examples of software programmes are discussed. The purpose is purely illustrative, and full coverage of these software programmes is not attempted here.

(a) *WaTER software*[71]

The United States Bureau of Reclamation, jointly with the National Institute of Standards and Technology, has developed a spreadsheet tool called Water Treatment Estimation Routine (WaTER) to facilitate parameter and system cost estimation. This tool is publicly available for download.[72] WaTER cost estimates are based on cost curves published by the Environmental Protection Agency (EPA)[73] of the United States and a report by S.R. Qasim.[74] The spreadsheet calculates dosage rates and costs for the processes listed below:

- pH adjustment with sulfuric acid;
- Disinfection with chlorine, chloramine, and ozone;
- Coagulation/flocculation with alum, ferric sulfate and lime/soda ash using upflow solids contact clarifiers;
- Filtration enhancement with polymer feed;

[71] M.C. Wilbert et al., *Water Treatment Estimation Routine (WaTER) User Manual* (Denver: United States Department of the Interior, August 1999).

[72] Available at: http://www.usbr.gov/water/media/spreadsheets/costpc.xls.

[73] USEPA, *Estimating Water Treatment Costs, Volume 2: Cost Curves Applicable to 1 to 200 mgd Treatment Plants*, EPA 600012-79-162.

[74] S.R. Qasim et al., "Estimating Costs for Treatment Plant Construction", *Journal of the American Water Works Association*, August 1992.

- Filtration with granular activated carbon and granular media;
- Microfiltration as pretreatment to remove particulate matter;
- Demineralization with ion exchange, electrodialysis and reverse osmosis;
- Pumping: raw water, backwash and finished water pumping.

The following input information is required for all processes:

- Planned plant feed flow rate in L/sec;
- Desired plant product flow rate in L/sec;
- Water analysis;
- Cost indices (February 1999 included).

The general input screen is shown in annex figure 4. In addition to the above, process-specific input is required, as illustrated in annex figure 5 for an RO-NF process. Additional input in this case includes membrane data from manufacturers' information sheets, system size, including number of modules and vessels, and number of pumps.

The output of the routine is the capital cost estimate, direct and indirect, and the O&M cost estimation. Annex figure 6 shows the output screen for an RO-NF process.

The advantage of this routine is that it facilitates sensitivity analysis with respect to process parameters. In addition, cost indices (such as workforce wages and power cost) can be updated by the user, according to local values. The major disadvantage is that user intervention and data manipulation are required to simulate a plant with multiple processes.

(b) *CAPDET*

In 1973, EPA joined forces with the United States Army Corps of Engineers in developing a model, CAPDET, that allows designers to perform preliminary cost comparisons between possible treatment options.

The CAPDET model was further developed by Hydromantis and implemented in a software tool, CapdetWorks. A free demonstration copy of this software can be obtained from the Hydromantis website.[75] The software is graphical, and is designed to require only a minimal amount of user input, including water influent and effluent quality and the treatment strategy in question. It uses design algorithms and cost estimation techniques to produce the process design and cost.

The unit processes included in the software are listed in the table in annex IV. Annex IV also shows some illustrative screens obtained from the demo version, comparing the costs of an activated sludge system to those of a trickling filter system.

B. ECONOMICS OF MEMBRANE AND ION EXCHANGE SYSTEMS

Due to their steadily falling costs and improving performance, membrane processes are now able to compete with conventional treatment technologies. While their performance, small land requirements and ease of O&M are uncontested, cost data are needed to prove that membrane technologies are truly viable,

[75] Available at: http://www.hydromantis.com/demos02.html.

and alter long-standing misconceptions.[76] This section looks at the costs of RO, MF, UF and NF, and gives an overview of IX costs for comparison purposes.

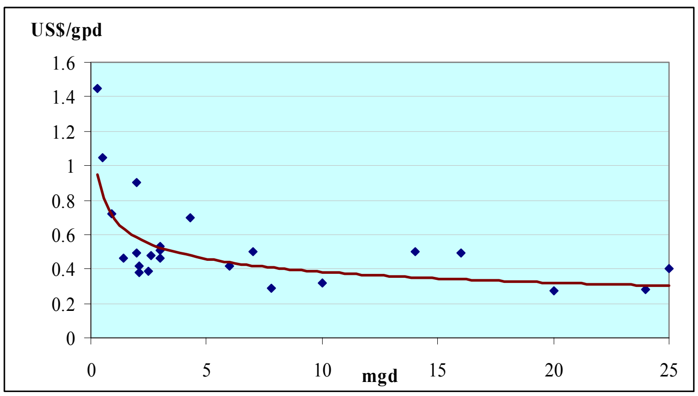
1. *Typical reverse-osmosis costs*

(a) *Equipment cost*

RO equipment typically includes the following components: membrane module, clean-in-place equipment, pumps, blowers, control equipment and tanks. Membrane module cost is proportional to capacity, while economies of scale can be achieved with respect to the cost of the remaining equipment. It follows that large-capacity systems are characterized by relatively low overall equipment costs. This trend, however, becomes insignificant with very large systems (over 2 mgd), because the membrane module cost represents the largest portion of the overall cost (see figure 32). As this figure shows, equipment costs ranging between US$ 0.4 and US$ 0.8 per gpd are common.[77]

Pretreatment equipment cost depends on the nature of the water supply; it is estimated at 30 per cent of the cost of an RO unit for moderate pretreatment. Polishing equipment cost is estimated at 30-50 per cent of RO unit cost, while the installation cost for the whole system usually amounts to 30 per cent of the RO equipment cost.

Figure 32. Unit installed equipment cost of RO filtration plants



Source: Elarde and Bergman, "The cost of membrane filtration".

Note that the cost curve is based on a flux of 50 gpd/sf. For other flux values, the cost curve must be multiplied by the ratio of the actual flux to 50gpd/sf. Fitting the data points, we obtain the curve defined by the equation:[78]

$$\text{Cost (US\$/gpd)} = 0.6946 \times [\text{capacity (mgd)}]^{-0.2582}$$

During the 1970s and 1980s, membrane module prices held steady in Europe, whereas they witnessed a steadey decline in the United States.[79] This drop in price is attributed to the adoption of RO technology by a number of industries in the United States, including in particular the dairy industry.

---

[76] J.R. Elarde and R.A. Bergman, "The cost of membrane filtration for municipal water supplies", Chapter 1 in *Membrane Practices for Water Treatment*, edited by S.J. Duranceau (Denver: American Water Works Association, 2001).

[77] Data in this figure were obtained from a survey of 25 recently constructed facilities in the US and Canada. The table in annex E gives the membrane filtration cost data obtained through this survey.

[78] Elarde and Bergman, "The cost of membrane filtration".

[79] Wagner, *Membrane Filtration Handbook*.

In fact, the massive use of spiral-wound elements in the dairy industry at the end of the 1980s was a contributing factor in the sharp fall in the price of these modules. To illustrate: the price of a complete spiral-wound system, including membrane, internal piping and tubing, valves, pumps and control equipment, dropped from US$ 1,400 per m^2 to US$ 370 per m^2 of membrane area installed.[80]

The price continued to decline through the 1990s, and as a result a dairy system nowadays costs approximately US$ 150-250 per square metre. Similarly, a pharmaceutical membrane system costs approximately US$ 200-300 per square metre, while a water system typically sells for US$ 70-150 per square metre. These falling prices will undoubtedly widen the client base, but are also expected to make services and warranties less accessible and more expensive.[81]

Table 28 provides a rough cost comparison between spiral-wound, tubular flat sheet, fiber and ceramic membrane systems. Prices vary greatly, depending on country, number of elements and element construction.

TABLE 28. COST COMPARISON OF VARIOUS RO MEMBRANE SYSTEMS

Type	Complete system cost per m^2 of membrane area (US$/$m^2$)	Membrane replacement cost (US$/$m^2$)	Remarks
Spiral-wound	300–500	Thin film RO: 15-25 Thin film NF: 20-40 Polysulfon UF: 25-50 Specialty element: 35–70	Prices are not expected to drop further in the near future, since suppliers' profit margins are minimal
Tubular sheet	300–500 (low end systems) 1,000 (high end systems)	120	
Plate and frame	2,000–3,000	130–180	Price is being kept high for political reasons
Fiber	> 1,700	700	Used mainly in oil emulsion treatment and whole milk
Ceramic	3,000–10,000	N/A	Used only for very special products due to high cost

Source: *J.* Wagner, *Membrane Filtration Handbook: Practical Tips and Hints (*Osmonics, Inc., 2001).

(b) *Plant construction cost*

Construction costs of the surveyed plants[82] are very scattered because of differences in pretreatment equipment, configuration and location. However, a cost curve plotted against plant capacity is useful as a means of obtaining an order-of-magnitude approximation of construction cost (see figure 33). The cost curve shows economies of scale up to a capacity of 5 mgd. When data are fitted, the following equation is obtained:[83]

$$\text{Cost (US\$/gpd)} = 2.4914 \text{ x [capacity (mgd)]}^{-0.3471}$$

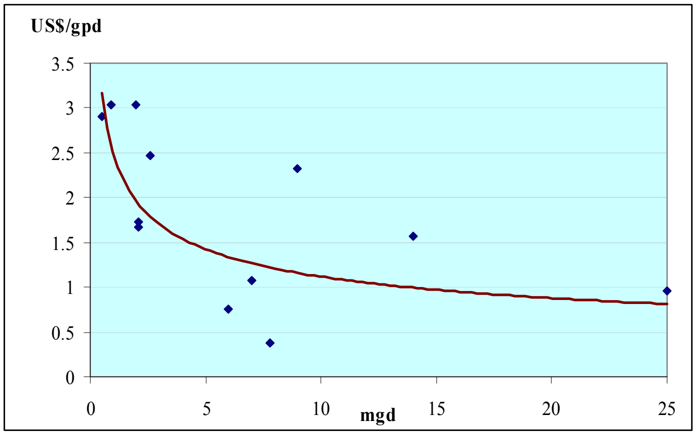
[80] Ibid.

[81] Ibid.

[82] Elarde and Bergman, "The cost of membrane filtration".

[83] Ibid.

Figure 33. Unit construction cost of membrane filtration plants

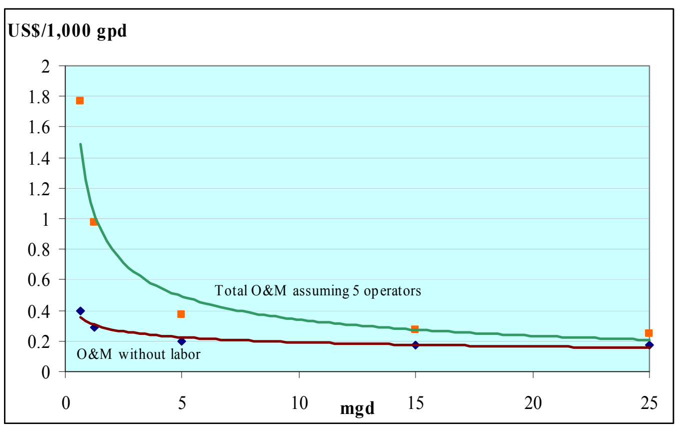


Source: Elarde and Bergman, "The cost of membrane filtration".

(c) *Operation and maintenance costs*

Excluding labour, critical O&M cost elements are primarily membrane replacement, chemicals and power. These costs are proportional to plant capacity, but do not vary greatly, and thus economies of scale can be achieved up to 5 mgd. For very large plants, with capacity in excess of 25 mgd, O&M costs are in the vicinity of US$ 0.1-0.15 per 1,000 gallons of produced water (see figure 34).[84]

Figure 34. Unit RO filtration O&M cost



Source: Elarde and Bergman, "The cost of membrane filtration".

(i) *Chemicals*

The cost of chemicals is variable, depending on location. The types of chemicals used include coagulants, salt, chemical conditioning agents, reducing agents, antiscalant and dispersants.

[84] Ibid.

(ii) *Power*

RO processes are heavy consumers of power. A single-stage, thin-film composite RO system with a pump efficiency of 78 per cent and a motor efficiency of 93 per cent requires 4 kWh per 1,000 gallons of produced water, while a double pass RO system consumes 8 kWh per 1,000 gallons of product water.

Power consumption is dependent on source water quality. Seawater RO, for example, will consume approximately 25-30 kWh per 1,000 gallons of product water. This is attributable to the fact that the system must operate at higher pressures with lower recovery rates.

(iii) *Membrane cleaning and replacement*

Membrane replacement accounts for 6-10 per cent of the total water production cost. Membrane cost is usually depreciated over a lifetime of 3-5 years. By way of example, the price of an 8 x 40 inch thin-film composite module is approximately US$ 1,200. The same membrane module, but for seawater RO, costs approximately US$ 1,700.

Membranes are cleaned every six months on average, depending on the quality of the water input. Cleaning frequencies of more than three years for good-quality water supplies and one month for low-quality water supplies are common. The cost of the chemicals required to clean averages some US$ 50.

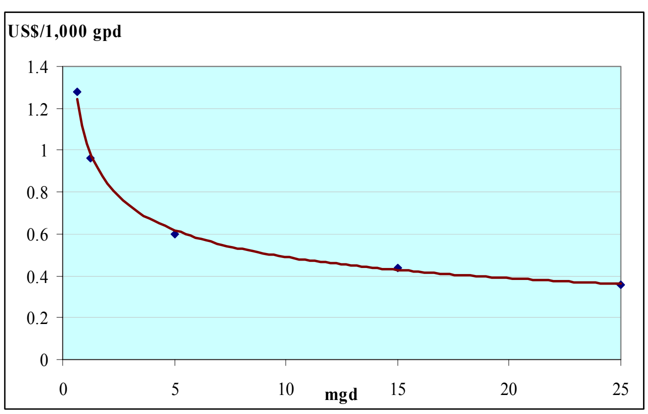
(iv) *Equipment maintenance*

Equipment maintenance accounts for approximately two per cent of equipment costs for brackish water RO, and may account for as much as four per cent of equipment costs for seawater RO, due to corrosion. Maintenance includes the repair and calibration of equipment and pumps, seal replacements and piping.

(d) *Total plant cost*

After amortizing equipment and construction costs over 20 years and adding in O&M costs, the total cost curve shown in figure 35 is obtained, expressed in US$ per 1,000 gallons. Above 5 mgd, membrane cost becomes the most important factor (more than 50 per cent of the total cost). The decreasing cost of membrane modules thus holds out the prospect of more widespread use of membrane technology. The quality of source water and target product water determines what type of membrane equipment must be used, and thus is a major component of plant cost.

Figure 35. Unit RO filtration total water treatment cost



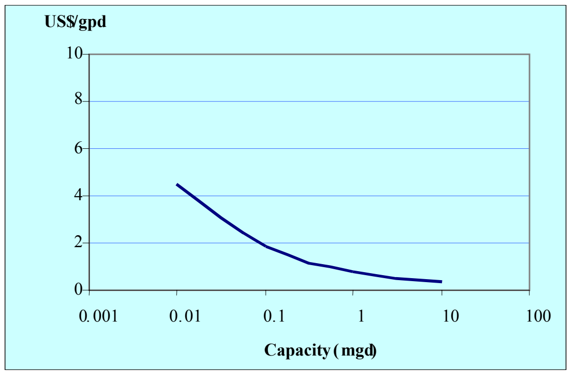
Source: Elarde and Bergman, "The cost of membrane filtration".

2. *Microfiltration and ultrafiltration costs*

Larger-capacity MF and UF plants are becoming economically viable, according to a recent survey of 74 such plants worldwide.[85] The treatment unit cost ranged between US$ 0.5 per 1,000 gallons for plants with capacities in excess of 5 mgd, and US$ 2.5 per 1,000 gallons for plants with a capacity of 0.01 mgd. Membrane system unit costs appeared to be similar for UF and MF. Fitting the data points, the following equation was obtained for membrane system unit cost (Y) as a function of plant capacity (X) (see figure 36):[86]

$$Y \text{ (US\$/gpd)} = 0.78\ X^{-0.38}$$

Figure 36. MF and UF system unit cost as a function of plant capacity

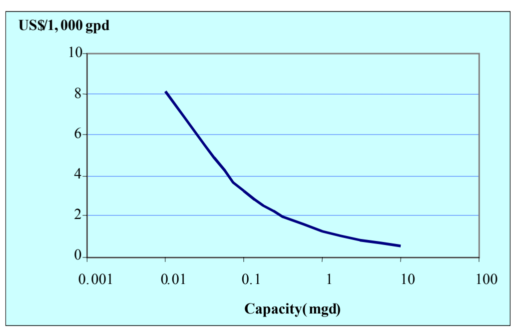


Source: Adham, Jacangelo and Lainé, “Characteristics and costs of MF and UF plants”.

As regards plant capital cost, including the cost of the membrane system in addition to the cost of all other process equipment,[87] the survey concluded that economies of scale were possible, and that both UF and MF were characterized by similar plant capital unit costs for small-scale plants (under 1 mgd). Fitting the data points, the following equation was obtained for plant capital unit cost (Y) as a function of plant capacity (X) (see figure 37):[88]

$$Y \text{ (US\$/1,000 gpd)} = 1.29\ X^{-0.40}$$

Figure 37. MF and UF plant capital unit cost as a function of plant capacity



Source: Adham, Jacangelo and Lainé, “Characteristics and costs of MF and UF plants”.

---

[85] S. Adham, J. Jacangelo and J.M. Lainé, “Characteristics and costs of MF and UF plants,” *Journal AWWA*, May 1996.

[86] Ibid.

[87] These include electrical supply, disinfection, storage, pumping and wash water recovery systems.

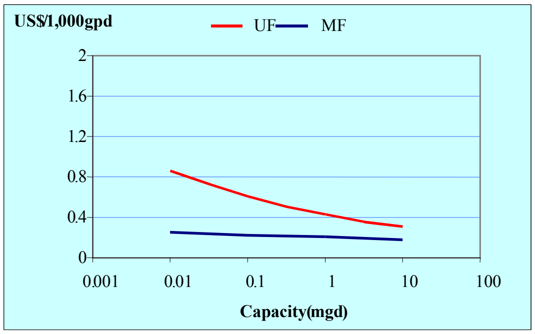
[88] Adham, Jacangelo and Lainé, “Characteristics and costs of MF and UF plants”.

With respect to O&M costs, MF plants appeared to have lower costs than UF plants, presumably because of their lower power consumption and membrane replacement costs.[89] Again, fitting the data points, the following equations were obtained for O&M cost (Y) as a function of plant capacity (X) (see figure 38):[90]

$$\text{UF: } Y \text{ (US\$/1,000 gpd)} = 0.43\ X^{-0.15}$$

$$\text{MF: } Y \text{ (US\$/1,000 gpd)} = 0.20\ X^{-0.053}$$

Figure 38. MF and UF O&M cost as a function of plant capacity



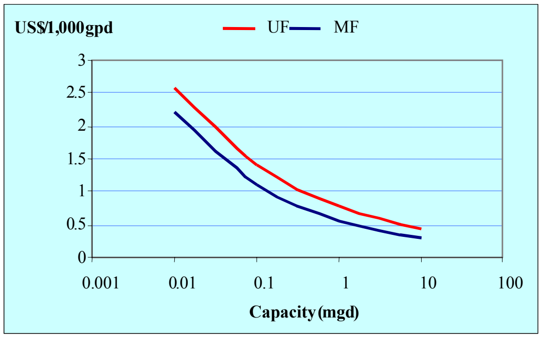
Source: Adham, Jacangelo and Lainé, "Characteristics and costs of MF and UF plants".

Finally, the capital cost was amortized over a 20-year period with a seven per cent interest rate, and the value obtained was added to the O&M cost to obtain the treatment unit cost. A lower treatment unit cost was found for MF than for UF, due to the lower O&M cost associated with the former. The equations obtained for MF and UF were as shown below (see figure 39):[91]

$$\text{UF: } Y \text{ (US\$/1,000 gpd)} = 0.78\ X^{-0.26}$$

$$\text{MF: } Y \text{ (US\$/1,000 gpd)} = 0.56\ X^{-0.30}$$

Figure 39. MF and UF treatment unit cost as a function of plant capacity



Source: Adham, Jacangelo and Lainé, "Characteristics and costs of MF and UF plants".

---

[89] Ibid.

[90] Ibid.

[91] Adham, Jacangelo and Lainé, "Characteristics and costs of MF and UF plants".

3. *Nanofiltration costs*

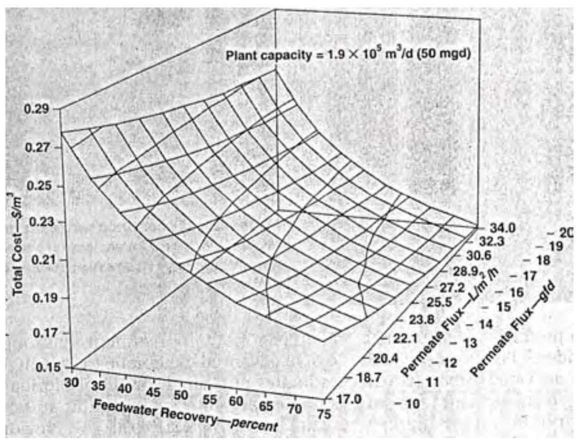
In a recent study,[92] the effects of permeate flux and fouling rates on the capital and O&M costs of NF systems were investigated in order to evaluate cost trade-offs. In addition, the effect of increasing capacity on plant cost was studied, as were the effects of pretreatment with MF, UF and conventional treatment systems. The results of this study are outlined in the following sections.

(a) *Cost versus operating conditions*[93]

Costs were estimated for different cleaning frequencies and various permeate flux and recovery values. Higher permeate fluxes and recovery rates were found to be associated with lower membrane lifecycle costs. For a 50 mgd facility operating at a flux of 10 gfd, for example, costs declined from US$ 0.278/m^3 to US$ 0.181/m^3 as recovery rates increased from 30 to 75 per cent. Similarly, when the recovery rate was fixed at 75 per cent and the flux was doubled from 10 to 20 gfd, the costs decreased from US$ 0.181/m^3 to US$ 0.152/m^3. This reduction occurred in spite of the fact that cleaning frequency increased fivefold.

