Water Pollution Control - A Guide to the Use of Water Quality Management Principles
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Chapter 3* - Technology Selection

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3.1 Integrating waste and water management

Economic growth in most of the world has been vigorous, especially in the so-called newly industrialising countries. Nearly all new development activity creates stress on the "pollution carrying capacity" of the environment. Many hydrological systems in developing regions are, or are getting close to, being stressed beyond repair. Industrial pollution, uncontrolled domestic discharges from urban areas, diffuse pollution from agriculture and livestock rearing, and various alterations in land use or hydro-infrastructure may all contribute to non-sustainable use of water resources, eventually leading to negative impacts on the economic development of many countries or even continents. Lowering of groundwater tables (e.g. Middle East, Mexico), irreversible pollution of surface water and associated changes in public and environmental health are typical manifestations of this kind of development.

Technology, particularly in terms of performance and available waste-water treatment options, has developed in parallel with economic growth. However, technology cannot be expected to solve each pollution problem. Typically, a wastewater treatment plant transfers 1 m^3 of wastewater into 1-2 litres of concentrated sludge. Wastewater treatment systems are generally capital-intensive and require expensive, specialised operators. Therefore, before selecting and investing in wastewater treatment technology it is always preferable to investigate whether pollution can be minimised or prevented. For any pollution control initiative an analysis of cost-effectiveness needs to be made and compared with all conceivable alternatives. This chapter aims to provide guidance in the technology selection process for urban planners and decision makers. From a planning perspective, a number of questions need to be addressed before any choice is made:

• *Is wastewater treatment a priority in protecting public or environmental health?* Near Wuhan, China, an activated sludge plant for municipal sewage was not financed by the World Bank because the huge Yangtse River was able to absorb the present waste load. The loan was used for energy conservation, air pollution mitigation measures (boilers, furnaces) and for industrial waste(water) management. In Wakayama, Japan, drainage was given a higher priority than sewerage because many urban areas were prone to periodic flooding. The human waste is collected by vacuum trucks and processed into dry fertiliser pellets. Public health is safeguarded just as effectively but the huge investment that would have been required for sewerage (two to three times the cost of the present approach) has been saved.

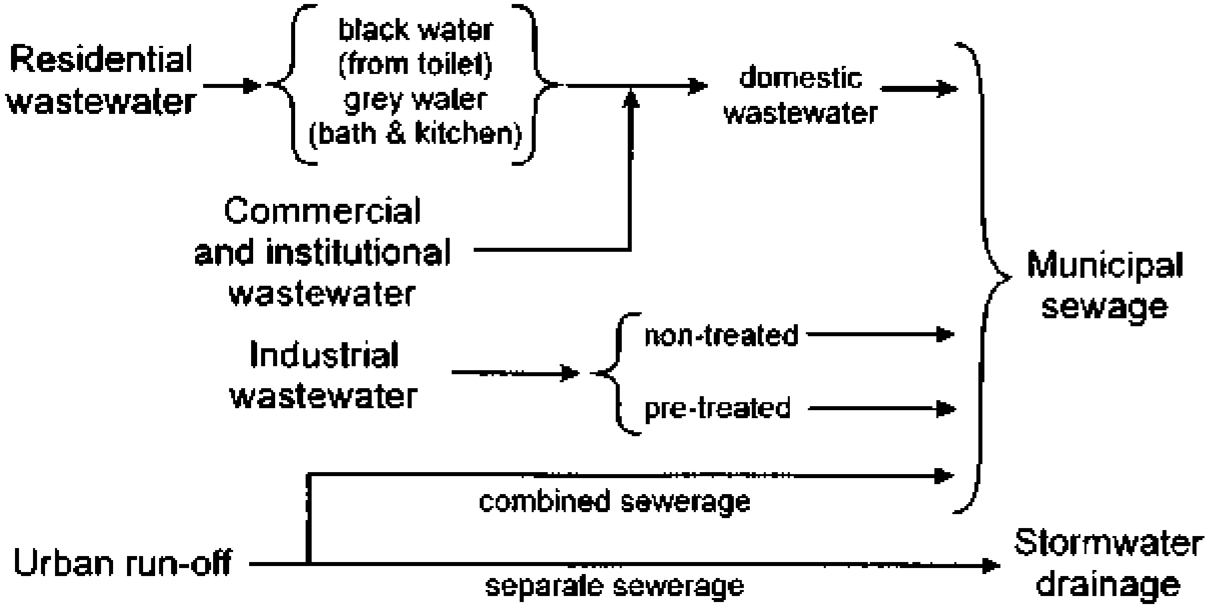
• *Can pollution be minimised by recovery technologies or public awareness?* South Korea planned expansion of sewage treatment in Seoul and Pusan based on a linear growth of present tap water consumption (from 120 l cap^{-1} d^{-1} to beyond 250 l cap^{-1} d^{-1}). Eventually, this extrapolation was found to be too costly. Funds were allocated for promoting water saving within households; this allowed the eventual design of sewers and treatment plants to be scaled down by half.

• *Is treatment most feasible at centralised or decentralised facilities?* Centralised treatment is often devoted to the removal of common pollutants only and does not aim to remove specific individual waste components. However, economies of scale render centralised treatment cheap whereas decentralised treatment of separate waste streams can be more specialised but economies of scale are lost. By enforcing land-use and zoning regulations, or by separating or pre-treating industrial discharges before they enter the municipal sewer, the overall treatment becomes substantially more effective.

• *Can the intrinsic value of resources in domestic sewage be recovered by reuse?* Wastewater is a poorly valued resource. In many arid regions of the world, domestic and industrial sewage only has to be "conditioned" and then it can be used in irrigation, in industries as cooling and process water, or in aqua- or pisciculture (see Chapter 4). Treatment costs are considerably reduced, pollution is minimised, and economic activity and labour are generated. Unfortunately, many of these potential alternatives are still poorly researched and insufficiently demonstrated as the most feasible.

Ultimately, for each pollution problem one strategy and technology are more appropriate in terms of technical acceptability, economic affordability and social attractiveness. This applies to developing, as well as to industrialising, countries. In developing countries, where capital is scarce and poorly-skilled workers are abundant, solutions to wastewater treatment should preferably be low-technology orientated. This commonly means that the technology chosen is less mechanised and has a lower degree of automatic process control, and that construction, operation and maintenance aim to involve locally available personnel rather than imported mechanised components. Such technologies are rather land and labour intensive, but capital and hardware extensive. However, the final selection of treatment technology may be governed by the origin of the wastewater and the treatment objectives (see Figure 3.2).

Figure 3.1 Origin and flows of wastewater in an urban environment



3.2 Wastewater origin, composition and significance

3.2.1 Wastewater flows

Municipal wastewater is typically generated from domestic and industrial sources and may include urban run-off (Figure 3.1). Domestic wastewater is generated from residential and commercial areas, including institutional and recreational facilities. In the rural setting, industrial effluents and stormwater collection systems are less common (although polluting industries sometimes find the rural environment attractive for uncontrolled discharge of their wastes). In rural areas the wastewater problems are usually associated with pathogen-carrying faecal matter. Industrial wastewater commonly originates in designated development zones or, as in many developing countries, from numerous small-scale industries within residential areas.

In combined sewerage, diffuse urban pollution arises primarily from street run-off and from the overflow of "combined" sewers during heavy rainfall; in the rural context it arises mainly from run-off from agricultural fields and carries pesticides, fertiliser and suspended matter, as well as manure from livestock.

Table 3.1 Typical domestic water supply and wastewater production in industrial, developing and (semi-) arid regions (l cap^{-1} d^{-1})

Water supply service	Industrial regions	Developing regions	(Semi-) arid regions
Handpump or well	na	<50	<25
Public standpost	na	50-80	20-40
House connection	100-150	50-125	40-80
Multiple connection	150-250	100-250	80-120
Average wastewater flow	85-200	65-125	35-75

na Not applicable

Within the household, tap water is used for a variety of purposes, such as washing, bathing, cooking and the transport/flushing of wastes. Wastewater from the toilet is termed "black" and the wastewater from the kitchen and bathroom is termed "grey". They can be disposed of separately or they can be combined. Generally, the wealthier a community, the more waste is disposed by water-flushing off-site. Such wastewater disposal may become a public problem for downstream areas.

Domestic wastewater generation is commonly expressed in litres per capita per day (l cap^{-1} d^{-1}) or as a percentage of the specific water consumption rate. Domestic water consumption, and hence wastewater production, typically depends on water supply service level, climate and water availability (Table 3.1). In moderate climates and in industrialising countries, 75 per cent of consumed tap water typically ends up as sewage. In more arid regions this proportion may be less than 50 per cent due to high evaporation and seepage losses and typical domestic water-use practices.

Industrial water demand and wastewater production are sector-specific. Industries may require large volumes of water for cooling (power plants, steel mills, distillation industries), processing (breweries, pulp and paper mills), cleaning (textile mills, abattoirs), transporting products (beet and sugar mills) and flushing wastes. Depending on the industrial process, the concentration and composition of the waste flows can vary significantly. In particular, industrial wastewater may have a wide variety of micro-contaminants which add to the complexity of wastewater treatment. The combined treatment of many contaminants may result in reduced efficiency and high treatment unit costs (US$ m^{-3}).

Hourly, daily, weekly and seasonal flow and load fluctuations in industries (expressed as m^3 s^{-1} or m^3 d^{-1} and as kg s^{-1} or kg d^{-1} of contaminant, respectively) can be quite considerable, depending on in-plant procedures such as production shifts and workplace cleaning. As a consequence, treatment plants are confronted with varying loading rates which may reduce the removal efficiency of the processes. Removal of hazardous or slowly-biodegradable contaminants requires a constant loading and operation of the treatment plant in order to ensure process and performance stability. To accommodate possible fluctuations, equalisation or buffer tanks are provided to even out peak flows. Fluctuations in domestic sewage flow are usually repetitive, typically with two peak flows (morning and evening), with the minimum flow at night.

Table 3.2 Major classes of municipal wastewater contaminants and their significance and origin

Contaminant	Significance	Origin
Settleable solids (sand, grit)	Settleable solids may create sludge deposits and anaerobic conditions in sewers, treatment facilities or open water	Domestic, run-off
Organic matter (BOD); Kjeldahl-nitrogen	Biological degradation consumes oxygen and may disturb the oxygen balance of surface water; if the oxygen in the water is exhausted anaerobic conditions, odour formation, fish kills and ecological imbalance will occur	Domestic, industrial
Pathogenic microorganisms	Severe public health risks through transmission of communicable water borne diseases such as cholera	Domestic
Nutrients (N and P)	High levels of nitrogen and phosphorus in surface water will create excessive algal growth (eutrophication). Dying algae contribute to organic matter (see above)	Domestic, rural run-off, industrial
Micro-pollutants (heavy metals, organic compounds)	Non-biodegradable compounds may be toxic, carcinogenic or mutagenic at very low concentrations (to plants, animals, humans). Some may bioaccumulate in food chains, e.g. chromium (VI), cadmium, lead, most pesticides and herbicides, and PCBs	Industrial, rural run-off (pesticides)
Total dissolved solids (salts)	High levels may restrict wastewater use for agricultural irrigation or aquaculture	Industrial, (salt water intrusion)

Source: Metcalf and Eddy Inc., 1991

3.2.2 Wastewater composition

Wastewater can be characterised by its main contaminants (Table 3.2) which may have negative impacts on the aqueous environment in which they are discharged. At the same time, treatment systems are often specific, i.e. they are meant to remove one class of contaminants and so their overall performance deteriorates in the presence of other contaminants, such as from industrial effluents. In particular, oil, heavy metals, ammonia, sulphide and toxic constituents may damage sewers (e.g. by corrosion) and reduce treatment plant performance. Therefore, municipalities may set additional criteria for accepting industrial waste flows into their sewers.

