Waste water treatment

3.2 Conventional wastewater treatment processes

Conventional wastewater treatment consists of a combination of physical, chemical, and biological processes and operations to remove solids, organic matter and, sometimes, nutrients from wastewater. General terms used to describe different degrees of treatment, in order of increasing treatment level, are preliminary, primary, secondary, and tertiary and/or advanced wastewater treatment. In some countries, disinfection to remove pathogens sometimes follows the last treatment step. A generalized wastewater treatment diagram is shown in Figure 5.

Figure 5: Generalized flow diagram for municipal wastewater treatment (Asano *et al.* 1985)

3.2.1 Preliminary treatment

The objective of preliminary treatment is the removal of coarse solids and other large materials often found in raw wastewater. Removal of these materials is necessary to enhance the operation and maintenance of subsequent treatment units. Preliminary treatment operations typically include coarse screening, grit removal and, in some cases, comminution of large objects. In grit chambers, the velocity of the water through the chamber is maintained sufficiently high, or air is used, so as to prevent the settling of most organic solids. Grit removal is not included as a preliminary treatment step in most small wastewater treatment plants. Comminutors are sometimes adopted to supplement coarse screening and serve to reduce the size of large particles so that they will be removed in the form of a sludge in subsequent treatment processes. Flow measurement devices, often standing-wave flumes, are always included at the preliminary treatment stage.

3.2.2 Primary treatment

The objective of primary treatment is the removal of settleable organic and inorganic solids by sedimentation, and the removal of materials that will float (scum) by skimming. Approximately 25 to 50% of the incoming biochemical oxygen demand (BOD_5), 50 to 70% of the total suspended solids (SS), and 65% of the oil and grease are removed during primary treatment. Some organic nitrogen, organic phosphorus, and heavy metals associated with solids are also removed during primary sedimentation but colloidal and dissolved constituents are not affected. The effluent from primary sedimentation units is referred to as primary effluent. Table 12 provides information on primary effluent from three sewage treatment plants in California along with data on the raw wastewaters.

Table 12: QUALITY OF RAW WASTEWATER AND PRIMARY EFFLUENT AT SELECTED TREATMENT PLANTS IN CALIFORNIA

Quality parameters (mg/l, except as otherwise indicated)	City of Davis		San Diego		Los Angeles County Joint Plant	
	Raw wastewater	Primary effluent	Raw wastewater	Primary effluent	Raw wastewater	Primary effluent
Biochemical oxygen demand, BOD_5	112	73	184	134	-	204
Total organic carbon	63.8	40.6	64.8	52.3	-	-
Suspended solids	185	72	200	109	-	219
Total nitrogen	43.4	34.7	-	-	-	-
NH_3-N	35.6	26.2	21.0	20.0	-	39.5
NO-N	0	0	-	-	-	-
Org-N	7.8	8.5	-	-	-	14.9
Total phosphorus	-	7.5	-	10.2	-	11.2
Ortho-P	-	7.5	11.2		-	
pH (unit)	7.7	-	7.3	7.3	-	-
Cations:						
Ca	-	-	-	-	78.8	-
Mg	-	-	-	-	25.6	-
Na	-	-	-	-	357	359
K	-	-	-	-	19	19
Anions:						
SO_4	-		160		270	
Cl	-		120		397	
Electrical conductivity, dS/m	2.52	2.34			2.19	-

Total dissolved solids	-	-	829	821	1404	1406
Soluble sodium percentage, %	-		-		70.3	
Sodium adsorption ratio	-	-	-	-	8.85	6.8
Boron (B)	-	-	-	-	1.68	1.5
Alkalinity *($CaCO_3$)*	-	-	-		322	332
Hardness ($CaCO_3$)	-		-		265	

Source: Asano and Tchobanoglous (1987)

In many industrialized countries, primary treatment is the minimum level of preapplication treatment required for wastewater irrigation. It may be considered sufficient treatment if the wastewater is used to irrigate crops that are not consumed by humans or to irrigate orchards, vineyards, and some processed food crops. However, to prevent potential nuisance conditions in storage or flow-equalizing reservoirs, some form of secondary treatment is normally requiredinthese countries, even in the case of non-food crop irrigation. It may be possible to use at least a portion of primary effluent for irrigation if off-line storage is provided.

Primary sedimentation tanks or clarifiers may be round or rectangular basins, typically 3 to 5 m deep, with hydraulic retention time between 2 and 3 hours. Settled solids (primary sludge) are normally removed from the bottom of tanks by sludge rakes that scrape the sludge to a central well from which it is pumped to sludge processing units. Scum is swept across the tank surface by water jets or mechanical means from which it is also pumped to sludge processing units.