Costs are shown plotted against permeate flux and feedwater recovery in figure 40.

Figure 40. Cost versus permeate flux and feedwater recovery for a 50 mgd NF plant



Source: Chellam, Serra and Wiesner, "Estimating costs for integrated membrane systems".

(b) *Cost versus capacity*[94]

Economies of scale were observed for NF plants when capacity was increased to 5 mgd. Beyond 15 mgd, plant capacity seemed to have little effect on cost. See figure 41.

(c) *Cost versus pretreatment options*[95]

The study investigated the result of the following blending scenarios on system cost:

- Conventional pretreatment[96] followed by NF filtration of 50 per cent of water flow;

[92] S. Chellam, C. Serra and M. Wiesner, "Estimating costs for integrated membrane systems," *Journal AWWA*, November 1998.

[93] Ibid.

[94] Chellam, Serra and Wiesner, "Estimating costs for integrated membrane systems".

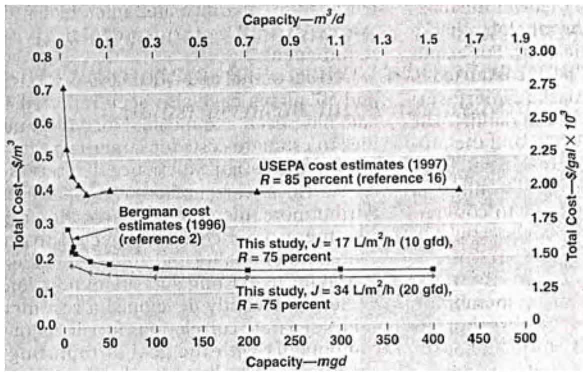
[95] Ibid.

[96] Such as flocculation, coagulation, sedimentation and granular media filtration.

- Conventional pretreatment followed by MF or UF treatment of the entire water flow, and followed by NF filtration of 50 per cent of water flow;
- MF or UF treatment followed by NF filtration of 75 per cent of water flow.

MF and UF were assumed to be characterized by very similar costs. Incremental membrane treatment costs for the above options are shown in figure 42. The figure suggests that the addition of MF or UF treatment over conventional pretreatment is not cost-effective based on improvements in NF performance alone. Furthermore, there is little difference in cost between the 50 per cent and the 75 per cent scenarios.

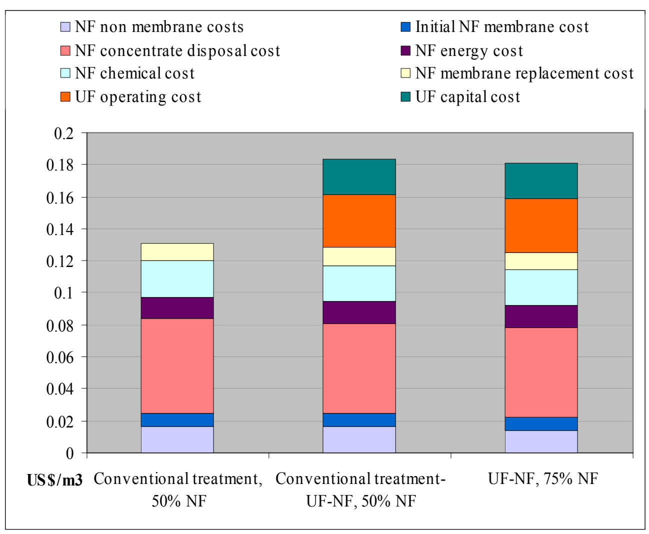
Figure 41. Cost versus NF plant capacity



Source: Chellam, Serra and Wiesner, "Estimating costs for integrated membrane systems".

Note: Documents referred to in this figure: R.A. Bergman, "Cost of Membrane Softening in Florida," *Journal AWWA*, May 1996, and USEPA, *Stage I D/DBP Cost and Technology Document*, 1997.

Figure 42. Incremental membrane treatment costs for three blending scenarios



Source: Chellam, Serra and Wiesner, "Estimating costs for integrated membrane systems".

Note: Cost of conventional pretreatment not included.

4. *Ion exchange costs*[97]

The cost of IX equipment varies widely, depending on the standard to which the units are built. Costly IX units are usually made of ASME code-stamped vessels, lined with natural rubber. They are fully automated and have a useful life of 20 to 30 years. Less expensive systems-costing one third or less as much as a high standard unit-are expected to operate for five to ten years, and may require some component replacements during that period. They usually consist of fiberglass vessels and PVC valves, with simple electronic control. Because of these wide variations, care is essential in making IX system cost estimates. For order-of-magnitude estimates, a rule of thumb is to multiply the cost of the resin used in the IX unit by seven. For example, a system that has 100 cubic feet of acid cation resin (cost US\$ 45/ft^3) and another 100 cubit feet of base anion resin (price US\$ 160/ft^3) would be expected to cost approximately 7 x (4,500 + 16,000) = US\$ 140,000. Equipment installation cost is estimated at 30 per cent of equipment cost, while the total plant cost may fluctuate in the vicinity of 250 per cent of equipment cost.

Energy costs constitute some three to five per cent of total O&M costs. Chemicals account for the largest portion of O&M costs, between six and 25 per cent, depending on water quality. Maintenance costs are estimated at two per cent of capital cost, excluding anion and cation replacements, which are required every three to five years.

Box 2 presents a case study in which an IX system is compared to a combined RO-IX system in order to determine which is more economically advantageous, and also to evaluate the sensitivity of each of these systems with respect to system size and the cost of power, chemicals and water.

Box 2. Comparison of the cost-effectiveness of RO and IX systems

For the purpose of determining which technology was more cost-effective, an IX system was compared with one using RO followed by IX polishing mixed beds. Both systems were studied at flow rates of 50 and 200 cubic metres per hour. Operating costs included chemicals, power, labour (1.5 man-year for both systems), maintenance, water and waste-water disposal costs. The costs of land, buildings and taxes were not included. The surface water input to both systems was pretreated with flocculation, clarification and sand filtration.

The characteristics of the two systems were as follows:

(a) IX: packed bed counterflow regenerated (using H_2SO_4) design, having 2 x 100% streams with cation-degasser-layered bed anion-mixed bed polishers containing uniform particle sized resins;

(b) RO followed by IX: 1 x 100% line with RO-degasser-mixed bed polisher for 50 m^3/hour and 2 x 50% lines for 200 m^3/hour. System recovery was set at 80%, and the same mixed bed design was used as for the IX system.

The results of the comparison are summarized in table 29. The IX system was found to be more dependent on feed TDS than the RO-IX system. Above a TDS value of 350-400 ppm as $CaCO_3$, it appeared to be more economical to use RO-IX than IX alone. The RO-IX system cost was dependent on power cost, and would not be recommended if effluent treatment cost was high. On the other hand, IX was found to be sensitive to chemical costs, such as caustic regenerant. Both systems achieved economies of scale, since O&M costs represented the largest component of total cost.

TABLE 29. COST COMPARISON OF IX VERSUS RO-IX FOR 50 AND 200 M^3

		50 m^3	200 m^3
IX	Treatment cost	US\$ 0.5-0.7/m^3	US\$ 0.25-0.45/m^3
	O&M cost as a percentage of total cost	70%	80%
RO-IX	Treatment cost	US\$ 0.6/m^3	US\$ 0.4/m^3
	O&M cost as a percentage of total cost	72%	80%

Source: Dow Chemical Company, *Ion Exchange or Reverse Osmosis?* http://www.dow.com/liquidseps/design/ix_ro.htm.

[97] Pittner, “Economics of Desalination”.

C. ECONOMICS OF EFFLUENT TREATMENT

The total cost of effluent treatment is primarily dependent on the influent flow rate to various processes within a waste-water treatment facility. The flow rate, including solid and organic loading, is the primary determinant of required equipment size and the associated capital and operations and maintenance costs, and thus constitutes the main variable in cost equations.[98] Annex F presents a series of generalized capital and O&M cost equations for common primary and secondary unit operations and processes used in a waste-water treatment plant. The cost equations there presented are updated to 1996 dollar values. Table 30 illustrates the application of these equations for the cost estimation of an activated sludge plant. These equations are often used for the comparison and evaluation of alternatives in a treatment facility rather than for actual cost determination.

TABLE 30. ESTIMATED CAPITAL AND O&M COSTS FOR AN ACTIVATED SLUDGE PLANT

System components and description[a/]	Service years	Construction cost[a/] (millions of USD)	Annual O&M cost[a/] (thousands of USD)
Lift station	15	5.399	172.6
Preliminary treatment	30	0.356	62.6
Primary sedimentation, $Q_E = 0.9\ Q_{Design}$[b/]	50	0.882	71.4
Anaerobic-anoxic-aerobic system[c/]	30	4.086	276.8
Final clarifier, $Q_E = 1.91\ Q_{Design}$	40	2.717	249.9
UV disinfection	15	0.557	40.2
Gravity thickener, combiner sludge, $Q_E = 1.84\ Q_{Design}$	50	0.353	15.5
Anaerobic digester, $Q_E = 0.95\ Q_{Design}$	50	1.229	51.5
Filter press $Q_E = 1.22\ Q_{Design}$	15	1.822	134.7
Biosolids recycle	20	0.130	48.3
Landfilling of residues	20	0.013	4.83
Miscellaneous structures, administrative offices, laboratories, shops, and garage	50	0.575	129.4
Support personnel			16.16
Subtotal 1, cost of activated sludge plant		18.119	1 273.89
Piping (31%), Electricity (8%), instrumentation (6%), and site preparation (5%)		9.059	
Subtotal 2		27.178	1 273.89
Engineering and construction supervision (15%) and contingencies (15%)		8.1535	
Subtotal 3		35.332	1 273.89
Total cost of activated sludge plant	36.605 million USD		

Source: Qasim, *Waste-water Treatment Plants.*

a/ Capital and O&M costs are obtained from the cost equations in annex F and adjusted to the 1998 cost. 1998 cost = 1996 cost × [(ENR Index 1998 = 5640)/ (ENR Index 1996 = 5572)].
ENR = *Engineering News Record*.

b/ Design average and peak flows are 440 L/s and 1320 L/s respectively.

c/ Capital and O&M costs are assumed to be 30 % higher than in the case of the conventional activated sludge process.

An analysis performed in Scandinavia and Denmark[99] compared the costs of several waste-water treatment combination alternatives. Table 31 presents the annualized unit cost data for the following five treatment processes:

---

98 C.W. Keller et al., *Financing and Charges for Wastewater Systems* (Hyattsville, Maryland: WPCF, ASCE and American Public Works Association, 1984).

99 Somlyódy and P. Shanahan, *Municipal Wastewater Treatment*.

(a) Mechanical (primary) waste-water treatment;
(b) Mechanical/chemical waste-water treatment;
(c) Biological treatment (high and low load);
(d) Biological/chemical treatment without nitrogen removal;
(e) Biological/chemical treatment with nitrogen removal.

TABLE 31. ANNUALIZED UNIT COSTS (USD/M3) FOR WASTE-WATER TREATMENT PLANTS OF VARYING CAPACITIES

	Plant capacity								
	2,000 capita			10,000 capita			100,000 capita		
Process	CC[3]	O&M[3]	TC[3]	CC	O&M	TC	CC	O&M	TC
Mechanical	0.250	0.108	0.358	0.175	0.083	0.258	0.110	0.050	0.160
Chemical									
High load[6]	0.250	0.167	0.417	0.175	0.125	0.300	0.117	0.075	0.192
Low load[7]	0.275	0.192	0.467	0.200	0.142	0.342	0.133	0.083	0.217
Biological									
High load[8]	0.333	0.175	0.508	0.233	0.133	0.367	0.150	0.083	0.233
Normal load[9]	0.417	0.175	0.592	0.258	0.125	0.383	0.180	0.083	0.263
Biological/chemical									
Simultaneous precipitation[10]	0.342	0.200	0.542	0.250	0.167	0.417	0.150	0.108	0.258
Preprecipitation[11]	0.383	0.250	0.633	0.275	0.175	0.450	0.167	0.125	0.292
Biological/chemical, N-removal	-	-	-						
Predenitrification/ simultaneous precipitation based on activated sludge[12]				0.433	0.200	0.633	0.283	0.283	0.283
Postdenitrification/ simultaneous preprecipitation based on biofilm process[13]				0.333	0.225	0.558	0.225	0.225	0.225

Source: Somlyódy and Shanahan, *Municipal Waste-water Treatment.*

1 WWTP = waste-water treatment plant; Q = 400 L/capita/day.
2 CC = capital costs; O&M = operations and maintenance costs; TC = total costs.
3 Chemical high load = chemically enhanced mechanical treatment.
4 Chemical low load = traditional chemical treatment (primary precipitation).
5 Biological high load = activated sludge with sludge load of 0.5 kg/BOD_5/kg SS.d.
6 Biological low load = activated sludge with sludge load of 0.2 kg/BOD_5/kg SS.d.
7 Biological/chemical = simultaneous precipitation in normally loaded activated sludge plant.
8 Biological/chemical = preprecipitation followed by normally loaded activated sludge plant.
9 Biological/chemical including N-removal = Predenitrification/simultaneous precipitation in activated sludge plant with total sludge age of 13 days.

10. Biological/chemical including N-removal = Preprecipitation followed by biofilm process with postdenitrification and external carbon source addition.

The annualized capital cost is computed assuming a 12 per cent interest rate and a 20-year life, leading to a capital recovery factor of 0.133.[102] Transportation costs are not included in the analysis. It should be noted that the cost estimates presented below are used only for comparison purposes. Accurate estimates are influenced substantially by site-specific or country conditions such as interest rates.

102 The annualized cost can be divided by 0.133 to obtain the initial investment cost.

According to table 29, the estimated costs vary in a range of approximately 1 to 3, depending on treatment goals and objectives. The unit cost of nutrient removal is about an order of magnitude higher than that of BOD alone. Furthermore, economies of scale significantly affect total costs, which decrease with increasing plant size/capacity.

D. ECONOMICS OF NATURAL WATER TREATMENT SYSTEMS

Natural treatment systems (NTSs) offer enormous savings by comparison with conventional treatment processes that produce the same water quality. This is especially true for rural communities and other locations where large, inexpensive sites are readily available. NTS operating costs, such as energy, are minimal compared to other treatment methods.

1. *Capital and O&M costs*

Capital and O&M costs of NTSs according to two different references are listed in this section. The figures from the first reference, published by the Water Environment Federation,[100] are shown in table 32. The systems are characterized by the same flow rate of approximately 400 m^3/d, except for on-site systems, for which the flow rate is 40 m^3/d. These figures provide an order-of-magnitude estimate only, and cannot be used for project cost estimation. Land cost is not included in the capital cost data, because it is a factor that is heavily country-and site-specific. A discussion of the equations used to determine land area requirements will be found in following section.

As will be seen from table 32, capital cost per m^3/d ranges between US$ 450 and US$ 3,000, with rapid infiltration being the least costly. O&M costs per m^3, on the other hand, vary between US$ 0.01 and US$ 0.2, with on-site systems being the least costly.

TABLE 32. TYPICAL CONSTRUCTION AND O&M COSTS FOR SELECTED NTSS

System	Capital cost (US$/$m^3$.d)	O&M costs (US$/$m^3$)
On-site[a/]	1 000-3 000	0.01-0.10
Slow rate[b/]	800-2 000	0.10-0.20
Rapid infiltration[c/]	450-900	0.05-0.1
Overland flow[d/]	600-1 000	0.08-0.15
Facultative pond[e/]	500-1 000	0.07-0.13
Aerated pond[f/]	600-1 200	0.10-0.16
Hyacinth pond[g/]	500-1 000	0.12-0.14
Constructed wetland[h/]	500-1 000	0.03-0.09

Source: S.C. Reed et al., *Natural Systems for Wastewater Treatment, Manual of Practice FD-16* (Alexandria, Virginia: Water Environment Federation, 1990).

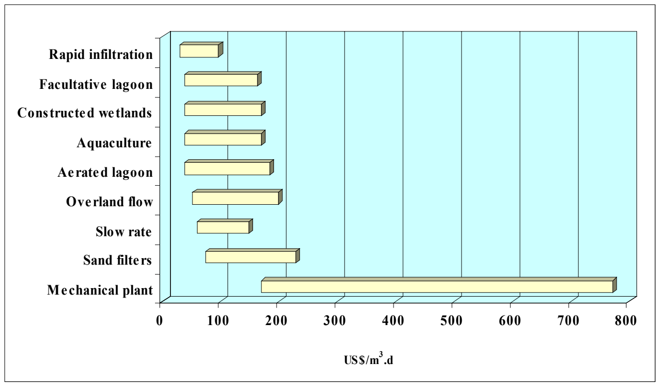
Note: Figures given in 1984 dollars.

a/ For daily flow rates up to 40 m^3/d.
b/ Includes an allowance for pretreatment and storage, flow rate ~ 400 m^3/d, crop harvest included.
c/ With pretreatment to primary, at a flow rate ~ 400 m^3/d.
d/ Pretreatment: screening or settling, at a flow rate ~ 400 m^3/d, crop harvest included.
e/ No pretreatment, at a flow rate ~ 400 m^3/d.
f/ Partial mix aeration, at a flow rate ~ 400 m^3/d, no pretreatment.
g/ Pretreatment: screening or settling, flow rate ~ 400 m^3/d, with plant harvest.
h/ Free water surface type; pretreatment: screening or settling, flow rate ~ 400 m^3/d, no regular harvest.

[100] Reed et al., *Natural Systems.*

Data obtained from a second source, published by UNEP,[101] are graphed in figure 43 and figure 44. These figures show the definitive advantage of NTSs over mechanical systems for water treatment.[102] Here again, the cost of land is not included in the data. The cost range reflects a capacity range of 0.1 to 1 million gallons per day, and the figures given are in 1993 US$ per gallon of waste-water treated per day.

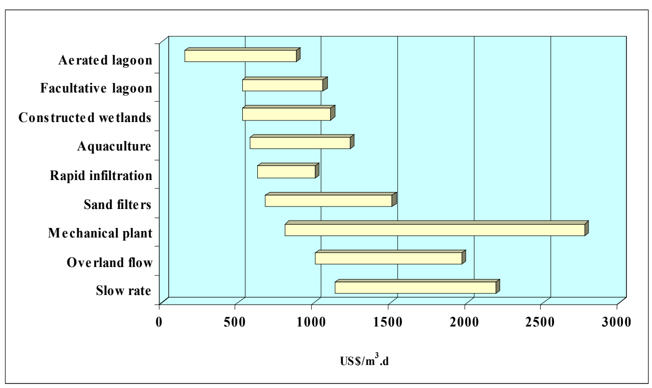
Figure 43. O&M costs of 1-0.1 mgd systems



Source: UNEP, *Sourcebook of Alternative Technologies for Freshwater Augmentation in Latin America and the Caribbean.*

Note: Figures converted from US$/gpd in original source.

Figure 44. Capital costs of 1-0.1 mgd systems



Source: UNEP, *Sourcebook of Alternative Technologies for Freshwater Augmentation in Latin America and the Caribbean.*

Note: Figures converted from US$/gpd in original source.

2. *Estimation of land area requirements*

A preliminary estimate of the land area (A) required for a small-to-medium size system (daily flows less than 20 m^3/d) is proportionate to the daily design flow to treatment site (Q) and inversely proportionate to soil permeability (k). In other words:[103]

---

[101] UNEP, *Sourcebook of Alternative Technologies for Freshwater Augmentation in Latin America and the Caribbean*. Available at: http://www.unep.or.jp/ietc/Publication/techpublications/TechPub-8c/.

[102] The mechanical treatment plant referred to in these figures is an oxidation ditch treatment system, and includes the cost of a clarifier, oxidation ditch, pumps, building, laboratory and sludge drying beds.

[103] Reed et al., *Natural Systems.*

$$A\ (m^3) = p \times Q\ (m^3/d) / k\ (m^3/m^2.\ d)$$

where p is a factor reflecting additional area requirements, depending on the system under consideration.

This equation can only be used to determine whether a particular site is large enough, and not for final treatment area sizing. Annex table 7 gives typical land area equations and assumptions applicable for different NTSs.

3. *Conclusion*

Table 33, reproduced from UNEP,[104] ranks various natural treatment systems with respect to cost, but also according to multiple indices of effectiveness. The selection of the best alternative depends heavily on local conditions and requirements.

TABLE 33. COST COMPARISON OF VARIOUS NATURAL WASTE-WATER TREATMENT PROCESSES

Rank (1=best)	Initial cost	O&M cost	Life Cycle cost	Operability	Reliability	Land area	Sludge production	Power use	Effluent quality
1	MA	SP	MA	SP	SP	MA	SP	SP	SP
2	AS	MA	AS	AL	AL	AS	AL	MA	AL
3	OD	AL	OD	OD	OD	OD	OD	AS	MA
4	AL	AS	AL	AS	MA	AL	AS	AL	OD
5	SP	OD	SP	MA	AS	SP	MA	OD	AS

Source: UNEP, Sourcebook of Alternative Technologies for Freshwater Augmentation in Some Countries in Asia.

Note: SP, stabilization ponds; AL, aerated lagoons; OD, oxidation ditches; AS, conventional activated sludge; MA, modified aeration activated sludge or trickling filter solids contactor. Flexibility and expandability are similar for all types.

E. ECONOMICS OF SLUDGE TREATMENT

The following cost factors must be considered for sludge treatment:[105]

(a) Construction and O&M cost of the treatment plant;[106]
(b) Sludge transportation cost;
(c) Quality control of sludge;
(d) Marketing cost, if sludge is to be reused;
(e) Cost of disposal of final by-product.