Table 3.3 Variation in the composition of domestic wastewater

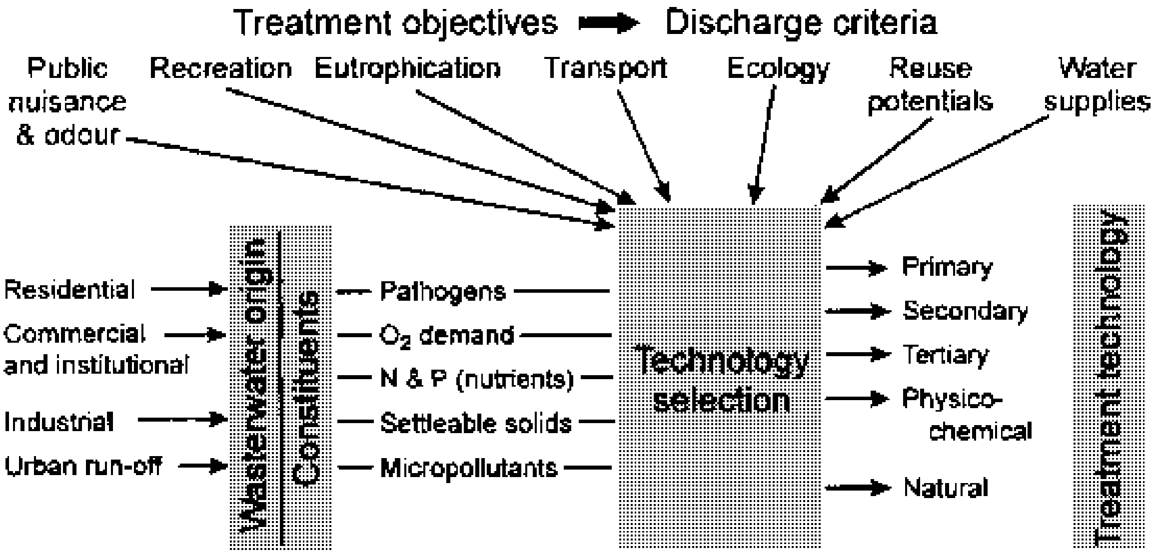
Contaminant	Specific production ($g\ cap^{-1}\ d^{-1}$)[2]	Concentration[1] ($mg\ l^{-1}$)[2]
Total dissolved solids	100-150	400-2,500
Total suspended solids	40-80	160-1,350
BOD	30-60	120-1,000
COD	70-150	280-2,500
Kjeldahl-nitrogen (as N)	8-12	30-200
Total phosphorus (as P)	1-3	4-50
Faecal coliform (No. per 100 ml)	10^6-10^9	4×10^6-1.7×10^7

BOD Biochemical oxygen demand
COD Chemical oxygen demand
[1] Assuming water consumption rate of 60-250 $l\ cap^{-1}\ d^{-1}$
[2] Except for faecal coliforms

Contaminated sewage may be rendered unfit for any productive use. Several in-factory treatment technologies allow selective removal of contaminants and their recovery to a high degree and purity. Such recovery may cover part of the investment if it is applied to concentrated waste streams. For example, in textile mills pigments and caustic solution can be recovered by ultra-filtration and evaporation, while chromium (VI) can be recovered by chemical precipitation in leather tanneries. In other situations, sewage can be made suitable for irrigation or for reuse in industry.

Domestic waste production per capita is fairly constant but the concentration of the contaminants varies with the amount of tap water consumed (Table 3.3). For example, municipal sewage in Sana'a, Yemen (water consumption of 80 $l\ cap^{-1}\ d^{-1}$), is four times more concentrated in terms of chemical oxygen demand (COD) and total suspended solids (TSS) than in Latin American cities (water consumption is around 300 $l\ cap^{-1}\ d^{-1}$). In addition, seepage or infiltration of groundwater may occur because the sewerage system may not be watertight. Similarly, many sewers in urban areas collect overflows from septic tanks which affects the sewage quality. Depending on local conditions and habits (such as level of nutrition, staple food composition and kitchen habits) typical waste parameters may need adjustment to these local conditions. Sewage composition may also be fundamentally altered if industrial discharges are allowed into the municipal sewerage system.

Figure 3.2 Treatment technology selection in relation to the origin of the wastewater, its constituents and formulated treatment objectives as derived from set discharge criteria



3.3 Wastewater management

3.3.1 Treatment objectives

Technology selection eventually depends upon wastewater characteristics and on the treatment objectives as translated into desired effluent quality. The latter depends on the expected use of the receiving waters. Effluent quality control is typically aimed at public health protection (for recreation, irrigation, water supply), preservation of the oxygen content in the water, prevention of eutrophication, prevention of sedimentation, preventing toxic compounds from entering the water and food chains, and promotion of water reuse (Figure 3.2). These water uses are translated into emission standards or, in many countries, water quality "classes" which describe the desired quality of the receiving water body (see also Chapter 2). Emission or effluent standards can be set which may take into account the technical and financial feasibility of wastewater treatment. In this way a treatment technology, or any other action, can be taken to remove or prevent the discharge of the contaminants of concern. Standards or guidelines may differ between countries. Table 3.4 gives some typical discharge standards applied in many industrialised and developing countries, in relation to the expected quality or use of the receiving waters.

3.3.2 Sanitation solutions for domestic sewage

The increasing world population tends to concentrate in urban communities. In densely populated areas the sanitary collection, treatment and disposal of wastewater flows are essential to control the transmission of waterborne diseases. They are also essential for the prevention of non-reversible degradation of the urban environment itself and of the aquatic systems that support the hydrological cycle, as well as for the protection of food production and biodiversity in the region surrounding the urban area. For rural populations, which still account for 75 per cent of the total population in developing countries (WHO, 1992), concern for public health is the main justification for investing in water and sanitation improvement. In both settings, the selected technologies should be environmentally sustainable, appropriate to the local conditions, acceptable to the users, and affordable to those who have to pay for them. Simple solutions that are easily replicable, that allow further upgrading with subsequent development, and that can be operated and maintained by the local community, are often considered the most appropriate and cost-effective.

Table 3.4 Typical treated effluent standards as a function of the intended use of the receiving waters

Variable	Discharge in surface water		Discharge in water sensitive to eutrophication	Effluent use in irrigation and aquaculture
	High quality	Low quality		
BOD (mg l^{-1})	20	50	10	100[1]
TSS (mg l^{-1})	20	50	10	<50[1]
Kjeldahl-N (mg l^{-1})	10	-	5	-
Total N (mg l^{-1})	-	-	10	-
Total P (mg l^{-1})	1	-	0.1	-
Faecal coliform (No. per 100 ml)	-	-	-	<1,000
Nematode eggs per litre	-	-	-	<1
SAR	-	-	-	<5
TDS (salts) (mg l^{-1})	-	-	-	<500[2]

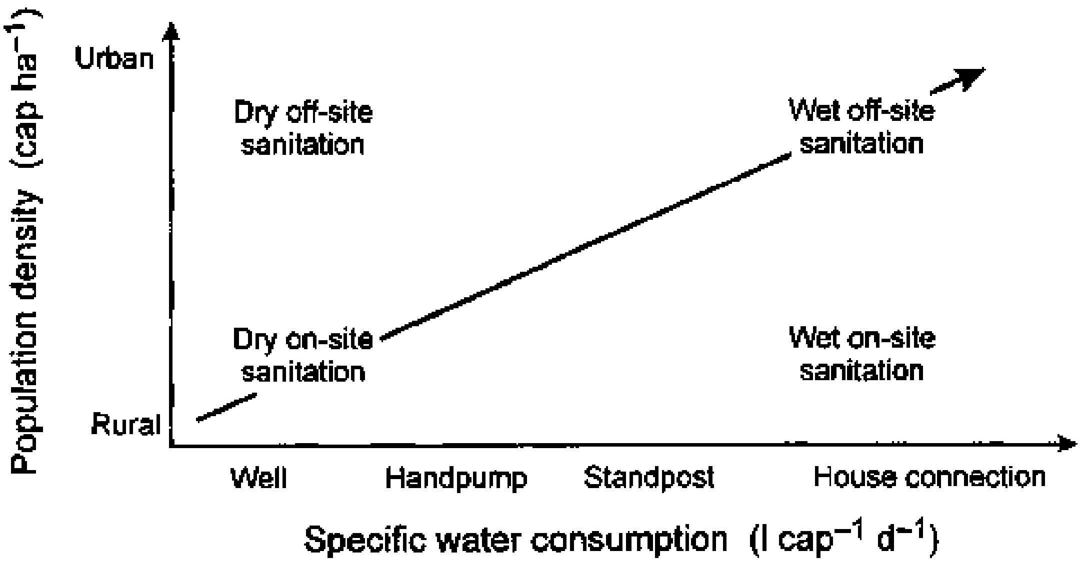
- No standards set
BOD Biochemical oxygen demand
TSS Total suspended solids
SAR Sodium adsorption ratio
TDS Total dissolved solids

[1] Agronomic norm
[2] No restriction on crop selection

Sources: Ayers and Westcot, 1985; WHO, 1989

The first issue to be addressed is whether sanitary treatment and disposal should be provided on-site (at the level of a household or apartment block) or whether collection and centralised, off-site treatment is more appropriate. Irrespective of whether the setting is urban or rural, the main deciding criteria are population density (people per hectare) and generated wastewater flow (m^3 ha^{-1} d^{-1}) (Figure 3.3). Population density determines the availability of land for on-site sanitation and strongly affects the unit cost per household. Dry and wet sanitation systems can be distinguished by whether water is required for flushing the solids and conveying them through a sewerage system. The present trend for increasing tap water consumption (l cap^{-1} d^{-1}) together with increasing urban population densities, is creating a continuing interest in off-site sanitation as the main future strategy for wastewater collection, treatment and disposal.

Figure 3.3 Classification of basic sanitation strategies. The trend of development is from dry on-site to wet off-site sanitation (After Veenstra, 1996)



In wealthier urban situations, off-site solutions are often more appropriate because the population density does not allow for percolation of large quantities of wastewater into the soil. In addition, the associated risk of ground water pollution reported in many cities in Africa and the Middle East is prohibitive for on-site sanitation. Frequently, towns and city districts cannot afford such capital-intensive solutions due to the lower population density per hectare and the resultant high unit costs involved. Depending on the local physical and socio-economic circumstances, on-site sanitation may be feasible, although if this is not satisfactory, intermediate technologies are available such as small bore sewerage. The latter approach combines on-site collection of sewage in a septic tank followed by off-site disposal of the settled effluent by small-bore sewers. The settled solids accumulate in the septic tank and are periodically removed (desludged). The advantage of this system is that the unit cost of small bore sewerage is much lower (Sinnatamby *et al.,* 1986).

3.3.3 Level of wastewater treatment

To achieve water quality targets an extensive infrastructure needs to be developed and maintained. In order to get industries and domestic polluters to pay for the huge cost of such infrastructure, legislation has to be set up based on the principle of "The Polluter Pays". Treatment objectives and priorities in industrialised countries have been gradually tightened over the past decades. This resulted in the so-called first, second and third generation of treatment plants (Table 3.5). This step-by-step approach allowed for determination of the "optimum" (desired) effluent quality and how it can be reached by waste-water treatment, on the basis of full scale experience. As a consequence, existing wastewater treatment plants have been continually expanding and upgrading; primary treatment plants were extended with a secondary step, while secondary treatment plants are now being completed with tertiary treatment phases.

Table 3.5 The phased expansion and upgrading of wastewater treatment plants in industrialised countries to meet ever stricter effluent standards

Decade	Treatment objective	Treatment	Operations included
1950-60	Suspended/coarse solids removal	Primary	Screening, removal of grit, sedimentation
1970	Organic matter degradation	Secondary	Biological oxidation of organic matter
1980	Nutrient reduction (eutrophication)	Tertiary	Reduction of total N and total P
1990	Micro-pollutant removal	Advanced	Physicochemical removal of micro-pollutants

In general, the number of available treatment technologies, and their combinations, is nearly unlimited. Each pollution problem calls for its specific, optimal solution involving a series of unit operations and processes (Table 3.6) put together in a flow diagram.

Primary treatment generally consists of physical processes involving mechanical screening, grit removal and sedimentation which aim at removal of oil and fats, settleable suspended and floating solids; simultaneously at least 30 per cent of biochemical oxygen demand (BOD) and 25 per cent of Kjeldahl-N and total P are removed. Faecal coliform numbers are reduced by one or two orders of magnitude only, whereas five to six orders of magnitude are required to make it fit for agricultural reuse.