Table 34 presents a description of the level of construction and O&M costs of a sludge treatment plant, and the sludge characteristics for different treatment methods. The volume of treated sludge affects both storage and transportation costs. Table 35 presents an order of magnitude of the treatment cost per ton of dry matter.

[104] UNEP, *Sourcebook of Alternative Technologies for Freshwater Augmentation in Some Countries in Asia*. http://www.unep.or.jp/ietc/Publications/techpublications/TechPub-8e/.

[105] International Solid Waste Association (ISWA), *Sludge Treatment and Disposal: Management Approaches and Experiences*, Environmental Issues Series No. 7 (Copenhagen: European Environment Agency, 1997).

[106] These costs are highly variable, depending on local conditions and plant size.

TABLE 34. CONSTRUCTION AND O&M COSTS OF DIFFERENT SLUDGE TREATMENT PLANTS, AND SLUDGE CHARACTERISTICS AFFECTING COST

Treatment technique	Construction cost	O&M costs	Volume of treated sludge	Marketability/quality of treated sludge
Composting	Moderate	Moderate (Energy costs can be high for forced aeration)	High	Moderate
Drying	High	High (especially power cost)	Low	High (used as fertilizer, fuel or top soil). Hygienic
Incineration	Very high (justified only for treating large volumes, or for co-incineration with other wastes)	High	Very low	High. Treatment by-product also marketable.
Landfilling	~ US$ 67 per m^2 of land. Not including land cost, which can be very high	~ US$ 80–US$ 350, depending on regulations governing disposal	Not applicable	Not applicable

Source: Compiled from information in reference by the International Solid Waste Association (ISWA), S*ludge Treatment and Disposal*.

TABLE 35. SLUDGE TREATMENT COST PER TON OF DRY MATTER

Treatment technique	Cost (US$)
Raw sludge use in agriculture/forestry	8–215
Composting	135–325
Drying	160–435
Incineration*	245–435
Landfilling	110–325

Source: ISWA, *Sludge Treatment and Disposal*.

* Lower commercial prices are possible where marginal prices are paid for sludge incineration at waste incineration plants.

An analysis performed in Scandinavia and Denmark[107] compares the costs of the following three sludge treatment alternatives:

(a) Sludge dewatering only;
(b) Anaerobic stabilization and sludge dewatering;
(c) Sludge dewatering and incineration.

The results of this analysis are shown in table 36. The costs of anaerobic digestion are discussed in box 3.

[107] Somlyódy and Shanahan, *Municipal Wastewater Treatment*.

TABLE 36. ANNUALIZED UNIT COSTS (USD/KG DRY SOLID) FOR SLUDGE TREATMENT PLANTS OF VARYING CAPACITIES

	Plant capacity					
	10,000 capita			100,000 capita		
Process	CC*	O&M*	TC*	CC	O&M	TC
Dewatering	0.175	0.117	0.292	0.117	0.075	0.192
Anaerobic stabilization and dewatering	0.200	0.183	0.383	0.158	0.108	0.267
Dewatering and incineration	-	-	-	0.292	0.217	0.509

Source: Somlyódy and Shanahan, *Municipal Waste-water Treatment*.

* CC = capital costs; O&M = operations and maintenance costs; TC = total costs.

Box 3. Anaerobic digestion

Compared to aerobic digestion, anaerobic digestion has the advantage of lower treatment cost, due to the fact that it does not require aeration. In contrast, since the process is slower, large tanks are needed to store waste-water, and this may mean higher capital costs. Anaerobic digesters cost approximately US$ 1,900 per cubic metre of bioreactor volume. In table 37, the costs of two anaerobic digesters in Europe are compared, and the average obtained for several European case studies is shown. Cost figures are expressed in US$ per kg of COD removed from waste-water.

TABLE 37. COSTS OF ANAEROBIC TREATMENT

Digester	Year built	Capital cost (US$/kg COD removed per year)	Running cost (cents/kg COD removed)
Completely stirred tank reactor at lager brewery in Wrexham	1986	1.6	10
Anaerobic filter in Denmark	1989	2.6	24
EC case studies data	1994	2.1	16

Source: S. Nesaratnam, *Effluent Treatment* (Leatherhead, Surrey: Pira International, 1998).

F. ECONOMICS OF EFFLUENT AND SLUDGE RECLAMATION AND REUSE

1. *Agricultural use of untreated sludge*

The spreading of untreated sludge on agricultural land is considered to be the cheapest disposal method. However, the use of sludge in agriculture is strictly regulated by legislation setting limitations on the heavy metals, dry solids and pathogens that it may lawfully contain. The law also restricts the types of soil and crops on which sludge may be used. These restrictions, combined with the fact that the spreading of sludge is seasonal, places various constraints on the agricultural use of untreated sludge, and increase its cost. Cost factors that should be considered in determining the feasibility of raw sludge reuse in agriculture include:[108]

(a) Large storage capacity required to store sludge for seeding periods;

(b) Farm equipment may not be suitable for spreading raw sludge, and thus investment in special equipment is necessary;

(c) Cost of transporting sludge from storage area to farmland;

[108] ISWA, *Sludge Treatment and Disposal*.

(d) Costly periodic analyses of both soil and sludge to ensure that legislative requirements are met;

(e) Administrative expenses in the form of farmer agreements.

The price of a ton of raw sludge used on farmland varies greatly in different countries. It is estimated to be of the order of US$ 80 - US$ 215 per ton.

2. *Agricultural use of treated effluent and sludge*

The above disadvantages of using raw sludge can be avoided if the sludge is treated before storage. When treated, sludge will:

(a) Occupy a smaller volume, owing to its reduced water content;

(b) Be easier to spread on farmland with conventional farm equipment, owing to its homogenous consistency;

(c) Have controlled nutrient levels;

(d) Be more hygienic to use.

However, sludge treatment will increase its cost to such an extent that it will be more difficult for it to compete with other, cheaper fertilizers. Different sludge treatment techniques must thus be compared in order to identify the option that is most advantageous in economic and environmental terms.

In this section, an attempt will be made to determine the economic factors affecting the use of treated effluent and sludge in agriculture, from the standpoint of both the municipal waste-water treatment plant (MWTP) and the farmer.

(a) *Standpoint of the municipal waste-water treatment plant*

From the standpoint of MWTP, additional costs are incurred from advanced treatment, effluent collection and storage, effluent transportation to farmland and irrigation management. Only costs associated with the additional level of treatment beyond what is necessary to meet waste-water disposal requirements must be considered.

A study of the cost of reclaimed water use in agricultural lands in Florida yielded the following figures:[109]

(i) Storage: 2.5 million gallons for every 10 million gallons of input waste-water per day;
(ii) Transportation cost: US$ 0.35 per 1,000 gallons;
(iii) Additional treatment requirements: filtration and chlorination of secondary treated effluent.

The total cost per 1,000 gallons of reclaimed water amounted to US$ 0.7 – US$ 0.9. This value is much higher than the cost of water pumped directly from an aquifer, which is approximately US$ 0.1 – US$ 0.15 - roughly comparable to the cost of municipal water.

Indirect economic benefits must be taken into account, since they will usually offset the high cost of reclaimed water. For example, a reduction in demand for drinking water due to reclaimed water use represents a cost saving in itself, especially if a town is faced with the need to expand its drinking water supply system due to growing demand.

---

[109] National Research Council, *Use of Reclaimed Water and Sludge in Food Crop Production* (Washington, D.C., National Academies Press, 1996).

With respect to sludge reuse, sludge handling constitutes about half of a plant's treatment cost. Sludge processing costs have been estimated at US$ 266 to US$ 925 per ton, depending on the process used.

(b) *Farmer's standpoint*[110]

In considering the option of using reclaimed water and sludge for soil irrigation and fertilization, farmers will take the following factors into account:

(i) The price and availability of alternative irrigation water and fertilizers;
(ii) Crop price and nutrient requirements;
(iii) Seasonality and the need to store reclaimed effluent;
(iv) Soil types that are poor in nutrients and organic matter;
(v) Cost of applying sludge to farmland;
(vi) Monitoring cost to ensure compliance with regulations for sludge use (this cost may be subsidized by the treatment facility).

The fertilizer value of sludge is approximately US$ 15 per dry ton of sludge. Yield improvements and fertilizer savings have been reported in the literature. These benefits will reduce the cost of raw food products, which in turn will lower the cost to food processors, to the benefit of the end user.

3. *Ground water recharge*[111]

The economics of ground water recharge are widely variable for different locations. Its economic viability depends on a number of factors, which may be summarized as follows:

(a) Demand for additional water supply;
(b) Cost of supply from alternative sources;
(c) Water treatment and injection cost.

The first condition, of course, is that there must be sufficient demand for additional water supplies. Strong demand is anticipated for the future, especially in arid and semi-arid regions, as those are found in the ESCWA member countries.

In these water-short areas, the cost of water supply from surface water is expected to increase considerably. This is due in the first place to the growing scarcity of water and in the second place to the costs associated with building new surface supply facilities. In addition to their high construction cost, surface water supply facilities also produce adverse environmental impacts.

The cost of waste-water treatment and injection may be regarded as high. However, waste-water must be treated before disposal in any case, and hence the economic viability of groundwater recharge depends only on the additional water treatment cost required to improve water quality to acceptable levels for spreading or reinjection purposes. In addition to the incremental cost of upgrading treated waste-water quality, the cost of acquiring land for use as spreading grounds, the cost of drilling injection wells and the cost of transporting the treated waste-water to the spreading grounds must be taken into account.

In summary, if water demand is high, and the cost of recharged waste-water is lower than the cost of obtaining water from other sources, artificial recharge is a viable option.

Other economic benefits of artificial recharge must be borne in mind when comparing this option with alternatives, such as the increased quantity of water that can be extracted at shallower pumping depth. In

---

[110] National Research Council, *Use of Reclaimed Water and Sludge*.

[111] National Research Council, *Ground Water Recharge Using Waters of Impaired Quality* (Washington, D.C., National Academies Press, 1994).

addition, artificial recharge guarantees that water is available all year round, whereas surface water supplies are subject to seasonal fluctuations.

Table 38, which is taken from a UNEP publication, shows cost estimates for several ground water recharge schemes in India. Injection wells feeding an alluvial aquifer appear to be the most costly option. As the table shows, injection wells in hard rock areas are less expensive because they are shallower and do not clog. The least expensive scheme is percolation tanks, especially if the tanks are already available.

In general, artificially recharged water is costly, and thus is not ordinarily used for irrigation, except perhaps in a supplementary capacity during periods of water shortage. Only net socio-economic and environmental benefits might make artificial recharge projects viable.

TABLE 38. COSTS ASSOCIATED WITH VARIOUS ARTIFICIAL (US$/M^3) RECHARGE SCHEMES IN INDIA

Artificial recharge structure	Initial cost	Running cost
Injection well (alluvial area)	100	100
Spreading channel (alluvial area)	9	10
Percolation tank (alluvial area)	2	7
Injection well (limestone area)	6	21
Spreading channel (limestone area)	7	6

Source: UNEP, *Sourcebook of Alternative Technologies for Freshwater Augmentation in Some Countries in Asia.*

G. ECONOMICS OF EFFLUENT DISCHARGE

1. *Waste-water discharge to sewer*

For small industries that cannot afford to treat their effluents in-house, the only viable option is to discharge their effluents to the sewer. This is usually done for a fee under an agreement with the municipal water treatment facility. According to the recommended guidelines for control and charging of trade effluents discharged to the sewer, published by the Confederation of British Industry in 1976, and then updated in 1986, the trade effluent charge (C) is calculated by means of the following formula:[112]

$$C = R + (V + B_v) + (O_t/O_s)\,B + (S_t/S_s)\,S + M$$

Where
- C = total cost per cubic metre of effluent discharged to sewer (US$/m^3).
- R = reception and conveyance charge per cubic metre of effluent (US$/m^3).
- V = primary treatment charge per cubic metre of effluent (US$/m^3).
- B_v = additional volume per cubic metre if there is biological treatment (US$/m^3).
- O_t = COD (mg/l) of the effluent after one hour settlement, with pH adjusted to 7.
- O_s = COD of average strength settled sewage (mg/l).
- B = biological treatment charge per cubic metre of effluent (US$/m^3).
- S_t = total suspended solids (mg/l) content of effluent after one hour of settlement at pH 7.
- S_s = total suspended solids (mg/l) content of average strength settled sewage.
- S = treatment and disposal cost of primary sludge per cubic metre of effluent (US$/m^3).
- M = treatment and disposal charge per cubic metre where the effluent goes to a marine outfall (US$/m^3).

[112] Nesaratnam, *Effluent Treatment*.

Four cost elements are included in this formula, reflecting the services offered by the sewage treatment plant, namely:

(a) Reception and conveyance;
(b) Primary treatment;
(c) Biological treatment;
(d) Sludge treatment and disposal.

The first two cost elements depend on the volume of the effluent, while the last two are proportionate to the composition of the effluent as compared to average sewage. The formula thus gives an incentive to industry to reduce the volume and improve the quality of discharged effluents. The sum accruing from collected charges is ordinarily used to finance the treatment and regulation of effluent. Box 4 gives an example of the charge paid by a sugar beet factory that discharges its effluent to the sewer, while box 5 describes a technique for reducing effluent discharge as applied in a paper mill, and the costs involved.

The disadvantage of this formula is that it involves continuous sampling and analysis to determine the average suspended-solids and COD content. An alternative calculation method is to define charge bands. In other words, standard charges are defined for different ranges of COD and suspended-solids values. This is particularly useful for industries with low effluent volume and invariable effluent composition.

Box 4. Cost calculation for discharge of a given effluent to sewer

A sugar beet factory discharges its 10,000 m^3 of effluent per year to the sewer. The effluent has an average COD (O_t) of 1,150 mg/l and an average total suspended-solids content (S_t) of 1,300 mg/l. The following parameters are used by the water service company that is treating the effluent:

R = 16.1 cents/m^3.
V = 25.2 cents/m^3.
B_v = 4.9 cents/m^3.
B = 24.8 cents/m^3.
S = 11.8 cents/m^3.
O_s = 456 mg/l.
S_s = 383 mg/l.

The charge per cubic metre C (cents/m^3) = 16.1 + 25.2 + 4.9 + (1,150/456)24.8 + (1,300/383) 11.8 = 148.8. The total yearly charge is thus equal to 10,000 x 1.488 = US$ 14,880.

Source: Nesaratnam, Effluent Treatment.

Box 5. Zero-liquid technology in paper mills

Zero-liquid effluent systems[a/] have been applied in the paper industry. With this technology, the effluent is first physically treated to remove fiber content. Membrane treatment is then applied to reduce dissolved organic and inorganic content. In the third step, mechanical vapor recompression is used to distill the effluent. Finally, the effluent enters a freeze-crystallizer. The treated water can then be reused in the pulp mill, while the solid residue is disposed of. An estimate of the construction and operating costs of a system of this kind treating 2,000 m^3 of effluent per day is given in table 39. Obviously, freeze crystallization is the most expensive step in the process. In evaluating the economic viability of this type of system, the total cost of the system must be compared to the alternative cost of using additional raw water and the treatment and discharge of additional effluent volume.

---

a/ A very brief description of this technology is provided here. For more information on details of the technique, the reader is referred to the original source (Nesaratnam, *Effluent Treatment*).

TABLE 39. COMPARATIVE COSTS OF ZERO-LIQUID EFFLUENT TECHNOLOGIES

	Operating cost (US$ per m^3)	Capital cost (US$)
Physical treatment	0.16	1 120 000
Physical/biological	0.40	4 800 000
Physical/biological/membrane	0.80	8 000 000
Physical/membrane	0.96	4 800 000
Mechanical vapor recompression	2.4	12 800 000
Freeze crystallization	3.2	16 000 000

Source: Nesaratnam, *Effluent Treatment.*

2. *Discharge to controlled waters*

When industries discharge directly into controlled waters, a charge is imposed that depends on the agreed discharge volume and composition, and also on the type of receiving water. The formula that is commonly used for the annual charge is:[113]

$$\text{Charge} = R\ (V \times C \times W)$$

Where R = the annual financial factor.
V = the volume factor.
C = the content factor.
W = the receiving water factor.

Multiplying V, C and W together yields the number of chargeable units, while R defines the unit charge per year. The sum accruing from collected charges is ordinarily used to finance the costs of regulatory bodies responsible for the receiving water.

3. *Pollutant trading*

Pollutant trading is a relatively recent policy that aims at achieving a mandated environmental target at lower cost. The World Resources Institute defines trading as a flexible strategy that "makes it profitable for sources with low treatment costs to reduce their own effluents beyond legal requirements, generate credits, and sell those credits to dischargers with higher treatment costs".[114] In other words, two or more sources polluting the same area agree together on the treatment level and amount of discharge, such that the sum of their environmental impact complies with the applicable regulations. In this way, a large facility with lower treatment costs treats its effluent to a level beyond what is required under the regulations, thereby giving a margin to smaller facilities with higher treatment costs. Cost reduction is achieved by taking advantage of economies of scale in the treatment process. This method has been successfully applied in other environmental areas, notably air emissions, and several new pilot trading programmes are currently under way in the United States.

A difficulty arises when trading is applied between 'point' and 'non-point' pollution sources, such as a factory and farmland. While pollution from the first source can be readily quantified, non-point discharges, such as those originating from farmland, are usually seasonal and difficult to measure. In these cases, a large margin or 'trading ratio' is set, that will allow a safety margin for the area of impact.

Box 6 illustrates the cost reductions that can be achieved for phosphorus control through trading as compared to other policies, in three locations in the United States.

[113] Nesaratnam, *Effluent Treatment*.

[114] P. Faeth, *Fertile Ground: Nutrient Trading's Potential to Cost-Effectively Improve Water Quality* (Washington, D.C.: World Research Institute, 2000).

Box 6. Trading for phosphorus control

Three cases were selected for study, all of them experiencing water quality problems related mainly to phosphorus discharge: the Saginaw Bay watershed, the Minnesota River watershed and the Rock River watershed. The three watersheds are characterized by different numbers of point sources, different sizes and different treatment levels. After analyzing the local conditions pertaining to each of them, the following policy options were defined:

(a) Point source performance requirement: whereby all point sources are required to lower their phosphorus level;

(b) Conventional subsidy programme for agricultural conservation “best management practices”;

(c) Point source performance requirement coupled with trading;

(d) Trading programme coupled with performance-based conservation subsidies: an option combining the second and third scenarios, whereby point and non-point sources contribute equally to phosphorus reduction.

Table 40 summarizes the costs of each option as compared to a theoretical ‘least-cost’ option that achieves the requirements with no constraints. This table clearly shows the savings achieved with a flexible trading strategy as compared to conventional programmes. The results were even better when the trading policy involved non-point (agricultural) sources directly.

TABLE 40. COST COMPARISON OF DIFFERENT POLICIES (US$ PER POUND OF PHOSPHORUS REMOVED)

	Point source performance requirement	Conventional subsidies for agricultural conservation practices	Point source performance requirement with trading	Trading programme with performance-based conservation subsidies	Least-cost solution
Minnesota River	19.57	16.29	6.84	4.45	4.36
Saginaw Bay	23.89	5.76	4.04	2.90	1.75
Rock River	10.38	9.53	5.95	3.82	3.22

Source: Faeth, *Fertile Ground*.

Note: The levels of phosphorus reduction from the base are different for each watershed.

H. CONCLUSIONS

New technologies have made growing numbers of water treatment alternatives available. Cost may be a major determining factor, especially in developing countries. Cost estimation is a difficult and even costly undertaking in itself, because of the large number of parameters involved and the fact that those parameters are usually unclear until the design process is well under way.

Historical data are very useful in generating preliminary cost estimates. When these data are sufficiently detailed, they are also useful for the purpose of deriving cost equations that reflect system cost variations according to basic system parameters, including capacity. These equations form the basis of several computer software tools for water treatment cost estimation that are now available.

As the cost of membrane modules declines, membrane techniques become progressively more viable, especially for large-capacity systems. In fact, all membrane systems yield economies of scale up to five mgd capacity. However, system designers must bear in mind that downmarket membrane systems will generally entail higher maintenance costs and will be difficult to expand and upgrade. A balance must be struck, depending on system requirements and projected lifetime.

Effluent and sludge possess high fertilizing value. Agricultural countries should consider the reuse of effluent and sludge for farmland irrigation, thus benefiting twice over. Effluent reuse programmes must be regulated, subsidized and efficiently marketed in order to win wider use and acceptance.

Natural treatment systems are very promising, especially for rural areas and other locations where large areas of inexpensive land are available. Great cost reductions are possible with systems such as rapid infiltration and aerated lagoons, compared to other mechanical water treatment systems of similar environmental effectiveness. ESCWA member countries are encouraged to pursue the construction of such systems.

Waste-water discharge to sewer and controlled waters is costly where charges are imposed by regulatory bodies. Dischargers are therefore encouraged to reduce waste-water volume while improving its quality. Under these conditions, waste-water reduction and treatment techniques can be highly lucrative.

Pollutant trading is a policy that has been successfully applied in different locations in the United States. This policy has resulted in great reductions in total treatment costs while achieving even higher levels of environmental benefit.

Ground water recharge is a costly undertaking that is feasible only when the cost of other water sources is very high. The environmental benefits associated with reduced demand for surface water may be the deciding factor governing selection of this technique.

In conclusion, economic criteria often determine which water treatment technology is deployed. The economic assessment of a particular technology must take several criteria into account including: affordability, cost, cost-effectiveness, labour and willingness to pay. Failure to consider all these aspects may lead to an inappropriate choice of treatment technology.

It is also desirable for technology assessment be based on a broad set of sustainability criteria that include, in addition to the economic criteria referred to above, environmental, socio-cultural and functional criteria, such as those outlined in annex VII.