Secondary treatment mainly converts biodegradable organic matter (thereby reducing BOD) and Kjeldahl-N to carbon dioxide, water and nitrates by means of microbiological processes. These aerobic processes require oxygen which is usually supplied by intensive mechanical aeration. For sewage with relatively elevated temperatures anaerobic processes can also be applied. Here the organic matter is converted into a mixture of methane and carbon dioxide (biogas).

Table 3.6 Classification of common wastewater treatment processes according to their level of advancement

Primary	Secondary	Tertiary	Advanced
Bar or bow screen	Activated sludge	Nitrification	Chemical treatment
Grit removal	Extended aeration	Denitrification	Reverse osmosis
Primary sedimentation	Aerated lagoon	Chemical precipitation	Electrodialysis
Comminution	Trickling filter	Disinfection	Carbon adsorption
Oil/fat removal	Rotating bio-discs	(Direct) filtration	Selective ion exchange
Flow equalisation	Anaerobic treatment/UASB	Chemical oxidation	Hyperfiltration
pH neutralisation	Anaerobic filter	Biological P removal	Oxidation
Imhoff tank	Stabilisation ponds	Constructed wetlands	Detoxification
	Constructed wetlands	Aquaculture	
	Aquaculture		

UASB Upflow Anaerobic Sludge Blanket

In primary and secondary treatment, sludges are produced with a volume of less than 0.5 per cent of the wastewater flow. Heavy metals and other micro-pollutants tend to accumulate in the sludge because they often adsorb onto suspended particles. Nowadays, the problems associated with wastewater treatment in industrialised countries have shifted gradually from the wastewater treatment itself towards treatment and disposal of the generated sludges.

Non-mechanised wastewater treatment by stabilisation ponds, constructed wetlands or aquaculture using macrophytes can, to a large extent, provide adequate secondary and tertiary treatment. As the biological processes are not intensified by mechanical equipment, large land areas are required to provide sufficient retention time to allow for a high degree of contaminant removal.

Tertiary treatment is designed to remove the nutrients, total N (comprising Kjeldahl-N, nitrate and nitrite) and total P (comprising particulate and soluble phosphorus) from the secondary effluents. Additional suspended solids removal and BOD reduction is achieved by these processes. The objective of tertiary treatment is mainly to reduce the potential occurrence of eutrophication in sensitive, surface water bodies.

Advanced treatment processes are normally applied to industrial wastewater only, for removal of specific contaminants. Advanced treatment is commonly preceded by physicochemical coagulation and flocculation. Where a high quality effluent may be required for reclamation of groundwater by recharge or for discharge to recreational waters, advanced treatment steps may also be added to the conventional treatment plant.

Table 3.7 reviews the degree to which contaminants are removed by treatment processes or operations. Most treatment processes are only truly efficient in the removal of a small number of pollutants.

3.3.4 Best available technology

In taking precautionary or preventive end-of-pipe treatment measures, authorities may by statute require the polluter, notably industry, to rely on the best available technology (BAT), the best available technology not entailing excessive costs (BATNEEC), the best environmental practices (BEP) and the best practical environmental option (BPEO) (see also Chapter 5).

The best available technology is generally accessible technology, which is the most effective in preventing or minimising pollution emissions. It can also refer to the most recent treatment technology available. Assessing whether a certain technology is the best available requires comparative technical assessment of the different treatment processes, their facilities and their methods of operation which have been recently and successfully applied for a prolonged period of time, at full scale.

The BATNEEC adds an explicit cost/benefit analysis to the notion of best available technology. "Not entailing excessive cost" implies that the financial cost should not be excessive in relation to the financial capability of the industrial sector concerned, and to the discharge reductions or environmental protection envisaged.

The best environmental practices and the best practicable environmental options have a wider scope. The BPEO requires identification of the least environmentally damaging method for the discharge of pollutants, whereas a requirement for the use of treatment processes must be based upon BATNEEC. Best practical environmental option policies also require that the treatment measures avoid transferring pollution or pollutants, from one medium to another (from water into sludge for example). Thus BPEO takes into account the cross-media impacts of the technology selected to control pollution.

3.3.5 Selection criteria

The general criteria for technology selection comprise:

- *Average, or typical, efficiency and performance of the technology.* This is usually the criterion considered to be best in comparative studies. The possibility that the technology might remove other contaminants than those which were the prime target should also be considered an advantage. Similarly, the pathways and fate of the removed pollutants after treatment should be analysed, especially with regard to the disposal options for the sludges in which the micro-pollutants tend to concentrate.

- *Reliability of the technology.* The process should, preferably, be stable and resilient against shock loading, i.e. it should be able to continue operation and to produce an acceptable effluent under unusual conditions. Therefore, the system must accommodate the normal inflow variations, as well as infrequent, yet expected, more extreme conditions. This pertains to the wastewater characteristics (e.g. occasional illegal discharges, variations in flow and concentrations, high or low temperatures) as well as to the operational conditions (e.g. power failure, pump failure, poor maintenance). During the design phase, "what if scenarios should be considered. Once disturbed, the process should be fairly easy to repair and to restart.

• *Institutional manageability.* In developing countries few governmental agencies are adequately equipped for wastewater management. In order to plan, design, construct, operate and maintain treatment plants, appropriate technical and managerial expertise must be present. This could require the availability of a substantial number of engineers with postgraduate education in wastewater engineering, access to a local network of research for scientific support and problem solving, access to good quality laboratories, and experience in management and cost recovery. In addition, all technologies (including those thought "simple") require devoted and experienced operators and technicians who must be generated through extensive education and training.

• *Financial sustainability.* The lower the financial costs, the more attractive the technology. However, even a low cost option may not be financially sustainable, because this is determined by the true availability of funds provided by the polluter. In the case of domestic sanitation, the people must be willing and able to cover at least the operation and maintenance cost of the total expenses. The ultimate goal should be full cost recovery although, initially, this may need special financing schemes, such as cross-subsidisation, revolving funds, and phased investment programmes.

• *Application in reuse schemes.* Resource recovery contributes to environmental as well as to financial sustainability. It can include agricultural irrigation, aqua- and pisciculture, industrial cooling and process water re-use, or low-quality applications such as toilet flushing. The use of generated sludges can only be considered as crop fertilisers or for reclamation if the micro-pollutant concentration is not prohibitive, or the health risks are not acceptable.

• *Regulatory determinants.* Increasingly, regulations with respect to the desired water quality of the receiving water are determined by what is considered to be technically and financially feasible. The regulatory agency then imposes the use of specified, up-to-date technology (BAT or BATNEEC) upon domestic or industrial dischargers, rather than prescribing the required discharge standards.

Table 3.7 Percentage efficiency for potential contaminant removal of different processes and operations used in wastewater treatment and reclamation

Variable or contaminant	Primary treatment	Activated sludge (AS)	Nitrification	Denitrification	Tricking filter	RBC	Coag.-Floc.-Sedim.[1]	Filtration after AS	Carbon adsorption	Ammonia stripping	Selective ion exchange	Break point chlorination	Reverse osmosis	Overland flow	Irrigation	Infiltration-percolation	Chlorination	Ozone
BOD	25-50	>50	>50	25	>50	>50	>50	25-50	>50		25-50		>50	>50	>50	>50		25
COD	25-50	>50	>50	25	>50		>50	25-50	25-50	*25*	25-50		>50	>50	>50	>50		>50
TSS	>50	>50	>50	25	>5	>	>5	>5	>50		>50		>5	>50	>5	>50		

					0	50	0	0					0		0			
NH_3-N	25	>50	>50	25-50		>50	25	25-50	25-50	>50	>50	>50	>50	>50	>50	>50		
NO_3-N				>50				25-50	25					25-50				
Phosphorus	25	25-50	>50	>50			>50	>50	>50				>50	>50	>50	>50		
Alkalinity		25-50					25-50	>50								25-50		
Oil arid grease	>50	>50	>50				25-50		25-50					>50	>50	>50		
Total coliform		>50	>50		25		>50		>50			>50		>50	>50	>50	>50	>50
TDS													>50					
Arsenic	25-50	25-50	25-50				25-50	>50	25									
Barium		25-50	25				25-50	25										
Cadmium	25-50	>50	>50		25	25-50	>50	25-50	25							25		
Chromium	25-50	>50	>50		25	>50	>50	25-50	25-50									
Copper	25-50	>50	>50		>50	>50	>50	25	25-50							>50		
Fluoride							25-50		25							25-50		
Iron	25-50	>50	>50		25-50	>50	>50	>50	>50									
Lead	>50	>50	>50		25-50	>50	>50	25	25-50							25-50		
Manganese	25	25-50	25-50		25		25-50	>50	25-50				>50					
Mercury	25	25	25		25	>50	25	25-50	25									

Selenium	25	25	25				25	>50	25									
Silver	>50	>50	>50		25-50		>50		25-50									
Zinc	25-50	25-50	>50		>50	>50	>50		>50							>50		
Colour	25	25-50	25-50		25		>50	25-50	>50				>50	>50	>50	>50		>50
Foaming agents	25-50	>50	>50		>50		25-50		>50				>50	>50	>50	>50		25
Turbidity	25-50	>50	>50	25	25-50		>50	>50	>50				>50	>50	>50	>50		
TOC	25-50	>50	>50	25	25-50		>50	25-50	>50	25	25		>50	>50	>50	>50		>50

The percentage relates to the influent concentration. Where no percentage efficiency is indicated no data are available, the results are inconclusive or there is an increase.

[1] Coagulation-Floculation-Sedimentation
RBC Rotating Biological Contactor (bio-disc)
BOD Biochemical oxygen demand
COD Chemical oxygen demand
TSS Total suspended solids
TDS Total dissolved solids
TOC Total organic carbon

Source: Metcalf and Eddy, 1991

3.4 Pollution prevention and minimisation

Although end-of-pipe approaches have reduced the direct release of some pollutants into surface water, limitations have been encountered. For example, end-of-pipe treatment transfers contaminants from the water phase into a sludge or gaseous phase. After disposal of the sludge, migration from the disposed sludge into the soil and groundwater may occur. Over the past years, there has been growing awareness that many end-of-pipe solutions have not been as effective in improving the aquatic environment as was expected. As a result, the approach is now shifting from "waste management" to "pollution prevention and waste minimisation", which is also referred to as "cleaner production".

Pollution prevention and waste minimisation covers an array of technical and non-technical measures aiming at the prevention of the generation of waste and pollutants. It is the conceptual approach to industrial production that demands that all phases of the product life cycle should be addressed with the objective of preventing or minimising short- and long-term risks to humans and the environment. This includes the product design phase, the selection, production and preparation of raw materials, the production and assembly of final products, and the management of all used products at the end of their useful life. This approach will result in the generation of smaller quantities of waste reducing end-of-pipe treatment and emission control technologies. Losses of material and resources with the sewage are minimised and, therefore, the raw material is used efficiently in the production process, generally resulting in substantial financial savings to the factory.

In the past, pollution prevention and minimisation were an indirect, although beneficial, result of the implementation of water conservation measures. Water demand management aimed to conserve scarce water by reducing its consumption rates. This was an important and relevant issue in the industrial, domestic and agricultural sector because of the rapid growth in water demand in densely populated regions of the world.

With regard to the generation of wastewater, pollution prevention and minimisation technologies are mainly implemented in the industrial sector (Box 3.1). Minimisation of wastewater from domestic sources is possible to a limited extent only and is mainly achieved by the introduction of water-saving equipment for showers, toilet flushing and gardening. In the Netherlands a new concept has been developed for residential areas where the grey water fraction is used for toilet flushing after treatment by a constructed wetland (Figure 3.4). In the agricultural sector, measures are directed primarily at water conservation through the application of, for example, water-saving irrigation techniques.

Box 3.1 Examples of successful waste minimisation in industry

Example 1

Tanning is a chemical process which converts putrescible hides and skins into stable leather. Vegetable, mineral and other tanning agents may be used (either separately or in combination) to produce leather with different qualities and quantities. Trivalent chromium is the major tanning agent, producing a modern, thin, light leather. Limits have been set for the discharge of the chromium. Cleaner production technology was used to recover the trivalent chromium ion from the spent liquors and to reuse it in the tanning process, thereby reducing the necessary end-of-pipe treatment cost to remove chromium from the wastewater.

Tanning of hides is carried out with basic chromium sulphate, $Cr(OH)SO_4$. The chromium recovery process consists of collecting and treating the spent tanning solution after its use, instead of simply wasting it. The spent liquor is sieved to remove particles and fibres. Through the addition of magnesium oxide, the valuable chromium precipitates as a hydroxide sludge. By the addition of concentrated sulphuric acid, this sludge dissolves and yields the chromium salt ($Cr(OH)SO_4$) solution that can be reused. Whereas in a conventional tanning process 20-40 per cent of the used chrome is lost in the wastewater, in this waste minimisation process 95-98 per cent of the waste chromium can be recycled.

This recovery technique was first developed and applied in a Greek tannery. The increased yearly operating costs of about US$ 30,000 were more then compensated for by the yearly chromium savings of about US$ 74,000. The capital investment of US$ 40,000 was returned in only 11 months.

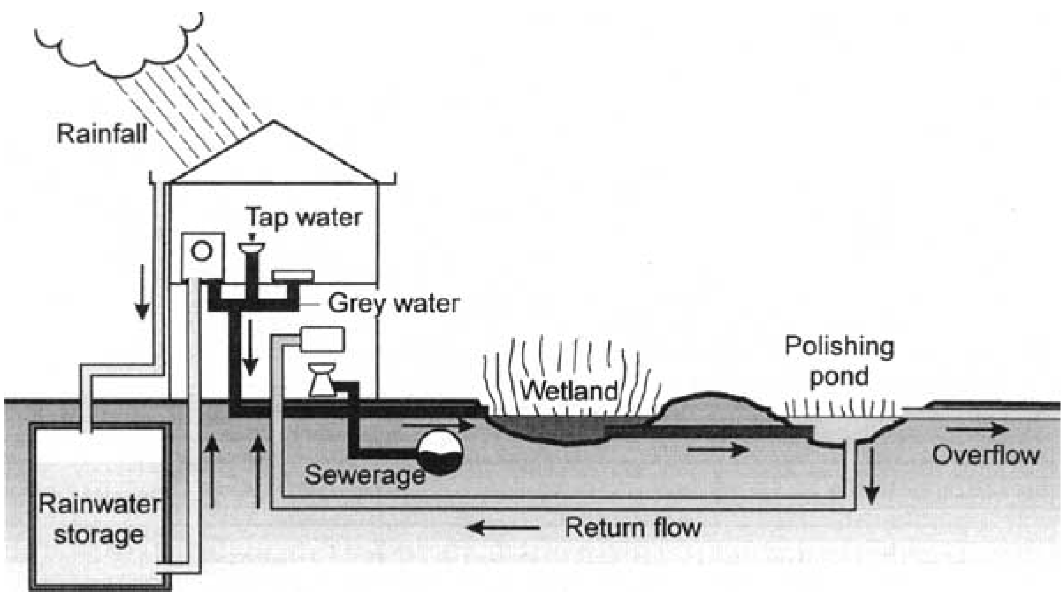
Example 2

Sulphur dyes are a preferred range of dyes in the textile industry, but cause a significant wastewater problem. Sulphur dyes are water-insoluble compounds that first have to be converted into a water-soluble form and then into a reduced form having an affinity for the fibre to be dyed. The traditional method of converting the original dye to the affinity form is treatment with an aqueous solution of sodium sulphide. The use of sodium sulphide results in high sulphide levels in the textile plant wastewater which exceed the discharge criteria. Therefore, end-of-pipe treatment technology is necessary.

To avoid capital expenditure for wastewater treatment, a study was undertaken in India of available methods of sulphur black colour dyeing and into alternatives for sodium sulphide. An alternative chemical for sodium sulphide was found in the form of hydrol, a by-product of the maize starch industry. Only minor adaptations in the textile dyeing process were necessary. The introduction of hydrol did not involve any capital expenditure and sulphide levels in the mill's wastewater were reduced from 30 ppm to less than 2 ppm. The savings resulting from not having to install additional end-of-pipe treatment to reduce sulphide level in the wastewater were about US$ 20,000 in investment and US$ 3,000 a year in running costs.

Waste minimisation involves not only technology but also planning, good housekeeping, and implementation of environmentally sound management practices. Many obstacles prevent the introduction of these new concepts in existing or even in new facilities, such as insufficient awareness of the environmental effects of the production process, lack of understanding of the true costs of waste management, no access to technical advice, insufficient knowledge of the implementation of new technologies, lack of financial resources and, last but not least, social resistance to change.

Figure 3.4 Potential reuse of grey water for toilet flushing after treatment by a constructed wetland (Based on van Dinther, 1995)



In the past, the requirements of most regulatory agencies have centred on treatment and control of industrial liquid wastes prior to discharge into municipal sewers or surface waters. As a result, over the last 20 years the number of industries emitting pollutants directly into aquatic environments reduced substantially. However, most of the implemented environmental protection measures consisted of end-of-pipe treatment technologies, with the "end" located either inside the factory or industrial zone, or at the entry of the municipal sewage treatment plant. As a consequence the industry pays for its share in the cost of sewer maintenance and treatment operation. In both cases, the industry should be charged for the treatment and management effort that has to take place outside the factory, in particular in the municipal treatment works. This charge should be made up of the true, overall treatment cost. By this principle, industries are specifically encouraged:

• To prevent waste production by Interfering in the production process.

• To reduce the occurrence of hydraulic or organic peak loads that may render a municipal treatment system more expensive or vulnerable.

• To treat their waste flows to meet discharge requirements, to prevent damage to the municipal sewer or to realise cost savings for municipal treatment.

Table 3.8 Typical regulations for industrial wastewater discharge into a public sewer system in the United Kingdom, Hungary and The Netherlands

Variable	UK	Hungary	Netherlands
pH	6-10	6.5-10	6.5-10
Temperature (°C)	<40	nrs	<30
Suspended solids (mg l^{-1})	<400	nrs	_1
Heavy metals (mg l^{-1})	<10	specific	_1
Cadmium (mg l^{-1})	<100	<10,000	_1
Total cyanide (mg l^{-1})	<2	<1	_1
Sulphate (mg l^{-1})	<1,000	<400	<300
Oil and grease (mg l^{-1})	<100	<60	_1

nrs No regulations set

[1] No coarse, explosive or inflammable solids are allowed. Contaminants that might interfere with biological treatment should be in concentrations that do not differ from domestic sewage

Sources: UN ECE, 1984; Appleyard, 1992

Table 3.8 provides examples of discharge criteria into municipal sewers. A method to calculate pollution charges into sewers or the environment is provided in Box 3.2.

3.5 Sewage conveyance

3.5.1 Storm water drainage

In many developing countries, stormwater drainage should be part of wastewater management because large sewage flows are carried into open storm water drains or because stormwater may enter treatment works with combined sewerage. In industrialised countries, stormwater drainage receives great attention because it may be polluted by sediments, oils and heavy metals which may upset the subsequent secondary and tertiary treatment steps.

In urbanised areas, the local infiltration capacity of the soil is not sufficient usually to absorb peak discharges of storm water. Large flows often have to be transported in short periods (20-100 minutes) over long distances (500-5,000 m). Drainage cost is determined, to a large extent, by the actual flow rate of the moment and, therefore, retention in reservoirs to dampen peak flows allows the use of smaller conduits, thereby reducing drainage cost per surface area. In tropical countries, peak flow reduction by infiltration may not be feasible because the peak flows can by far exceed the local infiltration capacities.

Box 3.2 Calculation of pollution charges based on "population equivalents"

Calculation of the financial charges for industrial pollution in the Netherlands is based on standard population equivalents (pe):

$$\text{pe load of industrial discharge} = \frac{Q \times [COD + 4.57TKN]}{136}$$

where	Q	=	wastewater flow rate ($m^3 d^{-1}$)
	COD	=	24 h-flow proportional COD concentration (mg COD l^{-1})
	TKN	=	24 h-flow proportional Kjeldahl-N concentration (mg N l^{-1})
	136	=	waste load of one domestic polluter (136 g O_2-consuming substances per day) and by definition set at one population equivalent.

Heavy metal discharges are charged separately:

• Each 100 g Hg or Cd per day are equivalent to l pe.
• Each 1 kg of total other metal per day (As, Cr, Cu, Pb, Ni, Ag, Zn) is equivalent to 1 pe.

An annual charge of US$ 25-50 (1994) is levied per population equivalent by the local Water Pollution Control Board; the charge is region specific and relates to the Board's overall annual expenses.

3.5.2 Separate and combined sewerage

In separate conveyance systems, storm water and sewage are conveyed in separate drains and sanitary sewers, respectively. Combined sewerage systems carry sewage and storm water in the same conduit. Sanitary and combined sewers are closed in order to reduce public health risks. Separate systems require investment in, and operation and maintenance of, two networks. However, they allow the design of the sanitary sewer and the treatment plant to account for low peak flows. In addition, a more constant and concentrated sewage is fed to the treatment plant which favours reliable and consistent process performance. Therefore, even in countries with moderate climate where the rainfall pattern would favour combined sewerage (rainfall well distributed over the year and with limited peak flows) newly developed residential areas are provided, increasingly, with separate sewerage. Combined sewerage is generally less suitable for developing countries because:

• Sewerage and treatment are comparatively expensive, especially in regions with high rain intensity during short periods of the year.

• It requires simultaneous investment for drainage, sewerage and treatment.

• There is commonly a lack of erosion control in unpaved areas.

Combined sewerage is most appropriate for more industrialised regions with a phased urban development, with an even rainfall distribution pattern over the year and with soil erosion control by road surface paving. The advantage of combined sewerage is that the first part of the run-off surge, which tends to be heavily polluted, is treated along with the sewage. The sewage treatment plants have to be designed to accommodate, typically, two to five times the average dry weather flow rate, which raises the cost and adds to the complexity of process control. The disadvantage of the combined sewer is that extreme peak flows cannot be handled and overflows are discharged to surface water, which gets contaminated with diluted sewage. These overflows can create serious local water quality problems.

Sanitary sewers are feasible only in densely populated areas because the unit cost per household decreases. Although most street sewers carry only small amounts of sewage, the construction cost is high because they require a minimum depth in order to protect them against traffic loads (minimum soil cover of 1 m), a minimum slope to ensure resuspension and hydraulic flushing of sediment to the end of the sewer, and a minimum diameter to prevent blockage by faecal matter and other solids (preferably 25 cm diameter). The required flushing velocity (a minimum of 0.6 m s^{-1} at least once a day) occurs when tap water consumption rates in the drainage area are in excess of 60 l cap^{-1} d^{-1}.

To reduce costs, sewers may use smaller diameters, may be installed at less depth and may apply a milder gradient. However, these measures require entrapment of settleable solids in a septic tank prior to discharge into the sewer. Such small-bore sewers are only cost-effective if they are maintained by the local community. This demands a high level of sustained community participation. Small-bore sewers may, ultimately, discharge into a municipal sanitary sewer or a treatment plant. Alternatively, in flat areas with unstable soils and low population density, small-bore pressure or vacuum sewers can be applied, but these are not considered a "low-cost" option.

Successful examples of low-cost small-bore sewerage are reported from Brazil, Colombia, Egypt, Pakistan and Australia. At population densities in excess of 200 persons per hectare, these small-bore sewer systems tend to become more cost effective than on-site sanitation. Companhia de Saneamento Basico do Estado de São Paulo (SABESP, São Paulo, Brazil) estimates the average construction cost (1988) for small towns to be US$ 150-300 per capita for conventional sewerage and US$ 80-150 per capita for simplified, small-bore sewerage (Bakalian, 1994). It is common in developing countries for most plot owners not to desludge their septic tank or cess pit regularly or adequately. Examples from Indonesia and India show that overflowing septic tanks are sometimes illegally connected to public open drains or sewers, and that during desludging operations often only the liquid is removed leaving the solids in the septic tank. Therefore, the implementation of small-bore sewerage requires substantial investment in community involvement to avoid the major failure of this technology.