VI. WASTE-WATER TREATMENT IN SELECTED ESCWA COUNTRIES

Most countries in the ESCWA region practise waste-water treatment and reuse. Treated waste-water is widely reused for irrigation, particularly in the arid Gulf Cooperation Council (GCC) countries. At the present time, an average of 700,000 cubic metres per day is used to meet irrigation and, to some extent, industrial demand in the six GCC States (Bahrain, Kuwait, Oman, Qatar, United Arab Emirates and Saudi Arabia), representing approximately 35 per cent of the total treated waste-water produced in those countries.[115] In this chapter, waste-water treatment and reuse practices in selected ESCWA countries will be described.

A. JORDAN

Since 1930, waste-water collection in Jordan had been restricted to the town of Salt, where primitive physical devices such as septic tanks and cesspits were in use. Effluent from these was often discharged to gardens, resulting in environmental problems such as groundwater pollution. As population increased, modern technology was introduced to collect and treat waste-water. Currently, there are nearly 20 treatment plants around the country, including two that are scheduled to be put into service in the near future. Furthermore, 56 per cent of the population of Jordan, i.e. some 2.5 million people, are connected to the waste-water collection network, including 50 per cent of the country's urban population (see table 41).[116,117]

TABLE 41. WASTE-WATER DISPOSAL METHODS CURRENTLY PRACTISED IN JORDAN
(*Percentage*)

District	Public systems	Cesspools	Others
Urban	50	50	0
Rural	2.8	95	2.2
Jordan as a whole	56	43.2	0.8

Source: Adapted from Water Authority of Jordan, *Wastewater Sector*.

1. *Current waste-water treatment plants*

The waste-water treatment plants (WWTP) in use in Jordan, receive about 82 million cubic metres per year. Thirteen facilities are conventional mechanical treatment plants and six employ waste stabilization ponds. Due to the high average salinity of potable water (TDS = 580 ppm) and the low average water consumption (about 70L/capita/day), the influent waste-water is characterized by high organic loads and high salinity levels. On the other hand, the waste-water is comparatively low in toxic pollutants such as heavy metals and organic compounds, since only 10 per cent of the biological load originates from industrial discharge. Table 42 lists operational treatment plants in Jordan, their waste-water loads, and their corresponding treatment methods, efficiencies and costs.[118]

[115] Fluid Knowledge, *Background on Water and Wastewater Industry* (2000). Available at: http://www.fluidknowledge.com/waterlist/html/waterindustry.html.

[116] F. Bataineh, M. Najjar and S. Malkawi, *Wastewater Reuse*, a paper presented at the Water Demand Management Forum, Amman, March 2002. Available at: http://www.idrc.ca/waterdemand/docs/english/jordan.doc.

[117] Water Authority of Jordan. *Wastewater Sector*. Available at: http://www.mwi.gov.jo/waj/WAJ%20Web%20Page/wastewater.htm.

[118] Ibid.

TABLE 42. CHARACTERISTICS OF WASTE-WATER TREATMENT PLANTS IN JORDAN
(*Percenatge*)

Plant	Treatment method	Hydraulic load (m^3/day)	Organic oad kg BOD_5/day	Efficiency	Treatment cost (USD/m^3)
As-Samra	Stabilization ponds	170 752	35 768	80	0.027
Aqaba	Stabilization ponds	2 000	3 510	73	0.054
Salt	Extended aeration	3 403	8 393	98	0.171
Jerash	Extended aeration	2 072	4 043	96	0.169
Mafraq	Stabilization ponds	1 847	1 485	62	0.106
Baqa'a	Trickling filter	11 185	1 155	92	0.074
Karak	Trickling filter	1 231	848	92	0.513
Abu-Nusir	Activated sludge	1 617	4 400	95	0.190
Tafila	Trickling filter	707	1 680	96	0.248
Ramtha	Stabilization ponds	2 340	1 574	71	0.058
Ma'an	Stabilization ponds	1 892	1 552	81	0.099
Madaba	Stabilization ponds	4 266	1 700	69	0.087
Kufranja	Trickling filter	1 889	1 615	96	0.193
Wadi Al Seer	Aerated lagoon	1 113	3 120	93	0.166
Fuhis	Activated sludge	1 218	2 388	97	0.307
Wadi Arab	Activated sludge	5 985	1 440	98	0.248
Wadi Hassan	Activated sludge		18 900	-	-
Wadi Musa	Activated sludge		3 060	-	-
Irbid	Activated sludge and trickling filter	4 610	8 800	96	0.190

Source: Adapted from Water Authority of Jordan, *Waste-water Sector*, and Bataineh, Najjar and Malkawi, *Wastewater Reuse*.

TSS = total suspended solids.

BOD_5 = biochemical oxygen demand (5 days).

Plans are under way to upgrade several existing plants in the near future and to construct new ones in other parts of the country, especially in rural areas. Table 43 lists plants that are scheduled to be constructed in the next five to ten years, including projected capacities and type of treatment.

TABLE 43. TREATMENT PLANTS SCHEDULED TO BE UPGRADED, EXPANDED OR BUILT IN JORDAN

WWTP	Type	Expected year of operation	Capacity (m^3/d)
As-Samra	Activated sludge	2004	267 000
Aqaba	Activated sludge	2005	18 000
Mafraq	Activated sludge	2005	5 000
Karak	To be decided	2003	5 000
Tafila	To be decided	2005	5 000
Ramtha	Activated sludge	Under construction	5 400
Ma'an	To be decided	2005	5 000
Madaba	Activated sludge	Under construction	7 600
Kufranja	To be decided	2002	7 000
Wadi Zarqa	Activated sludge	2009	146 000
Naur	Activated sludge	2008	5 200
North Queen Alia Airport	Activated sludge	2005	31 000
Al Jeeza	Activated sludge	2005	5 000
Um Al Basateen	Activated sludge	2005	1 000
North Shuna	Activated sludge	2003	12 000
Wadi Shallala (Irbid East)	Activated sludge	2003	15 000
Torra	Activated sludge	2012	3 100

TABLE 43 (*continued*)

WWTP	Type	Expected year of operation	Capacity (m^3/d)
Kofur Asad	Activated sludge	2007	6 000
Al Mazar Al Shamali	Activated sludge	2010	3 100
Mashari'e	Activated sludge	2003	3 100
Dair Abi Sa'id	Activated sludge	2013	3 100
Jerash West	Activated sludge	2009	6 000
Dair Alla	Activated sludge	2004	6 000
South Shuna	Activated sludge	2003	4 300

Source: Adapted from Bataineh, Najjar and Malkawi, *Wastewater Reuse.*

2. *Waste-water reuse*

Treated effluent discharged from the WWTP is used mainly for irrigation. Excess effluent is discharged to wadis, where it is mixed with surface waters (for example, in the King Talal Dam reservoir) and subsequently used for unrestricted irrigation in the Jordan Valley. In 1999, waste-water treatment plants produced 72.32 MCM, amounting to 13.8 per cent of all water available for irrigation (521 million cubic metres). By the year 2020, the quantity of treated waste-water effluent is expected to amount to 265.3 million cubic metres, accounting for approximately 25 per cent of total water available for irrigation. Table 44 shows current reuse applications for treated effluent from operating WWTPs in Jordan.[119]

TABLE 44. WASTE-WATER REUSE IN JORDAN

WWTP	Treated effluent (m^3/day)	Planted area (ha)	Irrigated crops	Excess effluent flow
Abu-Nusir	1 587	0.5	Forest, olive trees	King Talal reservoir
Aqaba	6 683	150	Forest, some olive trees, palm trees	none
As-Samra	149 589	1 000	Olive trees, forest, forage crops	King Talal reservoir
Baqa'a	10 626	-	-	King Talal reservoir
Fuhis	1 036	24	Forest, olive trees	none
Irbid	4 526	0.5	Forest, ornamental trees	Jordan River
Jerash	1 969	-	Private farm	King Talal reservoir
Karak	1 194	50	Olive trees, ornamental trees, forest	Wadi Karak
Kufranja	1 629	7	Forest, olive trees, sudan grass, alfalfa	Wadi Kufranjeh
Ma'an	1 704	7	Forest, olive trees, ornamental trees	none
Madaba	3 272	60	Forest, olive trees, forage crops, flowers	none
Mafraq	1 488	25	Forest, forage crops, olive trees	none
Ramtha	1 852	50	Forest, barley, barseem, sudan grass, alfalfa	none
Salt	3 307	6	Olive and citrus trees	Wadi Shieb
Tafila	702	1	Olive and fruit trees	Ghor Fifa
Wadi Al Seer	714		-	Jordan River
Wadi Arab	5 611	15	Forest, olive trees	Kafrein reservoir

Source: Adapted from Bataineh, Najjar and Malkawi, *Wastewater Reuse.*

B. YEMEN

In the Republic of Yemen, there are currently nine operational treatment facilities, treating a total actual flow of about 92,000 cubic metres per day, which amounts to 33.5 million cubic metres per year. See

[119] Water Authority of Jordan. *Wastewater Sector*.

Table 45. There are six new treatment plants, three of which were under construction and expected to come on stream in 2002. The three remaining plants (Beit Al-Faqih, Bagel and Zabid) are in the planning stage.[120]

TABLE 45. CHARACTERISTICS OF WASTE-WATER TREATMENT PLANTS IN YEMEN

Station	Design capacity (m^3/d)	Treatment type	Actual flow (m^3/d)	Treatment cost (USD/m^3)	Disposal method
Sana'a	50 000	Activated sludge	20 000	0.25	Uncontrolled irrigation
Ta'iz	17 000	Stabilization ponds	17 000	0.03	Uncontrolled irrigation
Al Hudeidah	18 000	Stabilization ponds	18 000	0.03	Sea disposal and irrigation
Aden	15 000	Stabilization ponds	15 000	0.03	Sea disposal and irrigation
Ibb	7 000	Activated sludge	7 000	0.25	Uncontrolled irrigation
Dhamar	10 000	Stabilization ponds	6 000	0.03	Uncontrolled irrigation
Hajja	5 000	Trickling filter	1 150	N/A	Uncontrolled irrigation
Mukalla	8 000	Stabilization ponds	6 000	0.025	Sea disposal
Rada'a	2 800	Stabilization ponds	1 500	0.025	Uncontrolled irrigation
Aden (new)	60 000	Stabilization ponds	-	-	
Yarim	3 500	Stabilization ponds	-	-	-
Amran	6 000	Stabilization ponds	-	-	-

Source: Abdul-Malik, *Yemen's Water Resources.*

The treated effluent is either discharged into the sea or reused in agriculture for controlled and uncontrolled irrigation. Controlled irrigation is practised by the Ministry of Agriculture and Irrigation for green belt building and sand dune fixation or desertification control along the coastal plains. Non-controlled irrigation is commonly practised by farmers in the highlands and wadis to grow corn, and forage crops as well in some areas (Ta'iz area), and to grow vegetable and fruit crops (Sana'a area). Farmers are working with this water without any form of training or extension services.[121]

The quality of the treated effluent varies from one area to another, depending on the method of treatment, the capacity of the plant and operational circumstances. The quality of treated waste-water at selected locations is presented in table 46.

TABLE 46. WASTE-WATER DISCHARGE QUALITY IN YEMEN

Parameter	Sana'a	Aden	Dhamar	Al Hudeidah	Yemen standards
BOD (mg/l)	24	N/A	102	106	150
COD (mg/l)	103	N/A	189	348	500
TDS (mg/l)	1 852	1 695	700	3 110	450-3 000
SS (mg/l)	28	N/A	580	128	50
FC colony /100ml	12 000	80 000	110 000	1 366	<1 000

Source: Abdul-Malik, *Yemen's Water Resources.*

N/A: not available.

The objectionable quality of the treated effluent has created a number of problems, particularly for the farmers who are the main users, including:

(a) Odours and insects at some treatment stations;
(b) Public health hazards and skin diseases among farmers;

[120] Q.Y. Abdul-Malik, *Yemen's Water Resources and Treated Wastewater* (Sana'a: Ministry of Agriculture and Irrigation of Yemen, n.d.). Available at: http://www.idrc.ca/waterdemand/docs/english/yemen-english.doc.

[121] Abdul-Malik, *Yemen's Water Resources*.

(c) Soil salinity problems;
(d) Plant diseases in crops irrigated with treated waste-water;
(e) Animal diseases due to direct contact with the treated waste-water.

Lately, various water-related strategies, policies, and laws in Yemen have been referring to treated waste-water as a water resource that should be utilized in a safe manner. A draft waste-water reuse strategy was under development in 2001. It supports the implementation of waste-water management activities in the form of targeted projects and programmes.[122]

C. KUWAIT

According to statistics reported by the Food and Agricultural Organization (FAO), the quantity of waste-water produced in Kuwait in 1994 was 119 million cubic metres, of which 103 million cubic metres were treated. Approximately 52 million cubic metres of the treated effluent were reused for agricultural irrigation, while the remainder was discharged into the sea.[123] Four sewage treatment plants have been in operation in Kuwait since 1987. The characteristics of these plants are presented in detail in table 47.

TABLE 47. CHARACTERISTICS OF MAJOR WASTE-WATER TREATMENT PLANTS IN KUWAIT

General description	Treatment processes	Final disposal
Ardiya Waste-water Treatment Plant		
Commissioned in 1965 Original capacity = 100,000 m^3/d Capacity extended in 1985 to 150,000 m^3/d	Preliminary and primary treatment - Screening - Grit removal - Pre-aeration using floating aerators - Primary aeration using bubble aeration - Primary settling Secondary treatment - Secondary aeration using bubble aeration - Secondary settling Tertiary treatment - Balancing tanks with chlorination - Sand filtration Sludge treatment - Prethickening - Digestion - Post thickening - Drying in beds	Effluent is pumped to the Data Monitoring Center to be reused for irrigation Treated sludge is used as fertilizer
Riqaa Waste-water Treatment Plant		
Commissioned in 1982 Full capacity = 85,000 m^3/d Plans for upgrading to 180,000 m^3/d	Secondary treatment - Extended aeration using mechanical agitation Tertiary treatment - Balancing tanks with chlorination - Sand filtration - Secondary chlorination Sludge treatment - Aeration tanks - Thickening followed by drying beds	Effluent is: - used for irrigation - pumped to the Ardiya plant to be pumped to the Data Monitoring Center Treated sludge is used as fertilizer

[122] Abdul-Malik, *Yemen's Water Resources*.

[123] Food and Agriculture Organization, *Irrigation in the Near East Region in Figures* (Rome: United Nations, 1997). Available at: http://www.fao.org/docrep/W4356E/w4356e0g.htm.

TABLE 47 (*continued*)

General description	Treatment processes	Final disposal
Jahra Waste-water Treatment Plant		
Commissioned in 1982 Full capacity = 70,000 m^3/d Projects to improve efficiency	Secondary treatment - Screens - Grit chambers - Extended aeration tanks with mechanical agitation - Settling tank Tertiary treatment - Balancing tanks with chlorination - Sand filtration - Secondary chlorination Sludge treatment - Aeration tanks - Thickening followed by drying beds	Effluent is - used for irrigation - pumped to the Data Monitoring Center - Discharged into the Gulf Treated sludge is used as fertilizer
Failaka Waste-water Treatment Plant		
Full capacity = 10,000 m^3/d	- A series of oxidation ponds with agitators - Filtration - Chlorination	Irrigation

Source: Sanitary Engineering Department, *The Kuwait Sanitary Scheme* (Kuwait: Ministry of Public Works, State of Kuwait, 1996).

Late in 1977, the Ministry of Public Works initiated the preparation of a master plan for the effective use of treated effluent in Kuwait, covering the period up to 2010. The general recommendations made under the plan are presented in table 48. For the western and northern sites (Jahra and Ardiyah respectively) the plans suggested that first priority should be given to the development of an integrated system of extensive vegetable production. The second priority should be the development of fresh forage/hay production in rotation with vegetables at other agricultural sites. Once these two major objectives had been attained, tree planting with a view to prime and subsistence environmental protection forestry would be initiated.[124]

TABLE 48. WASTE-WATER REUSE MASTER PLAN IN KUWAIT

	Irrigated area (ha)	
Land use	1980	2010
Western and northern sites		
Agriculture		
Forage: dairy enterprise	70	670
Forage: open market sale	149	589
Horticulture		
Extensive vegetables	50	200
Forestry		
Maximum production forestry	20	213
'Environmental protection' at recommended irrigation rate	3 808	7 826
'Environmental protection' forestry at subsistence irrigation rate	401	-
Others	20	
Existing trial site, vegetable areas	46	46
Subtotal	4 544	9 544

[124] Food and Agriculture Organization (FAO), *Wastewater Treatment and Use in Agriculture*, FAO Irrigation and Drainage Paper 47 (Rome: United Nations, 1992). Available at: http://www.fao.org/docrep/T0551E/t0551e0b.htm#9.5, wastewater treatment and human exposure control: Kuwait.

TABLE 48 (*continued*)

Land use	Irrigated area (ha)	
	1980	2010
Coastal village sites		
Forestry		
'Maximum production' 'Environmental protection' forestry	52	787
	1 673	1 673
Subtotal	1 725	2 460
Failaka Island		
'Environmental protection' forestry	176	284
Total	6 445	12 288

Source: Adapted from FAO, *Waste-water Treatment and Use in Agriculture.*

D. LEBANON

Lebanon generates an estimated 249 million cubic metres of waste-water per year, with a total BOD load of 99,960 tons. According to a Census of Buildings and Establishments conducted by the Central Administration for Statistics (CAS) in 1996-1997, approximately 37 per cent of the nearly 500 000 buildings in Lebanon were connected to a sewer network. The remaining buildings (62 per cent) used cesspools and septic tanks or simply released raw sewage directly into the environment. Since 1997, extensive waste-water works have been built, and this has presumably improved the waste-water collection capacity of the country.[125]

Thirty-five waste-water treatment plants (WWTPs) are planned for the near future, including seven that are under construction, 18 for which funding has been approved and are in the preparatory stage, and 10 for which no funding has yet been secured (see table 49). The only large-scale WWTP that is operational at the present time is the Ghadir plant, south of Beirut, which provides only preliminary treatment, namely grit and scum removal. An exploratory study is being conducted on the economic feasibility of upgrading the Ghadir WWTP to provide secondary treatment before discharge into the sea.[126]

TABLE 49. IMPLEMENTATION STATUS OF WASTE-WATER TREATMENT PLANTS IN LEBANON

Location/name	Implementation status		
	Under construction	Preparatory stage	Funding not secured
Jebrayal			X
Abdeh			X
Michmich		X	
Bakhoun		X	
Tripoli		X	
Becharre			X
Hasroun			X
Amioun			X
Chekka	X		
Batroun	X		
Jbeil	X		
Kartaba		X	
Khanchara			X
Harajel		X	

[125] Ministry of Environment of Lebanon, *State of the Environment Report 2001* (Beirut: Government of Lebanon, 2001). Available at: http://www.moe.gov.lb/ledo/soer2001pdf/chpt15_wwm.pdf.

[126] Ministry of Environment, *State of the Environment Report 2001*.

TABLE 49 (*continued*)

Location/name	Implementation status		
	Under construction	Preparatory stage	Funding not secured
Kesrouane/Tabarja			X
Dora			X
Ghadir			X
Chouf coastal area	X		
Mazraat el Chouf		X	
Saida	X		
Sour			X
Hermel		X	
Laboue		X	
Yammouneh		X	
Baalbeck	X		
Zahle		X	
Aanjar		X	
Jib Jinnine/Deir Tahnich		X	
Karoun		X	
Sohmor/Yohmor		X	
Hasbaya		X	
Jbaa		X	
Nabatiyeh	X		
Shakra		X	
Bint Jbeil		X	

Source: Ministry of Environment, *State of the Environment Report 2001*.

In the absence of operational waste-water treatment plants, effluent from coastal communities is discharged into the sea, while effluent from inland communities is disposed of in rivers, streams, dry river beds, on open land or underground through dry wells. There are approximately 53 outfalls along the coast. Most outfalls extend only a couple of metres or terminate at the surface of the water; thus, there is no submersed outfall and thus no effective dilution of waste-water. The Ghadir outfall, however, is a submersed pipeline 1,200 millimetres in diameter which extends 2.6 kilometres out into the Mediterranean Sea. The outlet point is approximately 60 metres deep, and consequently the waste-water is adequately diluted.

Delays in the construction of waste-water works in various parts of the country have prompted a number of municipalities and local communities to make their own arrangements with the technical and financial support of non-governmental organizations (NGOs) that secure funding throuhg international donors such as the United States Agency for International Development (USAID). Thirteen small community-level waste-water treatment plants became operational in this way in 2001. Most of these provide secondary treatment, producing water that is suitable for irrigation.[127]

E. EGYPT

According to 1994 statistics, sewer networks in Egypt are confronted with operational problems, mainly due to their dimensions, which are inadequate to accommodate the volume of waste-water generated by the rapidly increasing population. Furthermore, most of the collected waste-water is not treated or is treated ineffectually owing to the unsatisfactory state of the existing WWTPs. Twenty-five per cent of the population has no sewerage service at all, and of the waste-water that is collected, only 15 per cent is

[127] Ministry of Environment, *State of the Environment Report 2001*.

adequately treated. Of the remaining untreated water, 25 per cent is partially treated, while 60 per cent is carried raw via open canals to the Mediterranean Sea.[128]

Cairo, the largest city in the Middle East region, with more than 16 million inhabitants, is burdened with continued rapid population growth and spatial expansion. The sewerage network was built in the early years of the 20th century, and by the 1980s it was already incapable of coping with the growing strains imposed by an ever larger and still rapidly increasing population, and was regularly affected by overflows due to damaged pipes and overload. In 1995, there were at least six operating domestic WWTPs serving the Greater Cairo area: three plants discharging through agricultural drains to the Northern Lakes and the Mediterranean and one plant discharging into the Nile, while the effluent from the other two plants was used largely for desert irrigation and land reclamation (namely, desert development).[128] To resolve this unsanitary situation, the Government launched a sewerage extension programme, the Greater Cairo Waste-water Project, aimed at providing Cairo with a sanitation network that would be sufficient to cope with the city's growing needs. The main treatment plant for the Greater Cairo Waste-water Project is the Gabal El Asfar Treatment Plant, which has an ultimate capacity of three million cubic metres per day and is designed to serve a population of 3 million people. It consists of components listed below:[129]

(a) Inlet pumping station, 9 m lift with screws up to 3.2 m in diameter;

(b) On-nitrifying activated sludge process, including:

- (i) Screens and grit removal;
- (ii) Primary sedimentation tanks;
- (iii) Aeration tanks with surface aerators;
- (iv) Final clarifiers;
- (v) Chlorination of final effluent;

(c) Sludge treatment, including:

- (i) Thickening;
- (ii) Digestion and dewatering;
- (iii) Pumping stations;

(d) Utilization of produced gas in the power plant within the facility.