3.6 Costs, operation and maintenance

Investment costs notably cover the cost of the land, groundwork, electromechanical equipment and construction. Recurring costs relate mainly to the paying back of loans (interest and principal), and to the costs for personnel, energy and other utilities, stores, laboratories, repair and sludge disposal. Both types of cost may vary considerably from country to country, as well as in time. Any financial feasibility analysis requires the use of a discount factor. This factor depends on inflation and interest rates and is also subject to substantial fluctuations. Therefore, comparing different technologies is always difficult and requires extensive expert analysis. Nevertheless, Figure 3.5 offers typical comparative cost levels (for industrialised countries) for primary, secondary and tertiary treatment of domestic wastewater. Table 3.9 provides a comparison of the unit construction costs for on-site and off-site sanitation for different world regions.

Operation and maintenance (O&M) is an essential part of wastewater management and affects technology selection. Many wastewater treatment projects fail or perform poorly after construction because of inadequate O&M. On an annual basis, the O&M expenditures of treatment and sewage collection are typically in the same order of magnitude as the depreciation on the capital investment. Operation and maintenance requires:

- Careful exhaustive planning.
- Qualified and trained staff devoted to its assignment.
- An extensive and operational system providing spare parts and O&M utilities.
- A maintenance and repair schedule, crew and facility.
- A management atmosphere that aims at ensuring a reliable service with a minimum of interruptions.
- A substantial annual budget that is uniquely devoted to O&M and service improvement.

Maintenance policy can be corrective, i.e. repair or action is undertaken when breakdown is noticed, but this leads to service interruption and hence dissatisfied customers. Ideally, maintenance is preventive, i.e. replacement of mechanical parts is carried out at the end of their expected life time. This allows optimal budgeting and maintenance schedules that have minimal impact on service quality. Clearly, O&M requirements are important factors when selecting a technology; process design should provide for optimal, but low cost, O&M.

Figure 3.5 Typical total unit costs for wastewater treatment based on experience gained in Western Europe and the USA (After Somlyody, 1993)

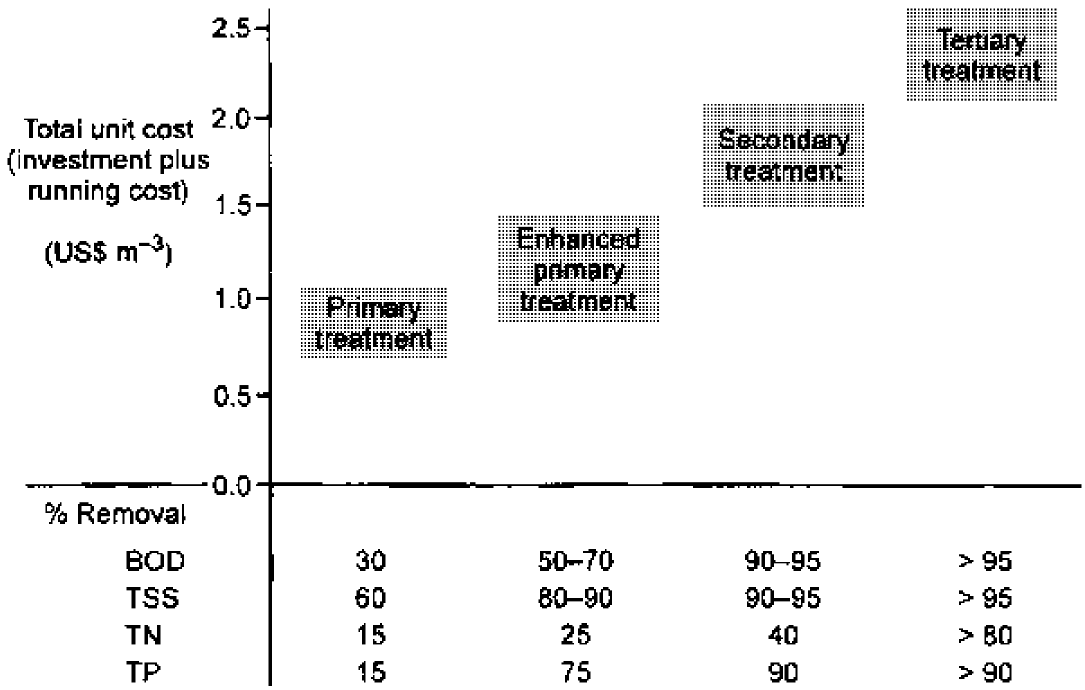


Table 3.9 Typical unit construction cost (US$ cap^{-1}) for domestic wastewater disposal in different world regions (median values of national averages)

Region	Urban sewer connection	Rural on-site sanitation
Africa	120	22
Americas	120	25
South-East Asia	152	11
Eastern Mediterranean	360	73
Western Pacific	600	39

Source: WHO, 1992

The most common reasons for O&M failure are inadequate budgets due to poor cost recovery, poor planning of servicing and repair activities and weak spare parts management, and inadequately trained operational staff.

3.7 Selection of technology

The technology selection process results from a multi-criteria optimisation considering technological, logistic, environmental, financial and institutional factors within a planning horizon of 10-20 years. Key factors are:

- The size of the community to be served (including the industrial equivalents).
- The characteristics of the sewer system (combined, separate, small-bore).
- The sources of wastewater (domestic, industrial, stormwater, infiltration).

- The future opportunities to minimise pollution loads.
- The discharge standards for treated effluents.
- The availability of local skills for design, construction and O&M.
- Environmental conditions such as land availability, geography and climate.

Considerations for industrial technology selection tend to be relatively straightforward because the factors interfering in selection are primarily related to anticipated performance and extension potential. Both of these are associated directly with cost.

3.7.1 On-site sanitation technologies

For domestic wastewater the suitability of various sanitation technologies must be related appropriately to the type of community, i.e. rural, small town or urban (Table 3.10). Typically, in low-income rural and (peri-)urban areas, on-site sanitation systems are most appropriate because:

- They are low-cost (due to the absence of sewerage requirements).
- They allow construction, repair and operation by the local community or plot owner.
- They reduce, effectively, the most pressing public health problems.

Moreover, water consumption levels often are too low to justify conventional sewerage.

With on-site sanitation, black toilet water is disposed in pit latrines, soak-aways or septic tanks (Figure 3.6) and the effluent infiltrates into the soil or overflows into a drainage system. Grey water can infiltrate directly, or can flow into drainage channels or gullies, because its suspended solids and pathogen contents are low. The solids that accumulate in the pit or tank (approximately 40 l cap^{-1} a^{-1}) have to be removed periodically or a new pit has to be dug (dual-pit latrine). Depending on the system, the sludge may or may not be well stabilised. At the minimum solids retention time of six months the sludge may be considered to be pathogen-free and it can be used in agriculture as fertiliser or as a soil conditioner. Digestion of the full sludge content for several months can be carried out if a second, parallel pit is used while the first is digesting.

Table 3.10 Typical sanitation options for rural areas, small townships and urban residential areas

	Rural area	Township	Urban area
Community size	<10,000 pe	10,000-50,000 pe	>50,000 pe
Density (persons per hectare)	<100	>100-<200	>200
Water supply service	Well, handpump	Public standpost	House connection
Water consumption	<50 l cap^{-1} d^{-1}	50-100 l cap^{-1} d^{-1}	>100 l cap^{-1} d^{-1}
Sewage production	<5 m^3 ha^{-1} d^{-1}	5-20 m^3 ha^{-1} d^{-1}	>20 m^3 ha^{-1} d^{-1}
Treatment options	Dry on-site sanitation by VIP or composting latrines	Dry and wet on-site sanitation; small-bore sewerage may be feasible depending on population density and soil conditions	Centre: Sewerage plus off-site treatment. Peri-urban: wet on-site sanitation with small-bore sewerage and septage handling

VIP Ventilated Improved Pit latrine

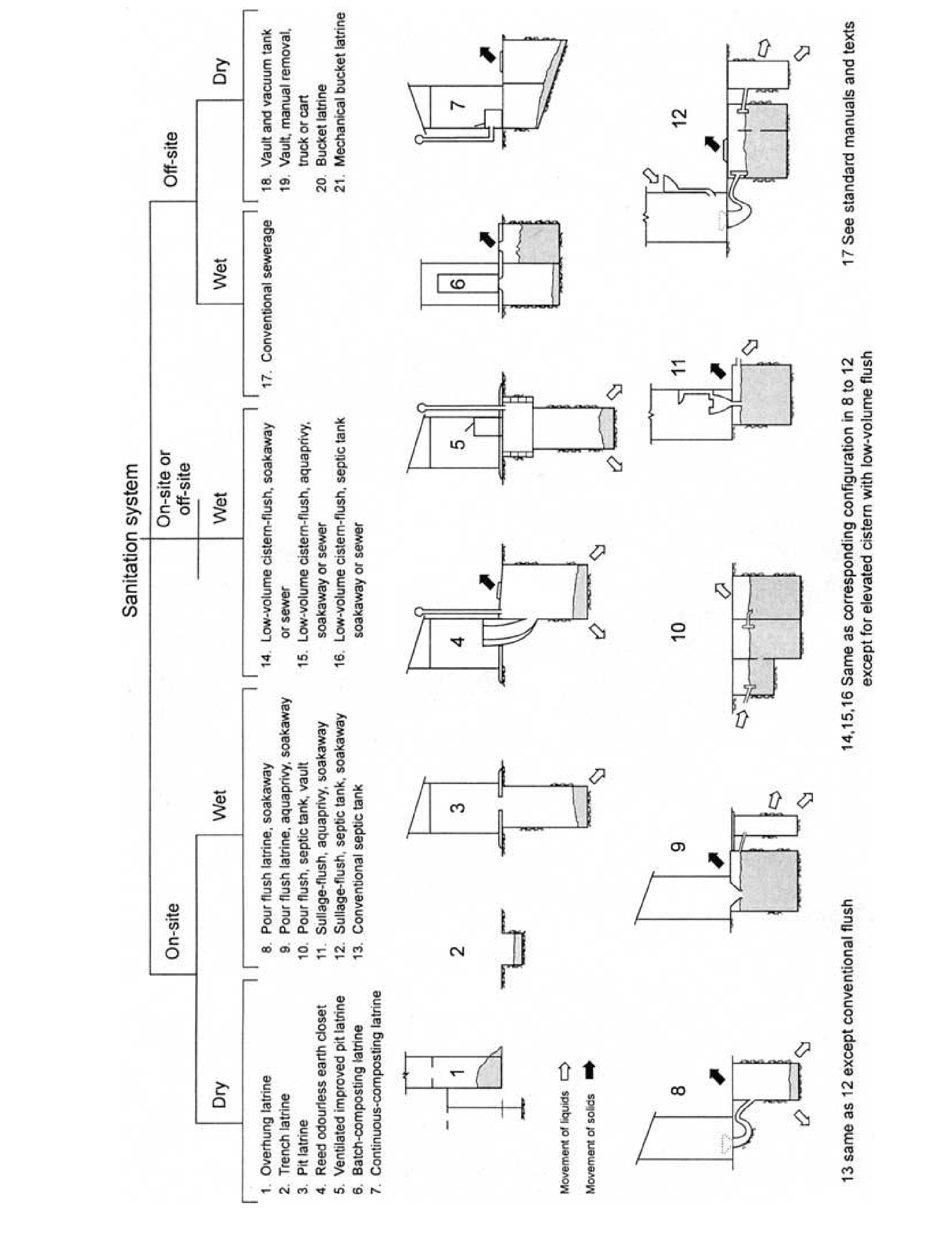
The accumulating waste (septage) in septic tanks must be regularly collected and disposed of. After drying and dewatering in lagoons or on drying beds it can be disposed at a landfill site, or it can be co-composted with domestic refuse. Reuse in agriculture is only feasible following adequate pathogen removal and provided the septage is not contaminated with heavy metals. Alternatively, the septage can be disposed of in a sewage treatment plant, or it can be stabilised and rendered pathogen-free by adding lime (until the pH>10) or by extended aeration. The latter two methods, however, are expensive.

3.7.2 On-site versus off-site options

In densely populated urban areas the generation of wastewater may exceed the local infiltration capacity. In addition, the risk of groundwater pollution and soil destabilisation often necessitates off-site sewerage. At hydraulic loading rates greater than 50 mm d^{-1} and less than 2 m unsaturated ground-water flow, nitrate and, in a later stage, faecal coliform contamination may occur (Lewis *et al.,* 1980).