With the new sewerage rehabilitation and extension projects, current plans call for 84,000 hectares of land in Egypt to be irrigated with treated waste-water by the year 2000. All urban waste projects include facilities for treatment up to the tertiary level and will produce water that would be reusable for irrigation purposes. Cairo, for example, will have facilities capable of treating up to 4 million cubic metres per day and producing enough treated waste-water to irrigate 168,000 hectares of desert land. However, many rural areas still lack such facilities.[130]

[128] S. Myllylä, *Cairo-A Mega-City and Its Water Resources*, a paper presented at the third Nordic conference on Middle Eastern Studies: Ethnic encounter and culture change, Joensuu, Finland, 19-22 June 1995. Available at: http://www.hf.uib.no/smi/paj/myllyla.html#fn7.

[129] Black and Veatch, *Gabal Al Asfar Treatment Plant.* Available at: http://www.bbv-ltd.com/Projects/WSTD/GlobslEIATP.htm.

[130] Centre International de Hautes Etudes Agronomiques Méditerranéennes (CIHEAM), *Annual Report 2000: Development and Agri-food Policies in the Mediterranean Region* (Paris: CIHEAM, 2000). Available at: http://www.ciheam.org/ressources/en/rapport2000/ chapter8.pdf.

VII. CONCLUSION AND RECOMMENDATIONS

Effective waste-water collection and treatment are of great importance from the standpoint of both environmental and public health. Extensive research activity in this field has led to significant improvement and diversification in the processes and methods used for waste-water treatment and sludge management. The present study begins with brief descriptions of the various technologies commonly used for waste-water treatment and indications of the estimated costs associated with each. The following section presents a brief overview of the application of instrumentation and control for process operation and monitoring at waste-water treatment plants. Lastly, the status of waste-water treatment and waste-water reuse in selected ESCWA countries are discussed. It is clear from this survey that the ESCWA region would be well advised to strive to improve its waste-water reuse and establish information networks for the transfer and sharing of technology and experience.

In recent years, there has been growing interest in waste-water reuse as a major component of water demand management. While many ESCWA countries reuse treated waste-water for agricultural purposes, governments must address the issue of waste-water reuse as part of an integrated water management strategy, at the basin level, with multi-disciplinary coordination among various sectors including environment, health, industry, agriculture and municipal affairs. In this context, public health hazards are often associated with waste-water reuse, and consequently it is essential to disseminate knowledge and information about the danger of raw waste-water reuse and issue safe reuse guidelines. Most importantly, governments must regulate and monitor effluent quality, reuse practices, public health, crop water quality and soil and groundwater quality.

Developments in waste-water treatment and reuse practices in the ESCWA countries could be facilitated through the creation of an information network, which can serve as a forum for the exchange of information and knowledge about applied research in the realm of waste-water management and practices appropriate to the developing world. Such a network must be broad in scope, addressing various aspects of waste-water management, including appropriate and affordable waste-water collection, treatment and disposal technologies and practices as well as the planning and regulation issues that are fundamental to waste-water management. It should be capable of accommodating various activities, including: summarizing and disseminating relevant information on research in the field; maintaining current information on research, studies or projects undertaken by network members; presenting relevant information on available training courses; responding to requests for information from network members; organizing online discussions among network members; and maintaining and expanding waste-water management information with electronic access

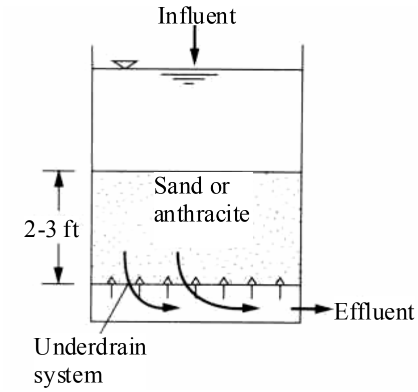
Finally, it would clearly be desirable to mount a data-gathering campaign aimed at addressing the current lack of information about waste-water treatment costs in the ESCWA region. In view of the fact that actual treatment costs are significantly influenced by site-specific characteristics and country conditions, this issue could best be approached through field surveys of waste-water treatment plants operating in selected ESCWA countries. A model survey questionnaire covering data of relevance for a comprehensive assessment of waste-water treatment costs is found in Annex III. It is worth noting that cost estimates for advanced treatment technologies (namely, reverse osmosis, microfiltration, ultrafiltration, and so on) can sometimes be obtained more readily from similar surveys targeting industrial facilities in Europe and the United States, since municipal WWTPs utilizing such state-of-the-art technologies are rarely encountered in ESCWA countries.

ANNEXES

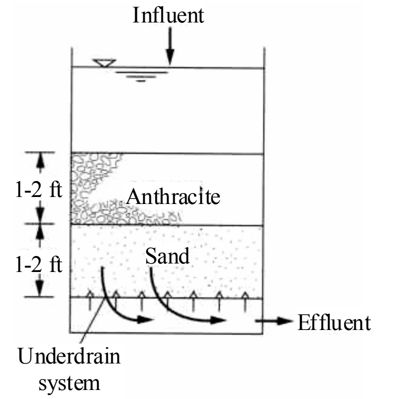
Annex I

TABLES AND FIGURES

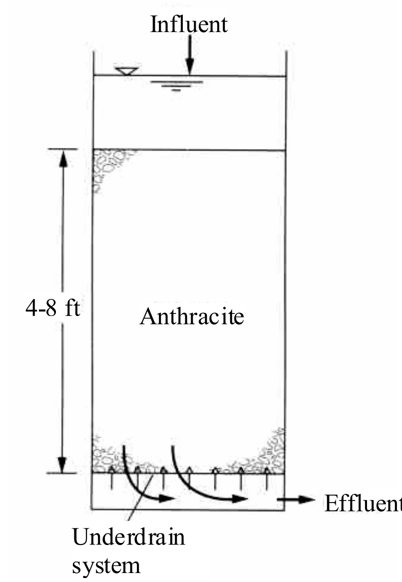
Annex figure 1. Types of filters used for the filtration of treated waste-water



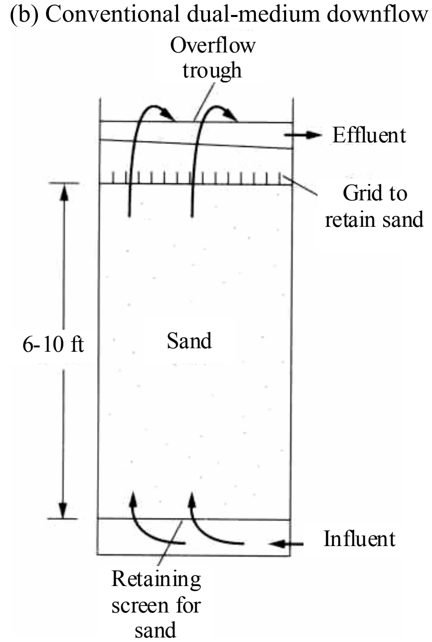
(a) Conventional mono-medium downflow



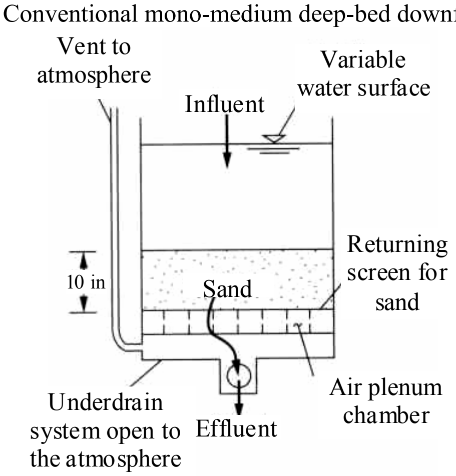
(b) Conventional dual-medium downflow

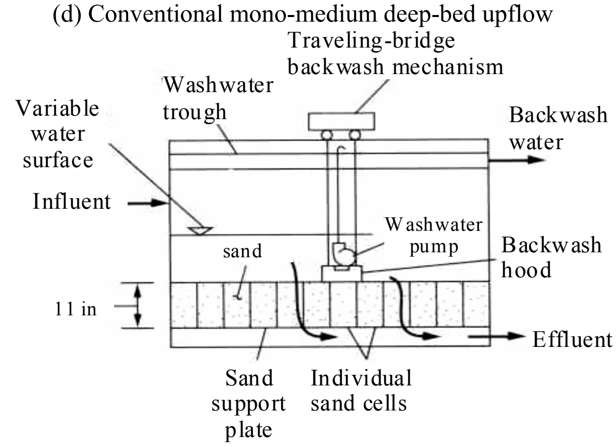


(c) Conventional mono-medium deep-bed downflow



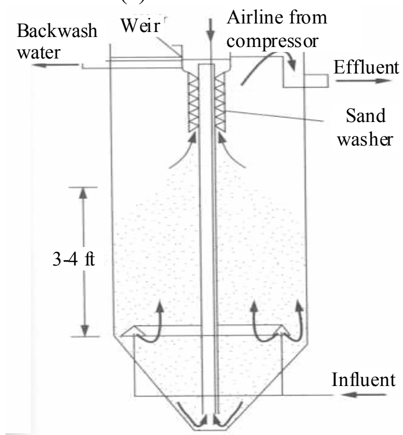
(d) Conventional mono-medium deep-bed upflow



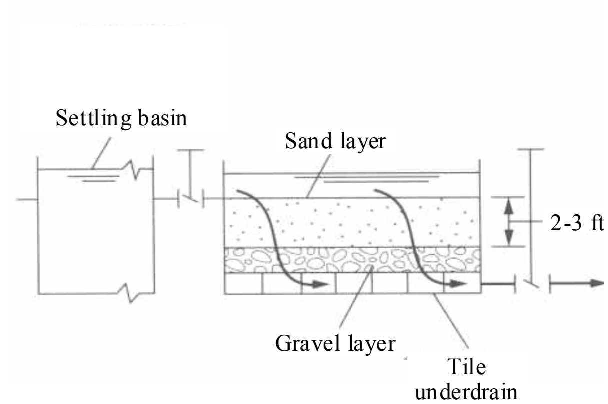


(e) Pulsed-bed filter

(f) Traveling bridge filter



(g) Continuous backwash deep-bed upflow filter



(h) Slow sand filter

Source: Adapted from Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

ANNEX TABLE 1. PHYSICAL AND OPERATIONAL CHARACTERISTICS OF COMMONLY USED GRANULAR-MEDIUM FILTERS

Type of filter	Type of filter bed	Filtering medium	Typical bed depth (in)	Operation during the filtration phase	Operation during the cleaning phase
Conven-tional Semicontinuous, downflow	Mono-medium	Sand or anthracite	30	Liquid is passed downward through the filter bed. Rate of flow through the filter may be constant or variable depending on the flow control method.	When effluent turbidity starts to increase or the allowable headloss is reached, the filter is backwashed by reversing the direction of flow through the filter. Both air and water are used in the backwash operation.
	Dual medium	Sand and anthracite	36		
	Multi-medium	Sand, anthracite and garnet	36		
Deep bed Semicontinuous, downflow	Mono-medium	Sand or anthracite		Liquid is passed downward through the filter bed. Rate of flow through the filter may be constant or variable depending on the flow control method.	When effluent turbidity starts to increase or the allowable headloss is reached, the filter is backwashed by reversing the direction of flow through the filter. Both air and water are used in the backwash operation.
Deep bed Semicontinuous, upflow	Mono-medium	Sand or anthracite	48-72	Liquid is passed upward through the filter bed. Rate of flow through the filter is usually constant.	When effluent turbidity starts to increase or the allowable headloss is reached, the filter is backwashed by increasing the flow rate through the bottom of the filter. Both air and water are used in the backwash operation.
Pulse-bed Semicontinuous, downflow	Mono-medium	Sand	48-72	Liquid is passed downward through the filter bed. As the headloss builds up, air is pulsed up through the bed to break up the surface mat and to redistribute the solids. Rate of flow through the filter is usually constant.	When effluent turbidity starts to increase or the allowable headloss is reached, the filter is backwashed by reversing the direction of flow through the filter. Liquid to be filtered continues to enter the filter during the backwash operation. Chemical cleaning is also used.

ANNEX TABLE 1 (*continued*)

Type of filter	Type of filter bed	Filtering medium	Typical bed depth (in)	Operation during the filtration phase	Operation during the cleaning phase
Deep bed Continuous, upflow	Mono-medium	Sand	48-72	Liquid is passed upward through the filter bed, the medium of which is moving downward in the countercurrent direction. Rate of flow through the filter is usually constant.	The filter medium is backwashed continuously by pumping sand from the bottom of the filter with an airlift to a sand washer located in the top of the filter. After passing through the washer, the clean sand is distributed on the top of the filter bed.
Traveling-bridge Continuous, downflow	Mono-medium	Sand	11	Liquid is passed upward through the filter bed. Liquid continues to be filtered while the individual cells are backwashed. Rate of flow through the filter is usually constant.	When the allowable headloss is reached, the individual cells of the filter are backwashed by reversing the direction of flow through each of the cells successively. The backwash water is removed through the backwash hood.
	Dual medium	Sand	16		

Source: Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

ANNEX TABLE 2. MAJOR BIOLOGICAL TREATMENT PROCESSES USED FOR WASTE-WATER TREATMENT

Type	Common name	Use
AEROBIC PROCESSES		
Suspended growth	Activated sludge process Conventional (plug-flow) Complete mix Step aeration Pure oxygen Sequencing batch reactor Contact stabilization Extended aeration Oxidation ditch Deep tank Deep shaft	Carbonaceous BOD removal, nitrification
	Suspended growth nitrification	Nitrification
	Aerated lagoons	Carbonaceous BOD removal, nitrification
	Aerobic digestion Conventional air Pure oxygen	Stabilization, carbonaceous BOD removal
Attached growth	Trickling filters Low rate High rate	Carbonaceous BOD removal, nitrification
	Roughing filters	Carbonaceous BOD removal
	Rotating biological contactors	Carbonaceous BOD removal, nitrification
	Packed-bed reactors	Carbonaceous BOD removal, nitrification
Combined suspended and attached growth processes	Activated biofilter process Trickling filter solids contact, biofilter activated sludge, series trickling filter activated sludge	Carbonaceous BOD removal, nitrification
ANOXIC PROCESSES		
Suspended growth	Suspended growth denitrification	Denitrification
Attached growth	Fixed-film denitrification	Denitrification
ANAEROBIC PROCESSES		
Suspended growth	Anaerobic digestion Standard rate, single-stage High rate, single-stage, Two-stage	Stabilization, carbonaceous BOD removal Stabilization, carbonaceous BOD removal Stabilization, carbonaceous BOD removal
	Anaerobic contact process	Carbonaceous BOD removal
	Upflow anaerobic sludge-blanket	Carbonaceous BOD removal
Attached growth	Anaerobic filter process	Carbonaceous BOD removal, waste stabilization
	Expanded bed	Carbonaceous BOD removal, waste stabilization
COMBINED AEROBIC, ANOXIC AND ANAEROBIC PROCESSES		
Suspended growth	Single or multi-stage processes, various proprietary processes	Carbonaceous BOD removal, nitrification, denitrification, and phosphorus removal
Combined suspended and attached growth	Single or multi-stage processes	Carbonaceous BOD removal, nitrification, denitrification, and phosphorus removal
POND PROCESSES		
	Aerobic ponds Maturation (tertiary) ponds Facultative ponds Anaerobic ponds	Carbonaceous BOD removal Carbonaceous BOD removal Carbonaceous BOD removal Carbonaceous BOD removal

Source: Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

ANNEX TABLE 3. DESCRIPTION OF ACTIVATED-SLUDGE PROCESSES AND PROCESS MODIFICATIONS

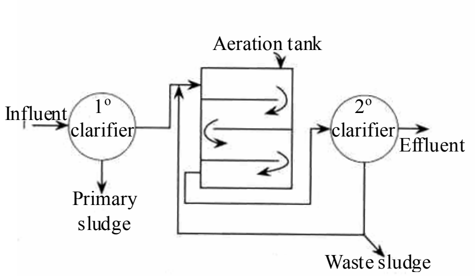
Process or process modification	Description	BOD removal efficiency (Percentage)
Conventional plug-flow	Settled waste-water and recycled activated sludge enter the head of the aeration tank and are mixed by diffused air or mechanical aeration. Air application is generally uniform throughout the tank length. During the aeration period, adsorption, flocculation, and oxidation of organic matter occur. Activated-sludge solids are separated in a secondary settling tank.	85-95
Complete-mix	Process is an application of the flow regime of a continuous-flow stirred-tank reactor. Settled waste-water and recycled activated sludge are typically introduced at several points in the aeration tank. The organic load on the aeration tank and the oxygen demand are uniform throughout the tank length.	85-95
Tapered aeration	Tapered aeration is a modification of the conventional plug-flow process. Varying aeration rates are applied over the tank length, depending on the oxygen demand. Greater amounts of air are supplied to the head end of the aeration tank, and the amounts diminish as the mixed liquor approaches the effluent end. Tapered aeration is usually achieved by using different spacing of the air diffusers over the tank length.	-
Step-feed aeration	Step feed is a modification of the conventional plug-flow process in which the settled waste-water is introduced at several points in the aeration tank to equalize the food to micro-organism (F/M) ratio, thus lowering peak oxygen demand. Three or more parallel channels are commonly used. Flexibility of operation is one of the important features of this process.	85-95
Modified aeration	Modified aeration is similar to the conventional plug-flow process except that shorter aeration times and higher F/M ratios are used. BOD removal efficiency is lower than in the case of other activated-sludge processes.	60-75
Contact stabilization	Contact stabilization uses two separate tanks for the treatment of the waste-water and the stabilization of the activated sludge. The stabilized activated sludge is mixed with the influent (either raw or settled) waste-water in a contact tank. The mixed liquor is settled in a secondary settling tank and return sludge is aerated separately in a re-aeration basin for stabilization of the organic matter. Aeration volume requirements are typically 50 per cent less than in the case of conventional plug flow.	80-90
Extended aeration	The extended aeration process is similar to the conventional plug-flow process except that it operates in the endogenous respiration phase of the growth curve, which requires a low organic loading and long aeration time. The process is used extensively for prefabricated package plants for small communities.	75-95
High-rate aeration	High-rate aeration is a process modification in which high mixed liquor suspended solids (MLSS) concentrations are combined with high volumetric loadings. The combination allows high F/M ratios and low mean cell-residence times with relatively short hydraulic detention times. Adequate mixing is very important.	75-90

ANNEX TABLE 3 (*continued*)

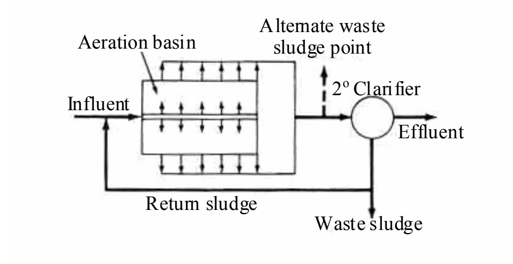
Process or process modification	Description	BOD removal efficiency (Percentage)
Kraus process	The Kraus process is a variation of the step aeration process used to treat waste-water with low nitrogen levels. Digester supernatant is added as a nutrient source to a portion of the return sludge in a separate aeration tank designed to nitrify. The resulting mixed liquor is then added to the main plug-flow aeration system.	85-95
High-purity oxygen	High-purity oxygen is used instead of air in the activated-sludge process. The oxygen is diffused into covered aeration tanks and is recirculated. A portion of the gas is wasted to reduce the concentration of carbon dioxide. pH adjustment may also be required. The amount of oxygen added is about four times greater than the amount that can be added by conventional aeration systems.	85-95
Oxidation ditch	The oxidation ditch consists of a ring- or oval-shaped channel and is equipped with mechanical aeration devices. Screened waste-water enters the ditch, is aerated, and circulates about 0.8 to 1.2 ft/s (0.25 to 0.35 m/s). Oxidation ditches typically operate in an extended aeration mode with long detention and solids retention times. Secondary sedimentation tanks are used for most applications.	75-95
Sequencing batch reactor	The sequencing batch reactor is a fill-and-draw type reactor system involving a single complete-mix reactor in which all steps of the activated-sludge process occur. Mixed liquor remains in the reactor during all cycles, and this eliminates the need for separate secondary sedimentation tanks.	85-95
Deep shaft reactor	The deep vertical shaft reactor is a form of the activated-sludge process. A vertical shaft about 400 to 500 ft (120 to 150 m) deep replaces the primary clarifiers and aeration basin. The shaft is lined with a steel shell and fitted with a concentric pipe to form an annular reactor. Mixed liquor and air are forced down the centre of the shaft and allowed to rise upward through the annulus.	85-95
Single-stage nitrification	In single-stage nitrification, both BOD and ammonia reduction occur in a single biological stage. Reactor configurations may be either a series of complete-mix reactors or plug-flow.	85-95
Separate-stage nitrification	In separate-stage nitrification, a separate reactor is used for nitrification, operating on a feed waste from a preceding biological treatment unit. The advantage of this system is that operation can be optimized to conform to nitrification needs.	85-95

Source: Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

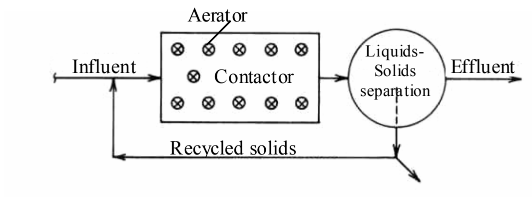
Annex figure 2. Selected activated-sludge processes



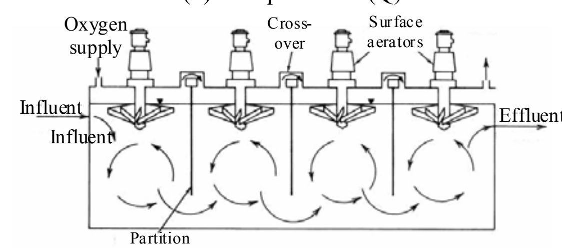
(a) Conventional plug flow



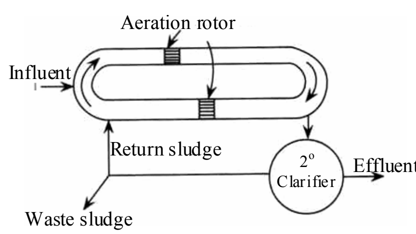
(b) Complete mix (Q)



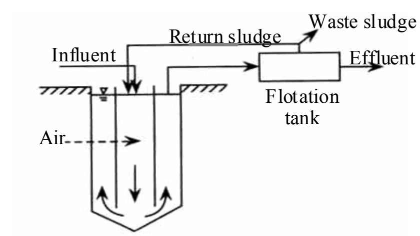
(c) Tapered aeration



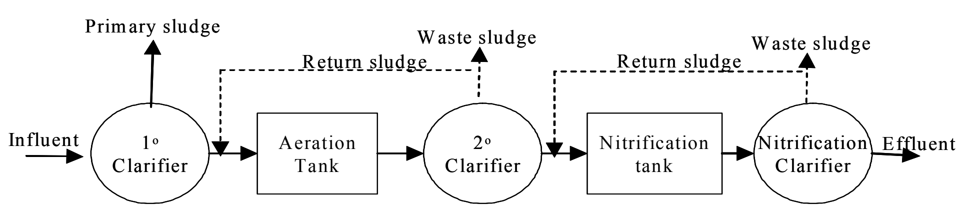
(d) Contactor using pure oxygen



(e) Oxidation ditch



(f) Deep shaft process



(g) Nitrification in separate stage

Source: Adapted from Liu and Lipták, *Wastewater Treatment.*

ANNEX TABLE 4. COMPARISON OF THE MAIN NATURAL TREATMENT PROCESSES

Characteristic	Slow rate	Rapid infiltration	Overland flow	Wetland	Floating aquatic plants
Climatic conditions	Storage often needed for cold weather and during precipitation	None (possible modification of operation in cold weather)	Storage often needed for cold weather and during precipitation	Storage may be needed for cold weather.	Storage may be needed for cold weather
Depth to groundwater	2-3 ft (minimum)	10 ft (lesser depths are acceptable when underdrainage is provided)	Not critical	Not critical	Not critical

ANNEX TABLE 4 (*continued*)

Characteristic	Slow rate	Rapid infiltration	Overland flow	Wetland	Floating aquatic plants
Slope	Less than 15 per cent on cultivated land; less than 40 per cent on forested land	Not critical; excessive slopes require much earthwork	Finish slopes 1-8 per cent	Usually less than 5 per cent	Usually less than 5 per cent
Soil permeability	Moderately slow to moderately rapid	Rapid (sands, loamy sands)	Slow (clays, silts and soils with impermeable barriers)	Slow to moderate	Slow to moderate
Application techniques	Sprinkler or surface	Usually surface	Sprinkler or surface	Sprinkler or surface	Surface
Minimum preapplication treatment	Primary sedimentation	Primary sedimentation	Screening	Primary sedimentation	Primary sedimentation
Disposition of applied waste-water	Evapotranspiration and percolation	Mainly percolation	Surface runoff and evaporation with some percolation	Evapo-transpiration, percolation and runoff	Some evapo-transpiration
Need for vegetation	Required	Optional	Required	Required	Required
Expected effluent quality (average, mg/L)					
BOD	< 2	< 2	< 10		
Suspended solids	< 1	< 2	< 15	-	-
ammonia nitrogen as N	< 0.5	< 0.5	< 1		
Total nitrogen as N	< 3	< 10	< 5		
Total phosphorus as P	< 0.1	< 1	< 4		

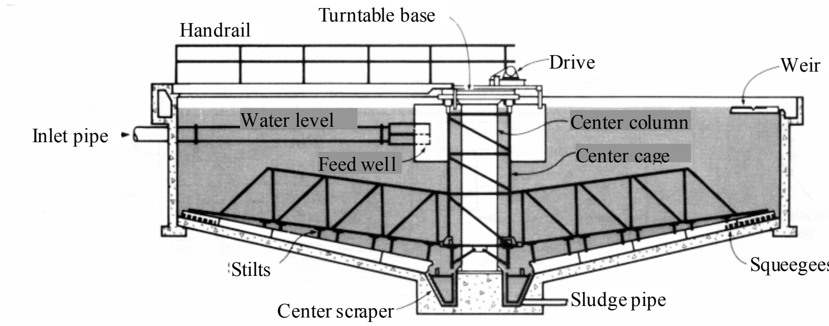
Source: Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition, and Reed et al., *Natural Systems*.

ANNEX TABLE 5. DESCRIPTION OF COMMON SLUDGE THICKENING TECHNOLOGIES

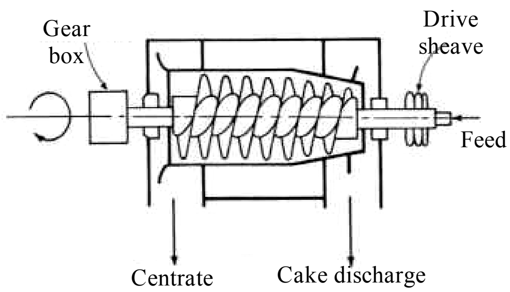
Thickening method	Description	Solids concentration achieved (Percentage)
Gravity	A gravity thickener is similar to a conventional circular sedimentation basin. Dilute sludge is fed to a centre feed well and allowed to settle and compact before being withdrawn from the bottom of the basin. The sludge scraping mechanism incorporates vertical pickets, which gently agitate the sludge and contribute to its densification by releasing trapped gas and waters. The thickened sludge is pumped to digesters or dewatering equipment, while the supernatant is returned to the headworks of the treatment plant, or to the primary settling tank. This method is most effective with primary sludge.	-
Flotation	Dissolved air flotation is used for thickening of sludge that originates from suspended growth biological treatment processes. It involves the introduction of air into a sludge solution that is being held at an elevated pressure. When the solution is depressurized, the dissolved air is released as finely divided bubbles. These carry the sludge to the top, where it is skimmed.	3.5-5
Centrifugation	Centrifuges are used to thicken and dewater waste activated sludges. They involve the settling of sludge particles under the influence of centrifugal forces. Two basic types of centrifuges are the solid bowl and the imperforate basket. - The solid bowl centrifuge consists of a long, horizontally mounted bowl, tapered at one end. Sludge is introduced continuously and the solids concentrate on the periphery. - The imperforate basket centrifuge consists of a vertically mounted spinning bowl, operating on a batch basis. The solids accumulate against the wall of the bowl and the liquid is decanted.	4-6 8-10
Gravity belt	Gravity belt thickeners consist of a gravity belt that moves over rollers driven by a variable-speed drive unit. It is used for the thickening of raw and digested sludges after conditioning by the addition of polymer. The conditioned sludge is fed into a box, which distributes it evenly across the width of the moving belt. As the water drains through, the sludge is carried to the discharge end of the thickener.	3-6
Rotary drum	A rotary drum thickening system consists of a waste activated-sludge conditioning system and rotating cylindrical screens. First, polymer is mixed with thin sludge in the conditioning drum. The conditioned sludge then passes to rotating screen drums, which separate the flocculated solids from the water.	5-9

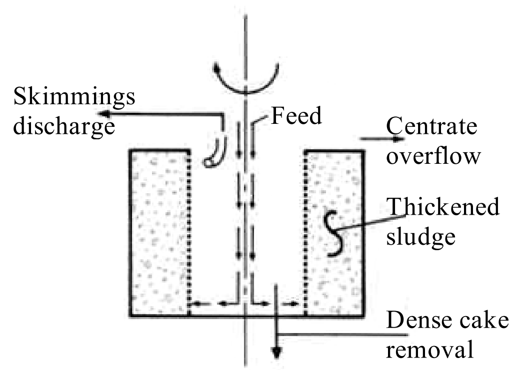
Source: Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

Annex figure 3. Common thickening technologies



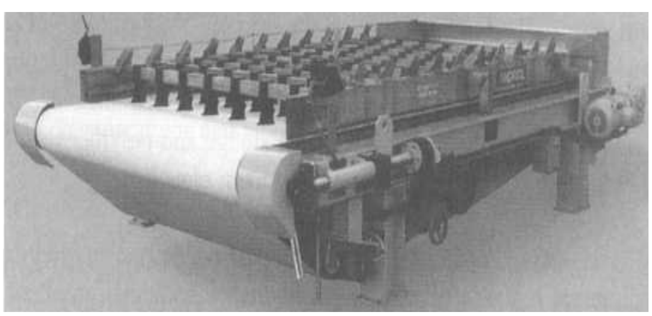
(a) Gravity thickening

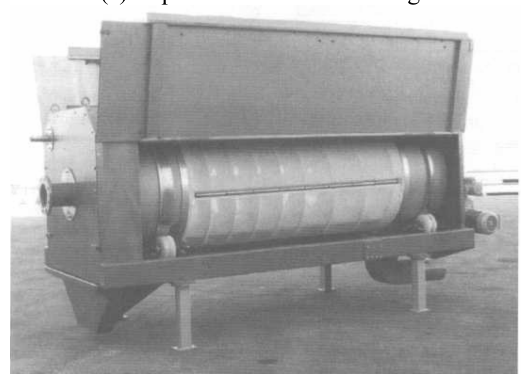




(b) Solid bowl centrifuge

(c) Imperforate basket centrifuge





(d) Gravity belt thickener

(e) Rotary drum

Source: Adapted from Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd edition.

ANNEX TABLE 6. DESCRIPTION OF THE VARIABLES MONITORED FOR VARIOUS TREATMENT PROCESSES

Treatment unit	Sensing device	Purpose	Description
Bar screen	Limit switch	Monitors gate position	Displays green light
	Time clock	Operation of rake	Displays green light
	High-level override by float in stilling well (excessive head loss)	Emergency operation of rake	Displays red light
Pumping station	Bubbler system in wet well	Controls pumping rate	Display of liquid level in wet well
	Conductivity switch or float	Liquid level in sump of dry well	Trips alarm
	Limit switches	Monitor gate position	Display green light
	Pressure switch	Monitors seal water pressure for pump protection	Displays red light
	Flow switch	Monitors seal and water flow to pump for pump protection	Displays red light
	Pressure indicator	Monitors the discharge pressure of the pumps	Pressure gauges
	Motor monitors	Monitor on-off condition of motor and motor malfunction	Display green light, red light for malfunction
	Liquid level sensor in dry pit	Leakage and flooding	Displays red light, trips alarm
	Temperature monitor and/or amperage monitor	Motor protection against overheating and burn out	Displays red light
	Sampling and analysis	Sensors for pH, H_2S, CH_4, DO. Sampler to deliver water sample in the lab	Continuous recording on strip chart. Routine chemical analysis TSS, BOD, TOC, P, N
	Main circuit breaker, auxiliary contact	Monitor power outage	Display red light (standby power required)
Flow measurement	Venturi tube in force main	Monitors influent flow to the plant	Displays, records and totalizes continuously
Aerated grit chamber	Orifice plate with square root extractor and display	Measures air flow to each chamber	Meters, displays, records and totalizes flow continuously
	Pressure indicators	Monitoring of discharge pressure of air blowers	Pressure gauges
	Motor monitors	Monitor on-off condition of blower motor	Display green light
	Torque monitors	Monitor spiral conveyer and bucket elevator	Display red light
Primary sedimentation	Level detector	Controls sludge and scum pumps and air agitator in scum box	Displays green light
	Pressure indicator	Monitors discharge from each sludge pump	Displays red light
	Magnetic flow meter	Sludge-pumping rate	Displays, records and totalizes continuously
	Motor monitor	Monitors on-off condition of each motor	Displays green light
	Torque monitor	Monitors motor torque for sludge-raking mechanism	Alarm signal
Anaerobic zone	Torque monitor	Monitors mixer motor for operation	Displays red light
	Speed regulator	Monitors and controls rotational speed of mixer blades	Displays rotational speed
	Thermocouple Selective ion electrode	Monitors temperature, pH, and ORP	Displays and records

ANNEX TABLE 6 (*continued*)

Treatment unit	Sensing device	Purpose	Description
Anoxic zone	Torque monitor	Monitors mixer motor for operation	Displays red light
	Speed regulator	Monitors and controls rotational speed of mixer blades	Displays rotational speed
	Thermocouple Selective ion electrode	Monitors temperature, pH, DO, NO_3	Displays and records Displays and records
Aerobic zone and final clarifiers	Dissolved oxygen measurement	Controls aeration rate	Display and continuous recording
	Flow meter, differential pressure type	Monitors air supply to each aeration basin	Meters, displays, records and totalizes flow continuously
	Ultrasonic sludge blanket in final clarifier	Monitors the sludge level and actuates sludge return pumps	Displays pump operation
	Magnetic flow meter	Controls return sludge flow	Displays, records and totalizes flow continuously
	Suspended solids analyzer	Measures MLSS concentration in aeration basin and actuates waste sludge pumps	Displays and records TSS, records and totalizes flow
	Pressure indicator	Monitors the discharge pressure of the pumps	Pressure gauges
	Motor monitors, torque monitor	Monitor on-off condition of each motor	Display green light
	Torque monitor	Monitors motor torque for sludge-raking mechanism, RAS pumps and blowers	Alarm signal
UV disinfection system	Parshall flume	Measures flow upstream of UV disinfection facility to control light intensity	Displays, records and totalizes flow continuously
	Electrical power module	Monitors electrical power to UV lamp	Displays red light
	Thermocouples	Monitor temperature of UV lamp module	Display red light
	Lamp status	Monitors burnt out lamp	Displays red light
	UV light intensity sensor	Measures UV light intensity	Displays light intensity and UV dose alarm
	Totalizer	Totalizes time for each lamp/row/bank	Displays total hours in operation
	Level control	Monitors liquid level upstream and downstream of UV banks	Displays and records the level. Sounds alarm for low and high levels
Gravity thickener	Magnetic flow meter	Flow measurement of feed sludge	Displays, records and totalizes flow
	Venturi meter	Flow measurement of dilution water	Displays, records and totalizes flow
	Ultrasonic sludge blanket detector	Monitors the sludge blanket level in the gravity thickener	Displays sludge blanket level
	Ultrasonic density meter	Monitors solids concentration in feed and thickened sludge	Displays and records
	Pressure indicator, motor monitor, torque monitor	Similar to those for primary and final clarifiers	Similar to those for primary and final clarifiers

ANNEX TABLE 6 (*continued*)

Treatment unit	Sensing device	Purpose	Description
Anaerobic digestion	Magnetic flow meter	Flow measurement of feed sludge	Displays, record and totalizes flow
	Ultrasonic density meter	Monitor solids concentration in feed and digested sludge, and mixing	Similar to those for gravity thickeners
	Thermocouple, selective ion electrodes	Monitor temperature, pH, and ORP of digester content and the recirculating sludge	Display and record
	Level indicator	Monitor liquid level in the digester and level of floating cover	Indicator
	Pressure and temperature	Control hot water heating system	Display temperature, pump operation
	Orifice meter	Measurement of digester gas flow	Displays, records and totalizes
	Pressure gauge	Gas storage pressure	Red light and alarm
	Flame detector	Monitors flame in building, flare status	Red light
	Chromatograph and calorimeter	Determination of gas composition and calorific value	Tabulation of result and data logging
	Venuri meter	Measurement of supernatant flow	Records and totalizes
	Pressure switch, flow switch pressure indicator, motor monitor	Monitor pump, motor, compressor as indicated above	Display red light
Filter press	Pressure indicators	Measurement of pressure and shearing forces exerted by belt filters	Dial display
	Belt speed	Frequency drive controller for belt speed adjustment	Displays speed
	Magnetic flow meter	Monitors the flow of conditioned feed sludge to each belt filter press	Records and totalizes
	Ultrasonic density meter	Monitors solids concentration in feed sludge	Records and totalizes
	Static scale	Measures weight of sludge cake	Records and logs data
	Ohm meter, lab test	Determine moisture content of the sludge cake	Record and log data
	Float and level indicator	Measure level of polymer solution in storage and feed banks	Record and log data
	Magnetic flow meter	Measures flow of lime and polymer solution	Records and logs data
	Pressure switch, flow switch, pressure indicator, motor monitor	Monitor pump, motor, compressor as indicated above	Display as indicated above

Source: Qasim, *Wastewater Treatment Plants*.

H_2S = hydrogen sulfide
CH_4 = methane
N = nitrogen
P = phosphorus
BOD = biological oxygen demand
DO = dissolved oxygen
ORP = oxidation-reduction potential
TSS = total dissolved solids
TOC = total organic carbon
UV = ultraviolet
MLSS = mixed liquor suspended solids

ANNEX TABLE 7. LAND AREA EQUATIONS FOR SELECTED NTSS

NTS	Area equation, A	Assumptions
On-site	A (m^2) = 1.5 x Q (m^3/d)/ k (m/d)	All year operation possible in all climates
Slow rate	A (acres) = 19 x 10^{-5} x Q (gallons/day) A (acres) = 28 x 10^{-5} x Q (gallons/day)	Warm climate, land application 12 months/yr Cold climate, land application, 6 months/yr
Rapid infiltration	A (acres) = 6 x 10^{-5} x Q (gallons/day)	Winter storage not required, all year operation
Overland flow	A (acres) = 9 x 10^{-5} x Q (gallons/day) A (acres) = 17 x 10^{-5} x Q (gallons/day)	Warm climate, land application 12 months/yr Cold climate, land application, 6 months/yr
Facultative pond	A (ha) = 5.1 x 10^{-3} x Q (m^3/d)	Warm climate, ~ 60 day HRT, 1.5 m deep, organic loading < 60 kg/ha.d
Aerobic pond	A (ha) = 3.2 x 10^{-3} x Q (m^3/d)	Warm climate, 30 day HRT, 1 m deep, organic loading < 90 kg/ha.d
Partial-mix aerated pond	A (ha) = 2.9 x 10^{-3} x Q (m^3/d)	Cold climate, 50 day HRT, 2.5 m deep, organic loading < 100 kg/ha.d
Controlled Discharge pond	A (ha) = 16.3 x 10^{-3} x Q (m^3/d)	180 day HRT, 1.5 m deep
Facultative hyacinth pond for secondary treatment	A (ha) = 9.5 x 10^{-3} x Q (m^3/d)	Very warm climate, 50 day HRT, 1.5 m deep, organic loading < 30 kg/ha.d, annual harvest
Hyacinth pond for tertiary treatment	A (ha) = 0.71 x 10^{-3} x Q (m^3/d)	Secondary effluent input, 6-day HRT, depth< 1m, organic loading < 50 kg/ha.d, water temperatures > 10°C, frequent harvest or vegetation
Aerated hyacinth pond for secondary treatment	A (ha) = 1.5 x 10^{-3} x Q (m^3/d)	5-day HRT, 1 m deep, input of screened or settled waste-water, organic loading < 300 kg/ha.d, water temperatures > 10°C, monthly plant harvest
Duckweed pond for effluent polishing	A (ha) = 2.0 x 10^{-3} x Q (m^3/d)	20-day HRT, < 2 m deep, organic loading < 30 kg/ha.d, water temperatures > 7°C, input of facultative pond effluent
Free water surface wetland	A (ha) = 8.2 x 10^{-3} x Q (m^3/d)	7-day HRT, 0.1 m deep, input of screened or settled waste-water, organic loading < 100 kg/ha.d
Surface flow wetland	A (ha) = 2.7 x 10^{-3} x Q (m^3/d)	7-day HRT, < 0.8 m deep, input of screened or settled waste-water, organic loading < 150 kg/ha.d

Source: Reed et al., *Natural Systems.*

Annex II

COMMON ON-LINE PROCESS MEASUREMENT DEVICES AND THEIR APPLICATION IN WASTE-WATER TREATMENT

Measured variables	Primary device	Measured signal	Common application
Flow	Venturi meter	Differential pressure	Gas, liquids
	Flow nozzle meter	Differential pressure	Gas, liquids
	Orifice meter	Differential pressure	Gas, liquids
	Electromagnetic meter	Magnetic field and voltage change	Liquids, sludges
	Turbine meter	Propeller rotation	Clean liquid
	Acoustic meter	Sound waves	Liquids, sludges
	Parshall flume	Differential elevation of water surface	Liquids
	Palmer-Bowlus flume	Differential elevation of water surface	Liquids
	Weirs	Head over weir	Clean liquids
Pressure	Liquid-to-air diaphragm	Balance pressure across a metal diaphragm	Pressure 0-200 kN/m^2
	Strain gauge	Dimensional change in sensor	Pressure 0-350 000 kN/m^2
	Bellows	Displacement of mechanical linkage connected to the indicator	Pressure 0-20 000 kN/m^2
	Bourdon tube	Uncurling motion of noncircular cross-sectional area of a curved tube	Pressure 0-35 000 kN/m^2
Liquid level	Float	Movement of a float riding on surface of liquid	Liquid head 0-11 m
	Bubbler tube	Measurement of back pressure in the tube bubbling regulated air at slightly higher pressure than the static head outside	Liquid head 0-56 m
	Diaphragm bulb	Pressure change in air on one side of the diaphragm caused by the liquid pressure on the other side of the diaphragm	Liquid head 0-15 m
	Ultrasonic	The sonic pulses are reflected from the target surface	Liquid level in channel or basin
Sludge level	Photocell	Detection of light in a probe by a photocell across the sludge blanket	Primary sedimentation; Final clarifier; gravity thickener
	Ultrasonic	Detection of the ultrasonic signal transmitted between two transducers	Primary sedimentation; Final clarifier; gravity thickener
Temperature	Thermocouple	Current flows in a circuit made of two different metals	Anaerobic digester, hot-water boiler
	Thermal bulb	Absolute pressure of a confined gas is proportional to the absolute temperature	Sludge lines, water lines
	Resistance temperature detector	Change in electrical resistance of temperature-sensitive element	Bearing and winding temperatures of electrical machinery, anaerobic digesters, hot-water boilers

Measured variables	Primary device	Measured signal	Common application
Weight	Weight beam, hydraulic load cell or strain gauge	Lever mechanism or spring, pressure transmitted across diaphragm, dimensional change in sensor	Chemicals
Density	Gamma radiation	Absorption of gamma rays by the liquid between the radiation source and the detector	MLSS concentration; returned, thickened and digested sludge solids
Speed	Tachometer	Voltage, current	Variable-speed pump, blower, or mixer
Suspended solids	Ultrasonic sensor	Loss of ultrasonic signal by the liquid between the ultrasonic transmitter and receiver	MLSS concentration; returned, thickened and digested sludge solids
PH	Selective ion electrode	Voltage produced by hydrogen ion activity	Influent, chemical solution, anaerobic digester, dewatering, effluent
Oxidation-reduction potential	Electrode	Change in potential due to oxidation or reduction	Influent, maintenance of proper DO in aeration basin. Anaerobic digester
Total dissolved solids	Conductivity	Flow of electrical current across the solution	Influent, effluent
Dissolved oxygen	Membrane electrode	Electrical current across the membrane because of reduction of molecular oxygen. Signal is temperature-compensated	Influent, aeration basin, plant effluent
Total organic carbon	Carbon analyzer	CO_2 produced from combustion of sample	Influent to plant, influent to aeration basin, plant effluent
Chlorine residual	Sensor	Electrical output	Chlorine contact tank, plant effluent
Gases: NH_3, CO, CO_2, H_2S, CH_4	Sensors	Various types of sensor modules utilizing electrical impulses	Detection of hazardous condition in room or around covered treatment units
Oxygen uptake rate	Respirometers using sensor	Decrease in DO level over time	Aeration basin
Anaerobic biological condition	Sensor, combustion	CO_2 and CH_4 production rate	Anaerobic sludge digester
Phosphate	Spectrophotometer	Electrical signal proportional to degree of coloured compound produced when stannous chloride reacts with a phosphate-molybdate complex	Influent, effluent
Nitrate/Nitrite	Spectrophotometer	Electrical signal proportional to degree of colour formed when nitrite and nitrate react with reagents to form coloured compounds	Influent, effluent Dosing alkali to remedy acid production of nitrification
Ammonia	Spectrophotometer	Electrical signal proportional to degree of change that occurs when ammonia gas causes a change in the pH of an indicator solution	Influent, effluent

Source: Adapted from Qasim, *Wastewater Treatment Plants*.