The unit cost for off-site sanitation decreases significantly with increasing population density, but sewering an entire city often proves to be very expensive. In cities where urban planning is uncoordinated, implementation of a balanced mix of on-site and off-site sanitation is most cost-effective. For example, in Latin America the population density at which small-bore sewerage becomes competitive with on-site sanitation is approximately 200 persons per hectare (Sinnatamby *et al.,* 1986). The deciding factor in these cost calculations is the cost of the collection and conveyance system.

Figure 3.6 Classification of sanitation systems as on-site and off-site (based on population density) and as dry and wet sanitation (based on water supply) (After Kalbermatten *et al*., 1980)



Box 3.3 provides guidance for preliminary decision-making with respect to on- or off-site sanitation. In situations where there is a high wastewater production per hectare per day, sewerage is needed to transport either the liquids alone (in the case of small-bore sewerage) or the liquid plus suspended solids (in the case of conventional sewerage). Additional decisive parameters are whether shallow wells used for water supplies need to be protected, the population density, the soil permeability and the unit cost. To minimise groundwater contamination, a typical surface loading rate of 10 m^3 ha^{-1} d^{-1} is recommended (Lewis *et al.,* 1980), provided that prevailing groundwater tables ensure at least 2 m unsaturated flow in a vertical direction.

When the wastewater production rate is in excess of 10 m^3 ha^{-1} d^{-1}, conventional sanitary sewerage may be feasible for managing municipal sewage, with or without the inclusion of storm water. Studies indicate that at 200-300 persons per hectare, gravity sewerage becomes economically feasible in developing countries; in industrialised countries the equivalent population density is about 50 persons per hectare.

If groundwater protection is not required, the infiltration rate may exceed 10 m^3 ha^{-1} d^{-1}, provided the soil permeability and stability allow it. If soil permeability is low, off-site sanitation needs consideration. Depending on the socio-economic environment and the degree of community involvement that can be generated, small-bore sewerage may be feasible. In such cases additional stormwater drainage facilities must be provided.

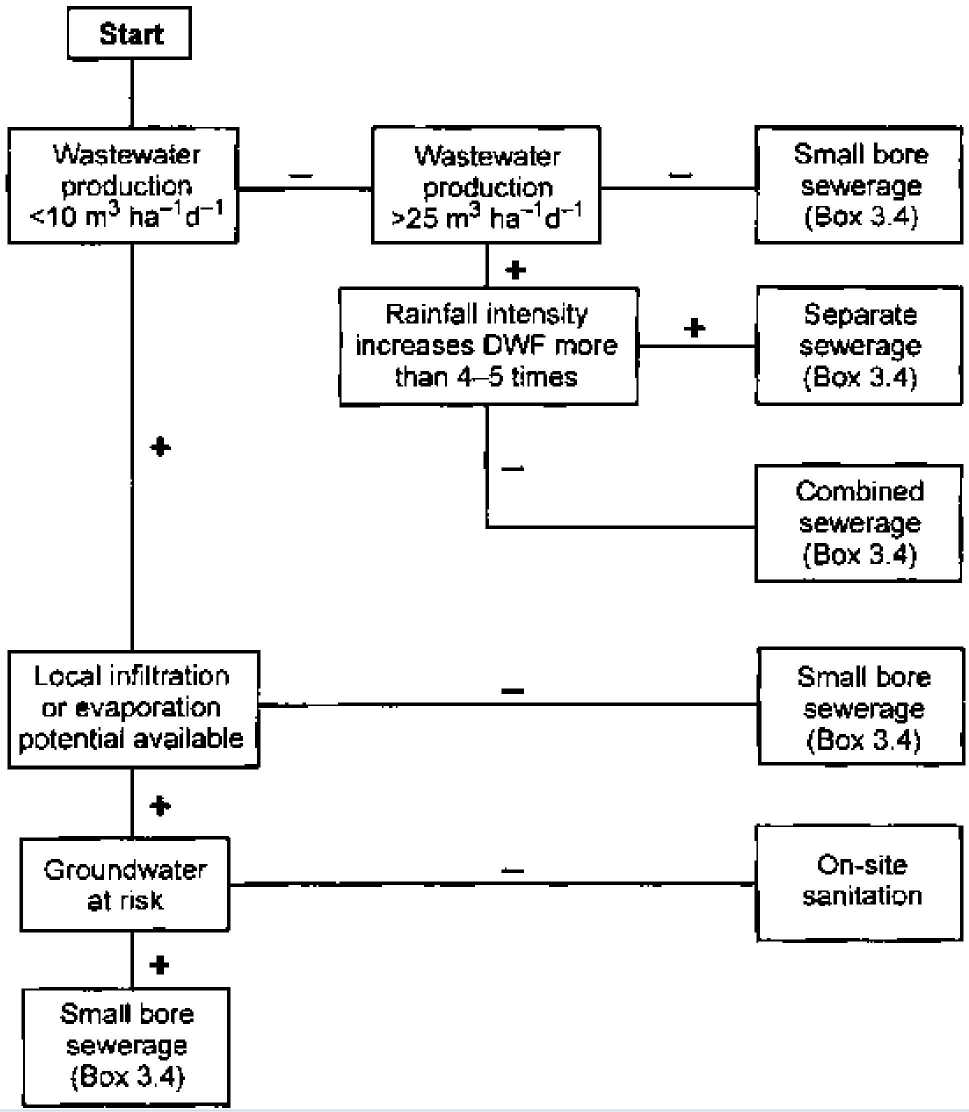
In addition to technical, logistic and financial criteria, reliable management by a local village-based entity or local government is essential for sustainable functioning of the system. Most off-site treatment technologies benefit from economies of scale although anaerobic technologies tend to scale down easily to township or local level without the unit cost rising seriously. This makes anaerobic technologies suitable for inclusion in urban sanitation at community level (Alaerts *et al.,* 1990). This "community on-site" option can stimulate more disciplined operation and desludging when compared with the often poor performance of individual units. At the same time, it retains the advantage that it can be managed by a local committee and semi-skilled caretakers.

3.7.3 Off-site centralised treatment technologies

There is a large variety of off-site treatment technologies. The selection of the most appropriate technology is determined, first of all, by the composition of the wastewater flow arriving at the treatment plant and also by the discharge requirements. Questions for assessing the expected composition and behaviour of the sewage to be treated include:

- To what extent is industrial wastewater included?
- Will sewerage be separate, combined or small-bore?
- Is groundwater expected to infiltrate into the sewer?
- Are septic tanks removing settleable solids prior to discharge into the conveyance system?
- What is the specific water and food consumption pattern?
- What is the quality of the drinking water?

Box 3.3 Preliminary assessment for on-site sanitation, intermediate small-bore sewerage or conventional off-site sewerage for domestic or municipal wastewater disposal



- Not valid	+ Valid	DWF Dry weather flow ($m^3 d^{-1}$)
Wastewater production	population density (pe ha^{-1}) × specific wastewater production (WPR) (l $pe^{-1} d^{-1}$)	
Local infiltration	infiltration area available ($m^2 ha^{-1}$) × long-term applicable potential (LIP): infiltration rate ($m^3 m^{-2} d^{-1}$); LIP at least equal to WPR	
Groundwater at risk	This may occur if: depth of unsaturated zone is less than 2 m, the hydraulic load exceeds 50 mm d^{-1}, or shallow wells for potable supplies exist within a distance (in metres) of 10 times the horizontal groundwater flow velocity (m d^{-1})	

Each off-site treatment plant is composed of unit processes and operations that enable the effluent quality to meet the criteria set by the regulatory agency. Therefore, when selecting a technology the first step is to develop a complete flow diagram where all unit processes and operations are put together in a logical fashion. Off-site treatment systems are generally composed of primary treatment, usually followed by a secondary stage and, in some instances, a tertiary or advanced treatment stage. Table 3.7 summarises the potential performance of common technologies that can be applied in wastewater treatment.

Primary treatment

In most treatment plants mechanical primary treatment precedes biological and/or physicochemical treatment and is used to remove sand, grit, fibres, floating objects and other coarse objects before they can obstruct subsequent treatment stages. In particular, the grit and sand conveyed through combined sewers may settle out, block channels and occupy reactor space. Additional facilities may be designed to equalise peak flows. Approximately 50-75 per cent of suspended matter, 30-50 per cent of BOD and 15-25 per cent of Kjeldahl-N and total P are removed at moderate cost by means of settling. Settling tanks that include facilities for extended sludge or solids retention may facilitate the stabilisation of sludge and are, therefore, convenient for small communities.

Physicochemical processes may be incorporated in the primary treatment stage in order to further enhance removal efficiencies, to adjust (neutralise) the pH, or to remove any toxic or inhibitory compounds that may affect the functioning of the subsequent treatment steps. Flocculation with aluminium or iron salts is often used. Such enhanced primary treatment is comparatively cheap in terms of capital investment but the running costs are high due to the chemicals that are required and the additional sludge produced. This approach is attractive when it is necessary to expand the plant capacity due to a temporary (e.g. seasonal) overload.

Secondary treatment

The most common technology used for secondary treatment of wastewater relies on (micro)biological conversion of oxygen consuming substances such as organic matter, represented as BOD or COD, and Kjeldahl-N. The technologies can be classified mainly as aerobic or anaerobic depending on whether oxygen is required for their performance, or as mechanised or non-mechanised depending on the intensity of the mechanised input required. Table 3.11 provides a matrix classification of available (micro)biological treatment technologies. Further detailed information is available in Metcalf and Eddy (1991) and Arceivala (1986).

The choice between aerobic and anaerobic technologies has to consider mainly the added complexity of the oxygen supply that is need for aerobic technologies. The supply of large amounts of oxygen by a surface aeration or bubble dispersion system adds to the capital cost of the aeration equipment substantially, as well as to the running cost because the annual energy consumption is rather high (it can reach 30 kWh per population equivalent (pe)).

The choice between mechanised or non-mechanised technologies centres on the locally or nationally available technology infrastructure which may ensure a regular supply of skilled labour, local manufacturing, operational and repair potential for used equipment, and the reliability of supplies (e.g. power, chemicals, spare parts). Additional key considerations are land requirements and the potential for biomass resource recovery. In general, non-mechanised technologies rely on substantially longer retention time to achieve a high degree of contaminant removal whereas mechanised systems use equipment to accelerate the conversion process. If land costs are in excess of US$ 20 per square metre, non-mechanised systems lose their competitive cost advantage over mechanised systems. Resource recovery may be possible if, for example, the algal or macrophyte biomass generated is marketable, generating revenue and employment opportunities. For example, constructed wetlands using *Cyperus papyrus* may generate about 40-50 tonnes of standing biomass per hectare a year which can be used in handicraft or other artisanal activities.

For non-biodegradable (mainly industrial) wastewaters physicochemical alternatives have been developed that rely on the physicochemical removal of contaminants by chemical coagulation and flocculation. The generated sludges are typically heavily contaminated and have no potential for reuse other than for landfill.

Overall, the selection process for the most appropriate secondary technology may have to be decided using multi-criteria analysis. In addition to the overall unit costs, the environmental, aesthetic and health risks involved, the quality standards to be met, the skilled staff and land requirements, and the reliability of the potential for recovery by the technology, all have to be evaluated to give a total score that indicates the feasibility of each technology for a particular country or location (Handa *et al.,* 1990).

Table 3.11 Classification of secondary treatment technology

Conversion method	Mechanised technology	Non-mechanised technology
Aerobic	Activated sludge	Facultative stabilisation ponds
	Trickling filter	Maturation ponds
	Rotating bio-contactor	Aquaculture (e.g. algal, duck weed or fish ponds)
		Constructed wetlands
Anaerobic	Upflow anaerobic sludge bed (UASB)	Anaerobic ponds
	Anaerobic (upflow) filter	

Physicochemical treatment. Physicochemical technologies can achieve significant BOD, P and suspended solids reduction, although it is generally not the preferred option for domestic sewage because removal rates for organic matter are rather poor (Table 3.12). It is often used for industrial wastewater treatment to remove specific contaminants or to reduce the bulk pollutant load to the municipal sewer. Physicochemical treatment can also be combined with primary treatment to enhance removal processes and to reduce the load on the subsequent secondary treatment stage. For wastewater with a high organic matter content, like domestic sewage, (micro)biological methods are commonly preferred because they have lower operational costs and achieve a higher reduction of BOD.