THE WATER SPREADSHEET TOOL

Annex figure 4. General input of the WaTER tool

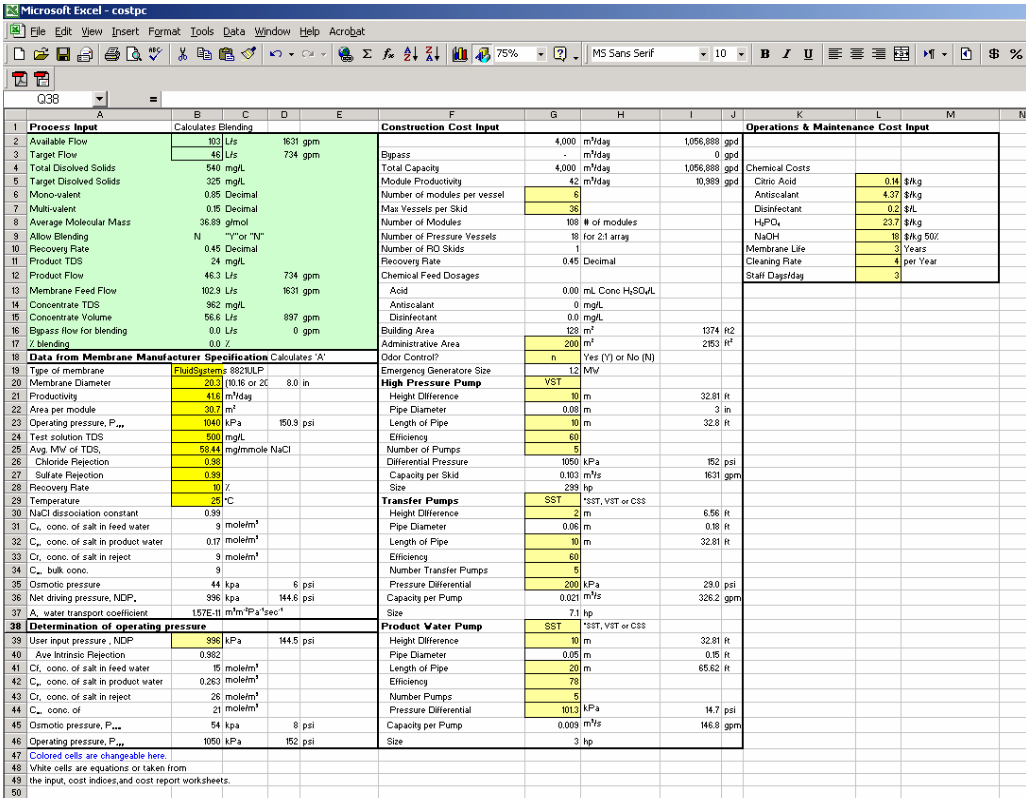
Microsoft Excel - costpc

H24 =

	A	B	C	D	E	F
1	**FLOW RATE INPUT PAGE, WATER DATA REPORT**		Links to this page are ORANGE			
2	Yellow colored cells are mandatory input cells					
3						
4						
5	***Enter Availability.***					
6	Plant availability due to down time (used to estimate production/year):	1.00				
7	Planned operation time per day (used to calculated energy & chemical cost):	1.00				
8						
9						
10		L/M	GPH	GPD	MGD	Acre-Ft/year
11	**INPUT CELLS: enter flowrate in ONE of these cells, set rest cells to 0**	2778	0	0	0	0
12	Flow rate converted to Liters/second and entered in workbook calculations.	46.30	0.00	0.0	0.0	0.0
13						
14	Flow rates converted to a variety of units.	2778	44,037	1,056,888	1.06	1183.79
15						
16						
17	**PLANT FLOW RATES**	**L/S**	**GPM**	**MGD**		
18	**Required Plant Feed Flow Rate:****	**103**	**1631**	**2.3**		
19	**Desired Plant Product Flow Rate:**	**46**	**734**	**1.1**		
20						
21	**Feed Flow = Plant Product Flow / RO Recovery entered on cost report.					
22						
23						
24						
25						
26	**WATER DATA REPORTS (based on Water Analysis)**					
27						
28	Total dissolved solids (TDS):	540	mg/L			
29	Average equivalent wt.:	20.8	g/equiv			
30	Total equiv./L:	0.022	eq/L	1.25E-02	mol/L	
31	Total equiv./L (Valence >+1):	0.004	eq/L	1.81E-03	>1 valence	
32	Average MW	36.89	g/mol			
33	Ionic Strength:	0.010	mole*charge^2/L			
34	Delta G:	-1.240				
35	LSI:	-0.994				
36	Tendancy to corrosion, may need remineralization.					
37						

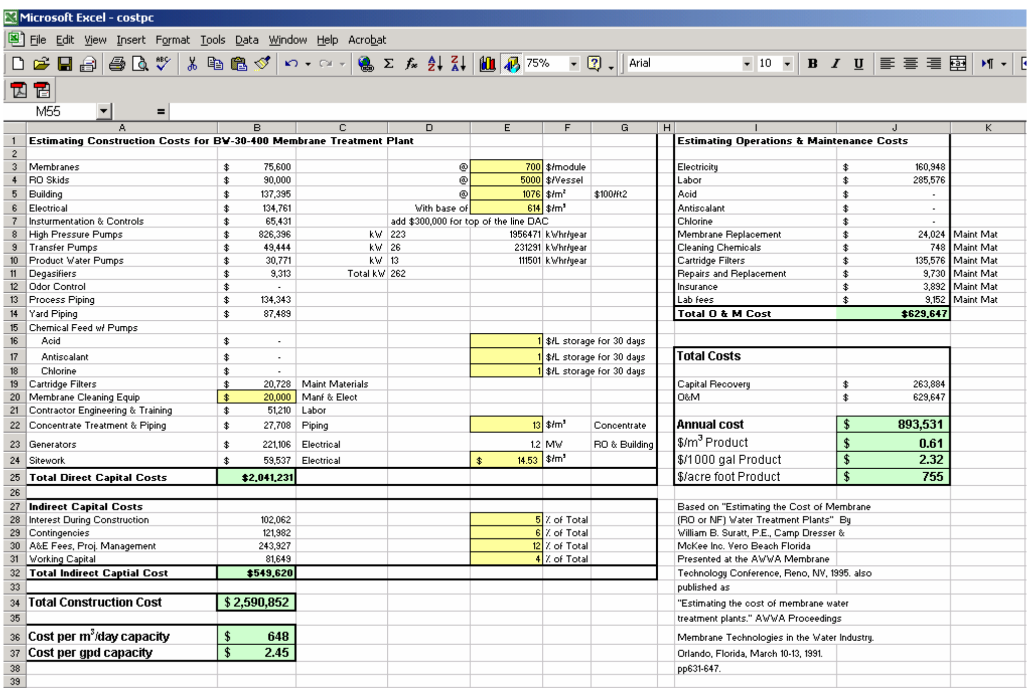
Source: WaTER software.

Annex figure 5. RO-NF input of the WaTER tool



Source: WaTER software.

Annex figure 6. RO-NF output of the WaTER tool



Source: WaTER software.

Annex IV

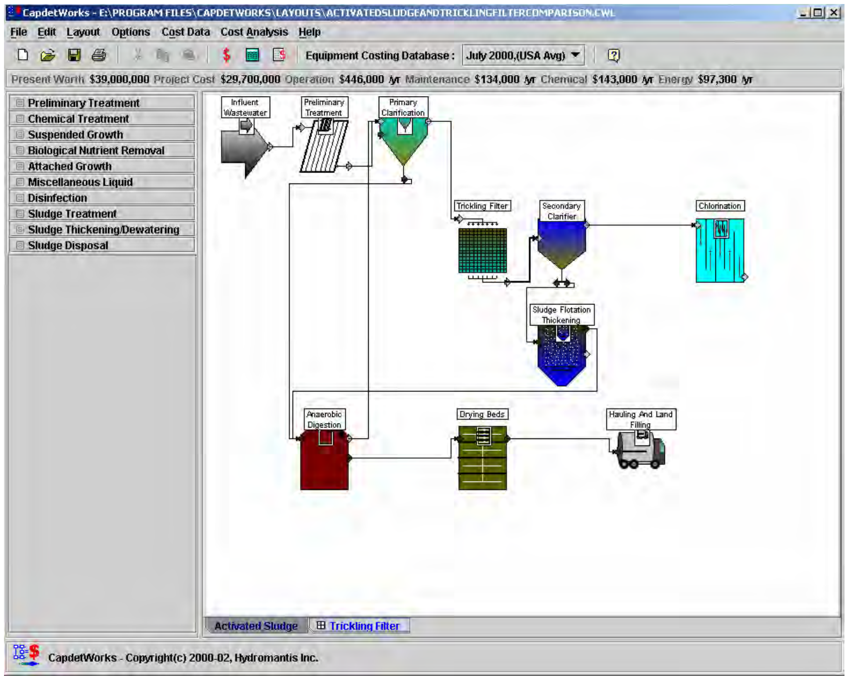
CAPDETWORKS SOFTWARE

Unit processes included in CapdetWorks

• Screening	• Plug flow activated sludge	• Slow infiltration land treatment
• Grit removal	• Srt-based plug flow activated sludge	• Secondary clarifier
• Microscreening	• Sequencing batch reactor	• Post aeration
• Equalization	• Contact stabilization activated sludge	• Filtration
• Dissolved air flotation	• Step aeration activated sludge	• User waste-water process
• Primary clarification	• High rate activated sludge	• Waste-water flow splitter
• Anion exchange	• Extended aeration activated sludge	• Influent sludge
• Cation exchange	• Oxidation ditch	• Aerobic digestion
• Neutralization	• Pure oxygen activated sludge	• Anaerobic digestion
• Coagulation	• Nitrification-suspended growth	• Wet oxidation
• Carbon adsorption	• Denitrification-suspended growth	• User specified sludge process
• Recarbonation	• Trickling filter	• Sludge flow splitter
• Flocculation	• Nitrifying trickling filter	• Gravity thickening
• Two-stage lime treatment	• Rotating biological contactor	• Sludge flotation thickening
• First stage recarbonation	• Nitrifying rotating biological contactor	• Belt filtration
• Second stage recarbonation	• Denitrification-attached growth	• Centrifugation
• Chlorination	• Biological nitrogen removal	• Drying beds
• Ultra-violet disinfection	• Biological nutrient removal-2 stage	• Filter press
• Lagoon	• Biological nutrient removal-3/5 stage	• Vacuum filtration
• Aerated lagoon	• Intermediate process pumping	• Sludge drying lagoon
• Activated sludge package plant	• Counter current ammonia stripping	• Hauling and land filling
• Complete mix activated sludge	• Cross current ammonia stripping	• Fluidized bed incineration
• Overland flow land treatment	• Rapid infiltration land treatment	• Multiple hearth incineration

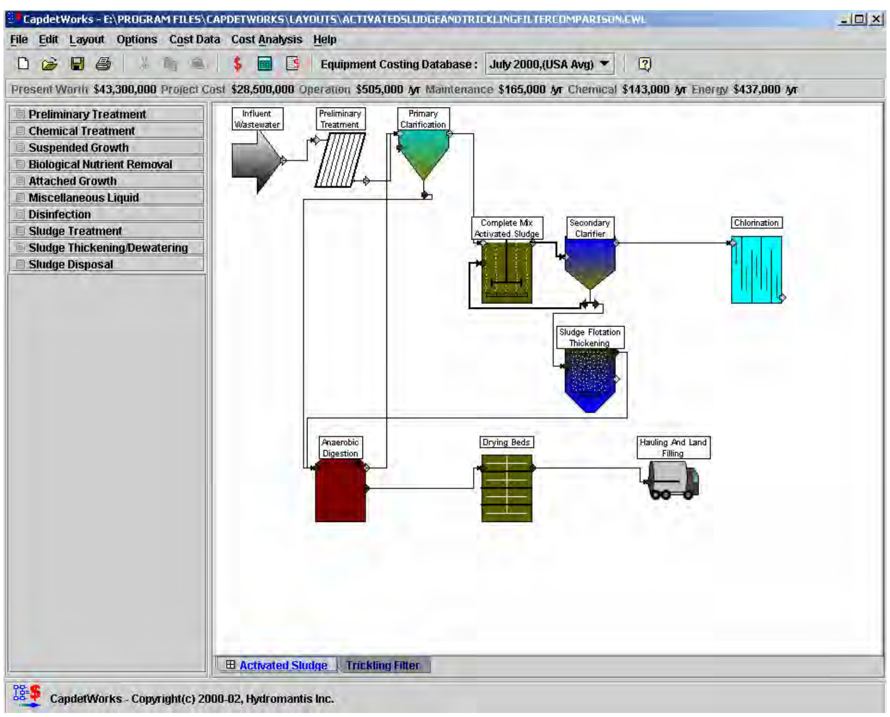
Source: CapdetWorks help file included in demonstration copy.

Annex figure 7. Trickling filter design and summary cost using CAPDET



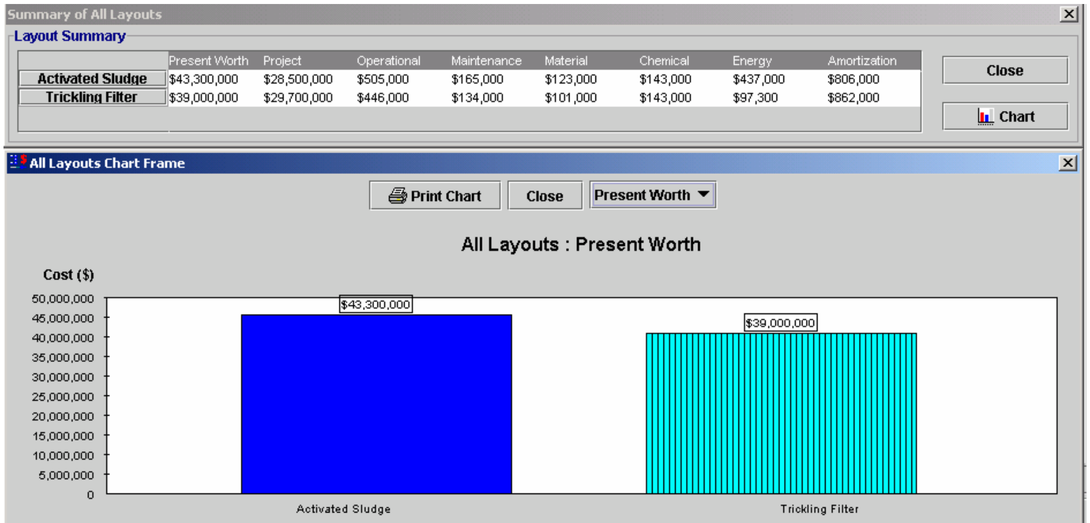
Source: CapdetWorks demonstration copy.

Annex figure 8. Activated sludge design and summary cost using CAPDET



Source: CapdetWorks demonstration copy.

Annex figure 9. Cost comparison of activated sludge versus trickling filter using CAPDET



Source: CapdetWorks demonstration copy.

Annex V

MEMBRANE FILTRATION COST DATA

Location	Capacity (mgd)	Construction cost (US$)	MF/UF equipment cost (US$)	Construction cost per gallon of installed capacity (US$/gpd)	Equipment cost per gallon of installed capacity (US$/gpd)	Equipment cost as percentage of construction cost
Meeteetse, WY	0.302	-	438 000	-	1.45	-
Youngs River, WA	0.5	1 450 000	525 000	2.90	1.05	36
Little Current, Ontario	0.9	2 730 000	650 000	3.03	0.72	24
Gibson Canyon, CA	1.4	-	640 000	-	0.46	-
Travis county, TX	2	-	980 000	-	0.49	-
Millersburg, OR	2	6 063 000	1 800 000	3.03	0.9	30
Amherstview, Ontario	2.1	3 500 000	880 000	1.67	0.42	25
Loyalist Township, Ontario	2.1	3 640 000	800 000	1.73	0.38	22
Holladay, UT	2.5	-	980 500	-	0.39	-
Parry Sound, Ontario	2.6	6 430 000	1 260 000	2.47	0.48	20
Canyon Regional, TX	3	-	1 540 000	-	0.51	-
Georgetown, TX	3	-	1 380 000	-	0.46	-
Parsons, KS	3	-	1 590 000	-	0.53	-
Seekonk, MA	4.3	-	3 000 000	-	0.7	-
Pendleton, OR	6	-	2 500 000	-	0.42	-
Warrenton, OR	6	4 520 000	2 525 000	0.75	0.42	56
Marquette, MI	7	7 500 000	3 500 000	1.07	0.50	47
San Patricio, TX	7.8	3 000 000	2 300 000	0.38	0.29	77
Bexar Met. Water Auth., TX	9	21 000 000	-	2.33	-	-
Canyon Regional, TX	10	-	3 170 000	-	0.32	-
Kenosha, WI	14	22 000 000	7 000 000	1.57	0.50	32
Del Rio, TX	16	-	7 777 778	-	0.49	-
Pittsburg, PA	20	-	5 400 000	-	0.27	-
Appleton, WI	24	-	6 800 000	-	0.28	-
Olivenhain, CA	25	24 000 000	10 000 000	0.96	0.4	42

Source: Elarde and Bergman, “The cost of membrane filtration”.