The skills required to operate chemical dosing equipment, and the difficulty in ensuring a reliable supply of chemicals are often prohibitive for the selection of physicochemical technologies in developing countries where systems are more prone to malfunctioning. In particular, the fluctuating flow and composition of the incoming sewage makes frequent adjustments of the chemical dosing necessary. Biological treatment systems are more sturdy and ensure a constant effluent quality because they have a high internal buffering capacity for peak flows and loads.

Examples of physicochemical processes used in industrial applications include:

• Chemical oxidation with, for example, O_2, O_3 or Cl_2 (cyanide removal and oxidation of refractory organic compounds).

• Chemical reduction (for example, H_2S assisted conversion of Cr (VI) into Cr (III)).

• Desorption (stripping) (NH_3 and odorous gas removal).

• Adsorption on activated carbon (removal of refractory organics and heavy metals).

• Ultra- and micro-filtration (separation of colloidal and dissolved compounds).

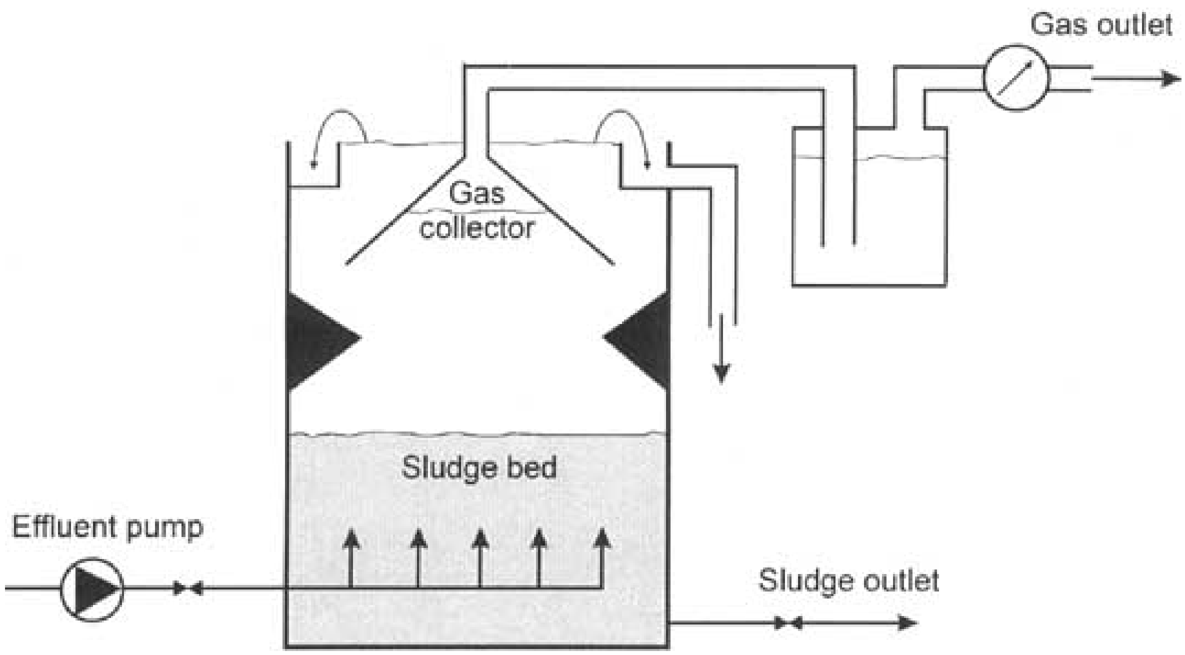
Table 3.12 Advantages and disadvantages of physicochemical treatment of domestic or municipal wastewater

Advantages	Disadvantages
Compact technology with low area needs	Chemical dosing is labour intensive due to fluctuating sewage load and composition
Good removal of micro-pollutants and P	Generation of chemical sludges
Fast start-up	High unit cost per m^3 of water treated
Insensitivity to toxic compounds	

Anaerobic treatment. Aerobic treatment methods have traditionally dominated treatment of domestic and industrial wastewater. Since the 1970s, however, anaerobic treatment has become the preferred technology for concentrated organic wastewater from, for example, breweries, alcohol distilleries, fermentation industries, canning factories, pulp and paper mills (Hulshoff Pol and Lettinga, 1986). The principal characteristic of anaerobic processes is that degradation of the organic pollutants takes place in the absence of oxygen. The bacteria produce considerable quantities of methane gas. In addition, the process can proceed at exceptionally high hydraulic loading rates. Of the many process design alternatives, the Upflow Anaerobic Sludge Blanket (UASB) process is the most cost-effective in most types of industrial wastewater treatment (Figure 3.7). The reactor consists of an empty volume covered with a plate settler zone to catch and to recycle suspended matter escaping from the sludge blanket below. The water flows upwards through a blanket of suspended granules or floes containing the active biomass. The methane and CO_2 bubbles are caught below the plate settlers and taken out of the reactor separately.

World-wide, over 400 anaerobic plants treat industrial wastewater, whereas operational experience on domestic sewage derives from approximately 10 full-scale UASB plants (size 20,000-200,000 pe) in Colombia, Brazil and India (Alaerts *et al.,* 1990; Draaijer *et al*., 1992; Schellinkhout and Collazos, 1992; van Haandel and Lettinga, 1994). Whereas the aerobic process achieves 90-95 per cent removal of BOD, the anaerobic process achieves only 75-85 per cent necessitating, in most cases, post-treatment to meet effluent standards. Anaerobic treatment also provides minimal N and P removal but generates much less, and a better stabilised, sludge. Biogas recovery is only feasible on a large scale or in an industrial context. Many tropical developing countries would probably prefer anaerobic processes because of the numerous agro-industries and the (often) high domestic sewage temperatures.

Figure 3.7 Schematic representation of the Upflow Anaerobic Sludge Blanket (UASB) reactor



The choice between aerobic and anaerobic treatment depends primarily on the wastewater characteristics (Box 3.4). If the average sewage temperature is above 20 °C (with a minimum of 18 °C over a maximum period of 2 months) and is highly biodegradable (COD:BOD ratio below 2.5) and concentrated (typically BOD > 1,000 mg l^{-1}), anaerobic treatment has clear economic advantages. If neither condition can be met, aerobic treatment is the only feasible option. If only one condition is met the choice is determined by additional considerations such as:

• Desired effluent quality: anaerobic technologies yield lower removal efficiencies. The presence of residual BOD, ammonium and, occasionally, sulphide in the effluent may require post-treatment.

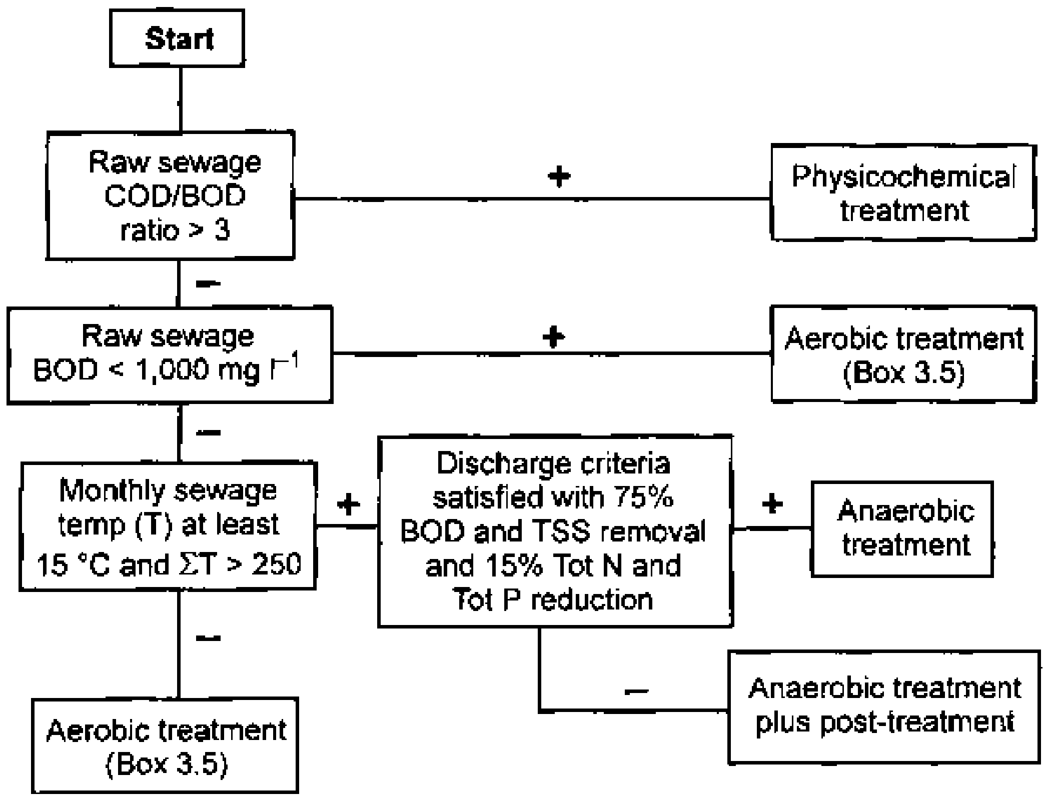
• Sludge handling and disposal: anaerobic sludge production is less than half of that in aerobic treatment plants, and the sludge is already stabilised which facilitates further processing.

• Effluent use: anaerobic treatment retains more nutrients (N, P, K) and thus effluent have higher potentials for use in irrigation.

• Reliability of power supply: aerobic treatment performance is highly dependent on power input for aeration and mixing. Power failure may create rapid malfunctioning of aerobic plants while anaerobic systems are fairly resistant to periods of no power supply.

• Local potential for selling biogas.

Box 3.4 Steps in deciding between the secondary treatment alternatives of physicochemical, aerobic and anaerobic treatment technologies

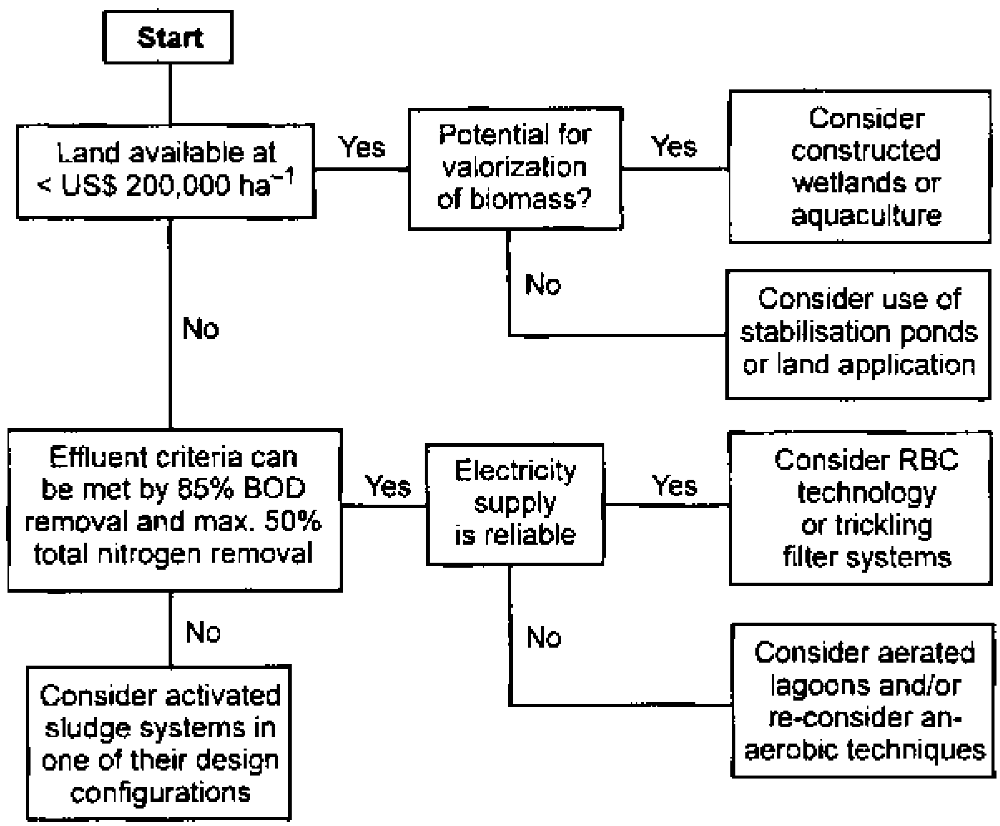


ΣT	Annual sum of monthly average sewage temperatures (in °C)
Tot N	Total nitrogen content of treated effluent (mg N l^{-1})
Tot P	Total phosphorus content of treated effluent (mg P l^{-1})

When high effluent standards are to be met, and the cost of land is moderate to high, the combination of a UASB plant plus aerobic post-treatment is often decisively more cost-effective than conventional aerobic treatment.