Annex VI

COST EQUATIONS FOR TREATMENT PROCESSES

Process	Equation	Service life (years)	Included elements
Screening and grit removal with bar screens	- $CC = 674Q^{0.611}$ - $O\&M = 0.96Q + 25{,}038$	30	- CC include flow channels and superstructures, mechanical bar screens, grinders for screenings, gravity grit chamber with mechanical grit handling equipment, Parshall flume and flow recording equipment
Screening & grit removal without bar screens	- $CC = 531Q^{0.616}$ - $O\&M = 0.96Q + 25{,}038$		
Primary sedimentation with sludge pumps	- $CC = -0.00002Q^2 + 19.29Q + 220{,}389$ - $O\&M = 1.69Q + 11{,}376$ - $Q_E = Q_{Design} \times \frac{32.6m^3/m^2.d}{ActualDesignSurfaceOverflowRate}$	50	- Clarifier is deigned for an overflow rate of 32.6 m^3/m^2.d
Ferric chloride addition	- $CC = 0.000002Q^2 + 3.6Q + 44{,}624$ - $O\&M = 9.68Q + 22{,}392$ - $Q_E = Q_{Design} \times \frac{FeCl_3 dose}{100mg/L}$	20	- CC include concrete rapid mix tank with stainless steel mixer, liquid containing 35 % $FeCl_3$ and dosage of 100 mg/L, chemical storage for 15 days, and price of building
Conventional activated sludge with diffused air	- $CC = 72Q + 368{,}043$ - $O\&M = 4.58Q + 36{,}295$	40	- CC include basin, air supply equipment and piping, and blower building. Clarifiers and return sludge pumps are not included. - Oxygen requirement is 1.2 g O_2 per g of BOD Aeration period is 6 hrs
Activated sludge with nitrification in single stage	- $CC = 90Q + 612{,}777$ - $O\&M = 93Q^{0.834}$	40	- CC include plug-flow aeration tanks and aeration devices. Clarifiers and return sludge pumps are not included. - Oxygen requirement is 1.5 g O_2 per g of BOD removed and 4.6 g O_2 per gram of NH_3-N oxidized
Final clarifier with aeration basin	- $CC = 2941Q^{0.609}$ - $O\&M = 3.32Q + 5{,}842$ - $Q_E = Q_{Design} \times \frac{24.5m^3/m^2.d}{ActualDesignSurfaceOverflowRate}$	40	- The clarifier is a flocculator type with a design overflow rate of 24.5 m^3/m^2.d - CC include sludge return and waste sludge pumps - Costs apply for circular clarifiers with area > 46.56 m^2 and diameter < 61 m and for rectangular clarifiers with area < 46.56 m^2

Process	Equation	Service life (years)	Included elements
High rate trickling filter	- $CC = -0.00007Q^2 + 56.89Q + 244.791$ - $O\&M = 278Q^{0.505}$	50	- CC include circular filter units with rotating distributor arms, synthetic media (1.8 m) and underdrains - Organic loading is 0.72 kg/m^3 and hydraulic loading is 28.3 m^3/m^2.d
Clarifier for high-rate trickling filter	- $CC = -0.00005Q^2 + 44.77Q + 323{,}702$ - $O\&M = -0.000003Q^2 + 5.2Q + 5733$ - $Q_E = Q_{Design} \times \frac{32.6 m^3/m^2.d}{ActualDesignSurfaceOverflowRate}$	40	- CC include sludge pumps, effluent recycle pumps, clarifier mechanisms, and internal piping - Design overflow rate is 32.6 m^3/m^2.d - Costs apply for circular clarifiers with area > 46.56 m^2 and diameter < 61 m and for rectangular clarifiers with area < 46.56 m^2
Gravity filtration (dual media)	- $CC = 2903Q^{0.656}$ - $O\&M = 194Q^{0.693}$ - $Q_E = Q_{Design} \times \frac{9.8 m^3/m^2.d}{ActualDesignHydraulicLoadingOnFilters}$	30	- CC include facilities for backwash storage, all feed and backwash pumps, piping, and filter building and pipe gallery - The design hydraulic loading 9.8 m^3/m^2.d and a backwash ratio of 36.7 m^3/m^2.h
Activated carbon adsorption	- $CC = -0.0002Q^2 + 156Q + 796.55$ - $O\&M = -0.00001Q^2 + 14Q + 229{,}458$	35	- CC include carbon columns, feed and backwash pumps, piping, operations building, carbon regeneration facilities and storage tanks - Contact time is 30 minutes
Chlorination	- $CC = 795Q^{0.598}$ - $O\&M = -0.000001Q^2 + 2.36Q + 24{,}813$ - $Q_E = Q_{Design} \times \frac{ActualChlorineDosage, mg/L}{10 mg/L}$	15	- CC include chlorine building, storage and handling facilities, chlorinators, injector and plug-flow contact chamber - Chlorine dosage is 10 mg/L and contact time is 30 minutes at average flow
Dechlorination using sulfur dioxide	- $CC = 1170Q^{0.598}$ - $O\&M = -0.000001Q^2 + 0.97Q + 15{,}058$ - $Q_E = Q_{Design} \times \frac{ActualSO_2Dosage, mg/L}{1 mg/L SO_2}$	30	- CC include SO_2 storage facility, feed system, mixers and reaction tank. - The SO_2 dosage is 1 mg/L SO_2 per mg/L residual chlorine
UV disinfection	- $-3 \times 10^{-5}Q^2 + 11.85Q + 142{,}439$ - $-3 \times 10^{-6}Q^2 + 1.038Q + 4585$	15	- CC include UV modules, power source and distribution, lamps, safety cleaning and monitoring equipment, piping, walkway, and miscellaneous equipment - O&M includes power, lamp displacement, cleaning labour, and others

Process	Equation	Service life (years)	Included elements
Sludge pumping	- $-0.00005Q^2 + 44.77Q + 323{,}702$ - $-0.000003Q^2 + 5.2Q + 5733$ - $Q_E = Q_{Design} \times \frac{ActualSludgeMass}{0.227\,kg/m^3} \times \frac{4\%}{ActualSolids\ Concentration\%}$	10	- Costs are based on sludge mass of 0.227 kg/m^3 at 4 % solid concentration
Gravity thickener	- $CC = 177Q^{0.68}$ - $O\&M = -0.0000003Q^2 + 0.18Q + 4136$ - $Q_E = Q_{Design} \times \frac{29.3\,kg/m^2.d}{ActualSolidsLoading} \times \frac{ActualSolidsMass}{0.098\,kg/m^3}$	50	- CC include thickener and all related mechanical equipment - Thickening is at a rate of 0.098kg/m^3 and solids loading is at a rate of 29.3kg/m^3.d - O&M do not include polymer or metal addition
Aerobic digester	- $CC = -0.00002Q^2 + 23.7Q + 208{,}627$ - $O\&M = 8.54Q^{0.916}$ - $Q_E = Q_{Design} \times \frac{20\,days}{ActualDigestion\ Period} \times \frac{ActualSolidsMass}{0.227\,kg/m^3} \times \frac{4\%}{ActualSolids\ Concentration\%}$	40	- CC include 20-day digestion period and sludge flow of 0.227 kg/m^3 at 4 % solids - Mechanical aerators provide an oxygen requirement of 1.6 g O_2/g VSS destroyed and mixing requirements of 26.3 W/m^3
Two-stage anaerobic digesters	- $CC = -0.00002Q^2 + 21.28Q + 471{,}486$ - $O\&M = 0.67Q + 26{,}784$ - $Q_E = Q_{Design} \times \frac{ActualSolidsMass,\,kg/m^3}{0.227\,kg/m^3}$	50	- CC include covered digestion tanks, heat exchanger, gas mixing and collection equipment, and control building - Rate of combined thickened sludge is 0.227 kg/m^3 with 4 % solids content - Digested sludge has 0.108 kg/m^3 solids content at 2.5 % solids
Sludge drying beds	- $CC = 89Q^{0.854}$ - $O\&M = -0.00002Q^2 + 2.57Q + 8003$ - $Q_E = Q_{Design} \times \frac{ActualSolidsMass\ inDigested\ Sludge}{0.108\,kg/m^3} \times \frac{97.6\,kg/m^2.yr}{ActualDesignSolidsLoading}$	20	- CC include sand beds, sludge inlets, underdrains, cell dividers, sludge piping, underdrain return and other structural elements - The sludge solids and solids loading on the beds are 0.108 kg/m^3 and 97.6 kg/m^2/year

Process	Equation	Service life (years)	Included elements
Filter press or belt filter	- $CC = 10{,}255Q^{0.481}$ - $O\&M = 3165Q^{0.348}$ - $Q_E = Q_{Design} \times \frac{ActualSolidsMassInDigestedSludge}{0.108 kg/m^3}$	15	- CC include filtration and conveyor equipment, chemical feed and storage facilities, conditioning and sludge storage tanks, and building. - Digested primary and secondary sludge is 0.108 kg/m^3 at 2.5 % solids - Conditioning chemicals dosage is 4.2 g/m^3 $FeCl_3$ or 10.8 g/m^3 CaO
Landfilling	- $-0.00005Q^2 + 2.33Q + 87{,}2571$ - $-0.000001Q^2 + 1.11Q + 25{,}026$ - $Q_E = Q_{Design} \times \frac{ActualSolidsMass\ inDewateredSludge}{0.108 kg/m^3} \times \frac{20\%}{ActualSolids\ Concentration\%} \times \frac{QuantityOfSludge\ Landfilled}{TotalQuantityOf\ Sludge\ Produced}$	20	- CC include site preparation, front-end loaders, monitoring wells, fencing, leachate collection, and treatment - O&M include labour costs and fuel for equipment operation - Digested solids quantity is 0.108 kg/m^3
Biosolids utilization	- $-0.00005Q^2 + 2.047Q + 76{,}790$ - $-0.000001Q^2 + 0.978Q + 22{,}031$ - $Q_E = Q_{Design} \times \frac{ActualSolidsMass\ inDewateredSludge}{0.108 kg/m^3} \times \frac{20\%}{ActualSolids\ Concentration\%} \times \frac{QuantityOfSludge\ UtilizedAsBiosolids}{TotalQuantityOf\ Sludge\ Produced}$	20	- CC include transportation vehicles and application vehicles, sludge loading and unloading apparatus, concrete pad and storage facility - O&M include oil, gas, preventive maintenance, labour and material - No land costs are incurred
Miscellaneous structures	- $CC = 1438Q^{0.567}$ - $O\&M = -0.000003Q^2 + 1.97Q + 57{,}349$	50	- CC include administrative offices, laboratories, machine shops, and garage facilities - O&M include utilities and normal upkeep
Support personnel	- $O\&M = 8.31Q^{0.717}$	-	Includes manpower for supervision and administration, clerical work, laboratory work, & administrative costs

Source: Qasim, *Wastewater Treatment Plants* and USEPA, *Detailed Costing Document.*

CC = capital costs, USD.

O&M = annual operation and maintenance costs.

Q = Q_{Design}= average design flow through the facility.

Q_E = Adjusted flow rate.

Annex VII

SUSTAINABILITY CRITERIA FOR THE ASSESSMENT OF WATER TREATMENT TECHNOLOGIES

Functional	
Performance	Expressed in removal of BOD/COD, heavy metals, organic micropollutants, pathogens and nutrients.
Adaptability	Indication of possibilities for implementation on different scales, increasing/decreasing capacity, anticipated changes in legislation, etc.
Durability	Lifetime of installation.
Flexibility	Indication of sensitivity of the process in terms of toxic substances, shock loads, seasonal effects etc.
Maintenance required	Indication of maintenance required: frequency/costs and time needed for maintenance.
Reliability	Indication of sensitivity of the process in terms of malfunctioning equipment and instrumentation.
Economic	
Affordability	Costs in relation to national/regional budget. Foreign exchange required in relation to national/regional foreign exchange requirements.
Costs	Net present value of the investment costs (specified for land, materials, equipment and labour), maintenance costs and cost for destruction.
Cost effectiveness	Performance relative to costs.
Labour	Number of employees needed for operation and maintenance.
Willingness to pay	The amount of money spent by users on sanitation in relation to their total budget. Indication of the amount of money the user is willing to pay for (improved) sanitation.
Environmental	
Emissions:	
Acidification	Acidification potential
Depletion: Abiotic	Mineral material depletion potential (ADP, yr-1)
Biotic	Biodiversity
Depletion of fossil fuels	Fossil energy carrier depletion potential (EDP, GJ)
Global warming	Global warming potential (GWP, kg aeq. CO2)
Nutrification	Nutrification potential (NP, kg aeq. PO4)
Ozone Depletion	Ozone depletion potential (ODP, kg aeq. R11)
Photochemical air pollution	Photochemical ozone creation potential (POCP, kg aeq. C2H4)
Toxicity: Aquatic	(ECA, m3 aeta)
Human	(HT, kg hta)
Terrestrial	(ECT, kg teta)
Waste production	Final waste (kg) Toxic final waste (kg) Nuclear final waste (kg)
Additional detailed information on emissions during operational phase:	
Heavy metals	Balances of Cu, Cr, Zn, Pb, Cd, Ni, Hg, Ar
Nutrients	Balances of N P, K
Organic matter	Balance of C, S
Organic pollutants	Indication of emissions of pesticides and other toxics
Pathogens	Bacteria, viruses, intestinal parasites
Resource utilization:	
Energy	Energy used, produced and 'lost' during installation, operation and destruction of the waste-water treatment system. Energy 'lost' indicates the amount of energy no longer available due to emissions of waste disposal. Indications of feasibility of applying sustainable energy sources.

Functional	
Land area	The total land area required. Indication of the feasibility of integrating the waste-water treatment system (partly) in green areas.
Nutrients	Amount of nutrients suitable for reuse. Indication of nutrient quality.
Organic matter	Amount of organic matter recycled through sludge reuse. Indication of sludge quality. Amount of organic matter recycled through biogas production.
Resource effectiveness	Performance relative to resource utilization.
Water	Amount of water suitable for reuse. Indication of water quality.
Social	
Institutional requirements	Indication of the effort needed to control and enforce existing regulations. Indication of embedding of technology in policymaking.
Cultural	
Acceptance	Indication of the cultural changes and impacts: convenience and compatibility with local ethics.
Expertise	Number of engineers needed for installation and operation. Indication whether a system can be designed and built or can be repaired, replicated and improved locally (in the country) or only by specialized manufacturers.
Stimulating sustainable behaviour	Indication of possibilities for technical stimulation of sustainable behaviour. Indication of possibilities for economic stimulation of sustainable behaviour. Indication of possibilities for participation by the end user.

Source: Balkema, *Sustainability criteria.*

Note: Depletion is listed under emissions, as an indication of resource utilization in the installation and destruction phase.

REFERENCES

Abdul-Malik, Q.Y. *Yemen's Water Resources and Treated Wastewater*. Sana'a: Ministry of Agriculture and Irrigation of Yemen, n.d. Available at: http://www.idrc.ca/waterdemand/docs/english/yemen-english.doc.

Adham, S, J. Jacangelo and J.M. Lainé. "Characteristics and costs of MF and UF plants". *Journal AWWA*, May 1996.

American Water Works Association and American Society of Civil Engineers. *Water Treatment Plan Design*. New York: McGraw-Hill, 1990.

Balkema, A. *Sustainability criteria for the comparison of wastewater treatment technologies*. Paper prepared for the Eleventh European Junior Scientist Meeting, "The Myth of Cycles versus Sustainable Water and Material Flux Management", Wildpark Eekholt, Germany, 12-15 February 1998.

Bataineh, F., M. Najjar and S. Malkawi. *Wastewater Reuse*. Paper presented at the Water Demand Management Forum, Amman, Jordan, March 2002. Available at: http://www.idrc.ca/waterdemand/docs/english/jordan.doc.

Black and Veatch. *Gabal Al Asfar Treatment Plant*. Available at: http://www.bbv-ltd.com/Projects/WSTD/GlobslEIATP.htm.

Centre International de Hautes Etudes Agronomiques Méditerranéennes (CIHEAM). *Annual Report 2000: Development and Agri-Food Policies in the Mediterranean Region*. Paris: CIHEAM, 2000. Available at: http://www.ciheam.org/en/ressources/report2000.htm.

Chellam, S., C. Serra and M. Wiesner. "Estimating costs for integrated membrane systems". *Journal AWWA*, November 1998.

Dow Chemical Company. *Ion exchange or reverse osmosis*? Available at: http://www.dow.com/liquidseps/design/ixro.htm.

Droste, R.L. *Theory and Practice of Water and Wastewater Treatment*. New York: John Wiley and Sons, 1996.

Elarde, J.R. and R.A. Bergman. "The cost of membrane filtration for municipal water supplies". Chapter 1 in *Membrane practices for water treatment*. Edited by S.J. Duranceau. Denver: American Water Works Association, 2001.

Faeth, P. *Fertile ground: Nutrient Trading's Potential to Cost-effectively Improve Water Quality*. Washington, D.C.: World Research Institute, 2000.

Fluid Knowledge. *Background on Water and Wastewater Industry*. 2000. Available at: http://www.fluidknowledge.com/waterlist/html/waterindustry.html.

Food and Agriculture Organization. *Irrigation in the Near East Region in Figures*. Rome: United Nations, 1997. Available at: http://www.fao.org/docrep/W4356E/w4356e0g.htm.

Food and Agriculture Organization. *Wastewater Treatment and Use in Agriculture*. FAO Irrigation and Drainage Paper 47. Rome: United Nations, 1992. Available at: http://www.fao.org/docrep/T0551E/t0551e0b.htm#9.5, waste-water treatment and human exposure control: Kuwait.

Garrett, T.M. Jr. "Instrumentation, Control and Automation Progress in the United States in the Last 24 Years". *Water Science and Technology*, 37, pp. 21-25.

Gilman, H.D. et al. *Instrumentation in Wastewater Treatment Facilities*. Manual of Practice No. 21. Arlington, Virginia: Water Environment Federation, 1993.

International Solid Waste Association. *Sludge Treatment and Disposal: Management Approaches and Experiences*. Environmental Issues Series No. 7. Copenhagen: European Environment Agency, 1997.

Keller, C.W. et al. *Financing and Charges for Wastewater Systems*. Hyattsville, Maryland: Water Pollution Control Federation, American Society of Civil Engineers, and American Public Works Association, 1984.

Liu, D.H.F. and B.G. Lipták. *Wastewater Treatment*. Boca Raton, Florida: Lewis, 1999.

McGhee, T.J. *Water Supply and Sewerage*. New York: McGraw-Hill, 1991.

Metcalf and Eddy, Inc. *Wastewater Engineering: Treatment Disposal and Reuse*, third edition. New York: McGraw-Hill, 1991.

Metcalf and Eddy, Inc. *Wastewater Engineering: Treatment and Reuse*, fourth edition. New York: McGraw-Hill, 2003.

Ministry of Environment of Lebanon. *State of the Environment Report 2001*. Beirut: Government of Lebanon, 2001. Available at: http://www.moe.gov.lb/ledo/soer2001.html.

Ministry of Public Works of Kuwait, Sanitary Engineering Department. *The Kuwait Sanitary Scheme*. Kuwait, 1996.

Myllylä, S. *Cairo - a Mega-City and its Water Resources*. Paper presented at the third Nordic conference on Middle Eastern Studies: Ethnic encounter and culture change, Joensuu, Finland, 19-22, June 1995. Available at: http://www.hf.uib.no/smi/paj/myllyla.html#fn7.

National Research Council. *Ground Water Recharge Using Waters of Impaired Quality*. Washington, D.C.: National Academies Press, 1994.

Use of Reclaimed Water and Sludge in Food Crop Production. Washington, D.C.: National Academies Press, 1996.

Nesaratnam, S. *Effluent Treatment*. Leatherhead, Surrey: Pira International, 1998.

Pittner, G.A. "The Economics of Desalination Processes". Chapter 3 in *Reverse Osmosis: Membrane Technology, Water Chemistry, and Industrial Applications*. Edited by Z. Amjad. New York: Van Nostrand Reinhold, 1993.

Qasim, S.R. *Waste-water Treatment Plants: Planning, Design, and Operation*, second edition. Lancaster, Pennsylvania: Technomic, 1999.

Qasim, S.R., S.W.D. Lim, E.M. Motley and K.G. Heung. "Estimating Costs for Treatment Plant Construction". *Journal of the American Water Works Association*, August 1992.

Reed, S.C., E.J. Middlebrooks and R.W. Crites. *Natural Systems for Waste Management and Treatment*. New York: McGraw-Hill, 1988.

Reed, S.C. *et al*. *Natural Systems for Wastewater Treatment*. Manual of Practice FD-16. Arlington, Virginia: Water Environment Federation, 1990.

Rowe, D.R. and I.H. Abdel-Magid. *Handbook of Wastewater Reclamation and Reuse*. Boca Raton, Florida: Lewis, 1995.

Sanks, R.L. and T. Asano. *Land Treatment and Disposal of Municipal and Industrial Wastewater*. Ann Arbor, Michigan: Ann Arbor Science, 1976.

Schoeman, J.J., J.F. van Staden, H.M. Saayman and W.A. Vorster. "Evaluation of reverse osmosis for electroplating effluent treatment". *Water Science and Technology*, vol. 25, No. 10, pp. 79-93.

Somlyódy, L. and P. Shanahan. *Municipal Wastewater Treatment in Central and Eastern Europe: Present Situation and Cost-Effective Development Strategies*. Washington, D.C.: The World Bank Group, 1998.

United Nations Environment Programme. *Sourcebook of Alternative Technologies for Freshwater Augmentation in Latin American and the Caribbean*. Available at: http://www.unep.or.jp/ietc/Publications/ techpublications/TechPub-8c/.

Sourcebook of Alternative Technologies for Freshwater Augmentation in Some Countries in Asia. Available at: http://www.unep.or.jp/ietec/Publications/ techpubliccations/TechPub-8e/.

United States Environmental Protection Agency. *Detailed Costing Document for the Centralized Waste Treatment Industry*. EPA 821-R-98-016. Washington, D.C.: USEPA, 1998. Available at: http://www.epa.gov/ostwater/guide/cwt/final/costing.pdf.

United States Environmental Protection Agency. *Estimating Water Treatment Costs, Vol. 2*, *Cost Curves Applicable to 200 mgd Treatment plants*. EPA-600012-79-162. Washington, D.C.: EPA, 1979.

United States Environmental Protection Agency. *National Pollutant Discharge Elimination System: Secondary Treatment Standards*. Washintgon, D.C.: USEPA, 2002. Available at: http://cfpub.epa.gov/npdes/ techbasedpermitting/sectreat.cfm.

Wagner, J. *Membrane filtration handbook: Practical tips and hints*. Osmonics, Inc., 2001.

Water Authority of Jordan. *Wastewater Sector*. Available at: http://www.mwi.gov.jo/waj/WAJ%20Web%20Page/waste-water.htm.

Water Environment Federation and American Society of Civil Engineers. *Design of Municipal Wastewater Treatment Plants, Volume 1*. WEF Manual of Practice No. 8 and ASCE Manual and Report on Engineering Practice No. 76. Vermont: Book Press Inc., 1992.

Wilbert, M.C., J. Pellegrino, J. Scott and Q. Zhang. *Water Treatment Estimation Routine (WaTER) User Manual*. Water Desalination Research and Development Programme Report No. 43. Washington, D.C.: United States Department of the Interior, Bureau of Reclamation, August 1999.