Non-mechanised treatment. The availability of flat land is a decisive criterion in selecting between non-mechanised and mechanised technologies (Box 3.5). Land-intensive systems such as stabilisation ponds, aquaculture, pisciculture and constructed wetlands may be feasible only when flat land costs are below US$ 5 per square metre. Such systems typically require 5-10 m^2 per population equivalent and are not usually demanding with respect to O&M, provided the wastewater is of domestic origin. Land-intensive treatment may, particularly in developing countries, better fit a resource recovery scenario because the produced biomass can sometimes be harvested and used to generate income. Algae-based stabilisation ponds are in operation on all continents for sewage treatment or for additional treatment of partially treated effluent; although they sometimes suffer from sulphide or ammonium and from comparatively high suspended solids content in the effluent. Such ponds are characterised according to their purpose and dimensions (Table 3.13). Stabilisation ponds operate without forced retainment of the active biomass while the oxygen is provided from the photosynthesis of the algae present in the ponds and by re-aeration by the wind.

Box 3.5 Steps in the selection of natural or mechanised wastewater treatment



RBC Rotating biological contactor (biodisc system)

According to studies by consultants, at a land cost of US$ 20 per square metre the total annual cost for natural wastewater treatment systems will reduce their feasibility over mechanised treatment technologies. The cost savings obtained by omitting mechanical equipment will be completely offset against the high cost for land acquisition (World Bank Workshop held in December 1993).

Mechanised aerobic treatment technologies include activated sludge, RBC and trickling filters.

Natural treatment technologies include stabilisation ponds, constructed wetlands and aquaculture systems.

Table 3.13 Typical features of stabilisation ponds

Typical feature	Anaerobic pond	Facultative pond	Maturation pond
Objective	TSS removal	BOD removal	Nutrient and pathogen removal
Loading rate	0.1-0.3 kg BOD m^{-3} d^{-1}	100-350 kg BOD ha^{-1} d^{-1}	At least two ponds in series, each 5 days retention
Typical depth	2-5 m	1-2 m	1-1.5 m
Performance	TSS: 50-70%	TSS: increase	TSS: 20-30%
	BOD: 30-60%	BOD: 50-70%	BOD: 20-50%
	Coliforms: 1 order of magnitude	Coliforms: 1-2 orders of magnitude	Coliforms: 3-4 orders of magnitude
Problems	Odour release	Algal TSS increase	Area requirement

TSS Total suspended solids
BOD Biochemical oxygen demand

In aquaculture and constructed wetlands, macrophytes (plants) are grown to suppress algal growth by shielding the water column from light, by absorbing the nutrients and by assisting the oxygen transfer into the water. The floating plant duckweed (Lemnaceae), is particularly promising for aquaculture because it grows abundantly and can easily be harvested. In constructed wetlands, wastewater is made to flow either horizontally or vertically through the root zone of a permeable soil planted with vegetation. The plants, if regularly harvested, create a sink for the nutrients by their uptake and assimilation of N and P. Importantly, they also provide niches for bacteria that reduce BOD, and that enhance nitrification, denitrification and P-fixation. They also provide niches for predator organisms that contribute to pathogen removal. Such wetlands offer good prospects for small-scale operation in remote tropical areas, although this approach has not yet been demonstrated at full scale. Fish can also be grown in stabilisation ponds to control algal growth, although their consumption can present public health risks. Sewage-based pisciculture is applied on a small scale in China, Indonesia and other East Asian countries; large-scale applications can be found in Calcutta and Munich, amongst other places.

Aerobic mechanised treatment. If flat land is scarce or expensive, and if anaerobic technologies are not feasible, the remaining option is to use conventional, aerobic, mechanised technologies. Most wastewater treatment plants all over the world are presently of this type, although they tend to be less appropriate in low-cost environments. They can be divided according to their method of sludge retention, i.e. in fixed-biofilm or in suspended growth reactors with sludge recycling. In biofilm reactors, micro-organisms are immobilised because they are attached to an inert support (e.g. lava stones, plastic rings or bio-disc) and are in constant contact with the wastewater and with the air that flows through the open pores. In suspended growth systems, the micro-organisms and the wastewater are in constant contact through mechanical mixing, which also ensures aeration.

Biofilm reactors retain their biomass better than suspended growth reactors and can therefore handle hydraulic fluctuations and low BOD concentrations more efficiently. However, the operational control of biofilm reactors is fairly limited. By contrast, suspended growth reactors allow better control and generally produce a higher quality effluent.

Typical suspended growth systems are the activated sludge system and extended aeration; trickling filter and rotating bio-discs are both biofilm-based systems. These systems require less than 1 m^2 pe^{-1} but, depending on the situation, they consume somewhat more space than anaerobic technologies. The activated sludge system, in its various designs, is the most widely applied - offering operational flexibility, high reliability and resilience. An added advantage is that process control also offers the opportunity to have several processes integrated in the system such as carbon oxidation, nitrification, denitrification and biological P-removal. This is of great benefit in achieving high quality effluents that meet the European Union (EU) guidelines (Table 3.14). Although trickling filters are technically feasible and attractive because they are easy to operate and they consume less energy, they generally have a lower removal efficiency for BOD and TSS, they are sensitive to low temperatures and may be infested with flies and mosquitoes. Their N and P removal is too low to justify wide application in countries with stringent effluent quality standards (Table 3.15). Rotating bio-discs are not widely used because they have low operational flexibility, potential mechanical problems and, often, a complicated biofilm development.

A typical activated sludge process design that is becoming more popular in many industrialised countries is the oxidation ditch. The low sludge loading (kg BOD per kg of biomass per day) ensures, all in one reactor, BOD removal, advanced nitrification, substantial denitrification, biological P removal and modest generation of well-stabilised sludge. This even allows the primary treatment to be skipped. The carousel is a modified version of the oxidation ditch with this enhanced capacity (Figure 3.8).

Table 3.14 European Community guidelines for wastewater discharged to sensitive surface water bodies based on typical raw wastewater composition

Variable	Raw sewage composition	EU guideline	Percentage removal (%)
BOD_5 (mg l^{-1})	250	25	90
Total N (mg l^{-1})	48	10	80
Total P (mg l^{-1})	12	1	90

Source: CEC, 1991

Table 3.15 Comparative analysis of the performance of the trickling filter and the activated sludge process for secondary wastewater treatment

Parameter	Trickling filter	Activated sludge
BOD removal (%)[1]	80-90	90-98
Kjeldahl-N removal (%)	60-85	80-95
Total N removal (%)	20-45	65-90
Energy required (kWh cap^{-1} a^{-1})	10-15	20-30
O&M requirement	Medium	High
Pathogen removal	1-2 orders of magnitude	1-2 orders of magnitude

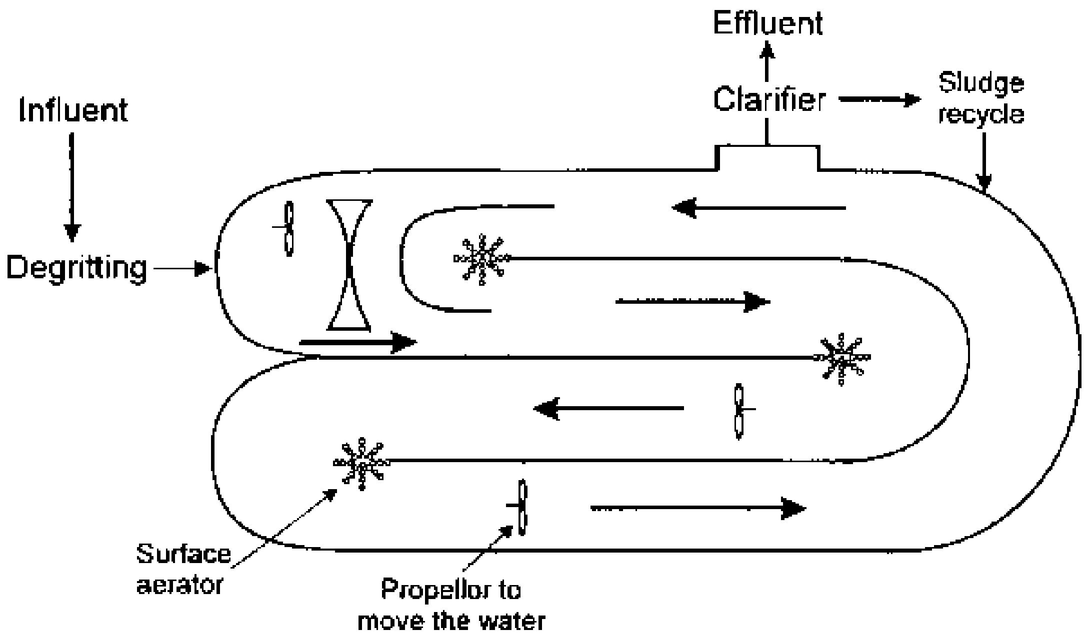
[1] Not including BOD removal in primary treatment steps

If pathogen removal is essential, only non-mechanised systems featuring hydraulic retention times of 20-30 days can provide satisfactory removal of faecal coliforms and nematode eggs to the standard required by the WHO guidelines (WHO, 1989). All mechanised treatment systems need additional chemical disinfection with chlorine or other oxidative chemicals, or with UV irradiation. This adds to the treatment cost and the operational complexity of the treatment technology and eventually may reduce the reliability of the treatment plant to provide "safe effluents".

3.8 Conclusions and recommendations

World-wide attitudes to sustainable water resources management for the future are being reconsidered. Conservation of water resources (with respect to quantity and quality) is being increasingly emphasised as the means to address the anticipated and increasing shortages of water resources of good quality in many parts of the world. This water is needed to meet ever increasing domestic, industrial and agricultural demands. Extrapolation of the increasing water consumption rates over the last ten years suggests that huge shortages will occur in many populated areas of the world, particularly in the arid and semi-arid world regions.

Figure 3.8 Novel carousel configuration of the oxidation ditch, activated sludge system for achieving a final effluent with low total N and P levels



Solving sanitary problems of human and industrial waste flows in the future, especially those generated in urban environments, may not necessarily be feasible using water consuming technologies that rely on conventional sewerage, carrying and transporting the suspended waste material away from the place where it was generated. Water saving technologies, water recycling and reuse, will play an increasingly dominant role in the future and will draw attention away from pollution control policies to waste prevention and waste minimisation policies. Scenarios including the potential for recovery of valuable resources will be increasingly promoted as they become more feasible aspects of sustainable water resources management.

With urbanisation taking place world-wide, attention to water and sanitation will shift to the densely populated urban and peri-urban areas where new incentives are created for technology development. These incentives will be aimed at people with only marginal financial resources available and with water supply levels that are too low to justify conventional sewerage.

Separating wastewater flows (black and grey water, domestic and industrial, sewage and rainwater) and the development of technologies that aim to make these individual wastewater flows fit for reuse or recycling will, in the long run, contribute to sound water resources management. In addition, such approaches will reduce public health risks and environmental pollution, as well as the burden on the pollution carrying capacity of the environment.

Technology selection for waste flows may therefore have to take a broader perspective than purely meeting the present discharge standards formulated for the local situation. Anticipating the above trends might stimulate the use of an additional criterion in technology selection, i.e. sustainable use of scarce resources whether it be water, nutrients, energy or space.

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