In large sewage treatment plants (> 7600 m^3/d in the US), primary sludge is most commonly processed biologically by anaerobic digestion. In the digestion process, anaerobic and facultative bacteria metabolize the organic material in sludge (see Example 3), thereby reducing the volume requiring ultimate disposal, making the sludge stable (nonputrescible) and improving its dewatering characteristics. Digestion is carried out in covered tanks (anaerobic digesters), typically 7 to 14 m deep. The residence time in a digester may vary from a minimum of about 10 days for high-rate digesters (well-mixed and heated) to 60 days or more in standard-rate digesters. Gas containing about 60 to 65% methane is produced during digestion and can be recovered as an energy source. In small sewage treatment plants, sludge is processed in a variety of ways including: aerobic digestion, storage in sludge lagoons, direct application to sludge drying beds, in-process storage (as in stabilization ponds), and land application.

Example 3: Biological treatment biochemistry

3.2.3 Secondary treatment

The objective of secondary treatment is the further treatment of the effluent from primary treatment to remove the residual organics and suspended solids. In most cases, secondary treatment follows primary treatment and involves the removal of biodegradable dissolved and colloidal organic matter using aerobic biological treatment processes. Aerobic biological treatment (see Box) is performed in the presence of oxygen by aerobic microorganisms (principally bacteria) that metabolize the organic matter in the wastewater, thereby producing more microorganisms and inorganic end-products (principally CO_2, NH_3, and H_2O). Several aerobic biological processes are used for secondary treatment differing primarily in the manner in which oxygen is supplied to the microorganisms and in the rate at which organisms metabolize the organic matter.

High-rate biological processes are characterized by relatively small reactor volumes and high concentrations of microorganisms compared with low rate processes. Consequently, the growth rate of new organisms is much greater in high-rate systems because of the well controlled environment. The microorganisms must be separated from the treated wastewater by sedimentation to produce clarified secondary effluent. The sedimentation tanks used in secondary treatment, often referred to as secondary clarifiers, operate in the same basic manner as the primary clarifiers described previously. The biological solids removed during secondary sedimentation, called secondary or biological sludge, are normally combined with primary sludge for sludge processing.

Common high-rate processes include the activated sludge processes, trickling filters or bio filters, oxidation ditches, and rotating biological contactors (RBC). A combination of two of these processes in series (e.g., bio filter followed by activated sludge) is sometimes used to treat municipal wastewater containing a high concentration of organic material from industrial sources.

i. *Activated Sludge*

In the activated sludge process, the dispersed-growth reactor is an aeration tank or basin containing a suspension of the wastewater and microorganisms, the mixed liquor. The contents of the aeration tank are mixed vigorously by aeration devices which also supply oxygen to the biological suspension . Aeration devices commonly used include submerged diffusers that release compressed air and mechanical surface aerators that introduce air by agitating the liquid surface. Hydraulic retention time in the aeration tanks usually ranges from 3 to 8 hours but can be higher with high BOD_5 wastewaters. Following the aeration step, the microorganisms are separated from the liquid by sedimentation and the clarified liquid is secondary effluent. A portion of the biological sludge is recycled to the aeration basin to maintain a high mixed-liquor suspended solids (MLSS) level. The remainder is removed from the process and sent to sludge processing to maintain a relatively constant concentration of microorganisms in the system. Several variations of the basic activated sludge process, such as extended aeration and oxidation ditches, are in common use, but the principles are similar.

ii. *Trickling Filters*

A trickling filter or bio filter consists of a basin or tower filled with support media such as stones, plastic shapes, or wooden slats. Wastewater is applied intermittently, or sometimes continuously, over the media. Microorganisms become attached to the media and form a biological layer or fixed film. Organic matter in the wastewater diffuses into the film, where it is metabolized. Oxygen is normally supplied to the film by the natural flow of air either up or down through the media, depending on the relative temperatures of the wastewater and ambient air. Forced air can also be supplied by blowers but this is rarely necessary. The thickness of the bio film increases as new organisms grow. Periodically, portions of the film 'slough off the media. The sloughed material is separated from the liquid in a secondary clarifier and discharged to sludge processing. Clarified liquid from the secondary clarifier is the secondary effluent and a portion is often recycled to the bio filter to improve hydraulic distribution of the wastewater over the filter.

iii. *Rotating Biological Contactors*

Rotating biological contactors (RBCs) are fixed-film reactors similar to bio filters in that organisms are attached to support media. In the case of the RBC, the support media are slowly rotating discs that are partially submerged in flowing wastewater in the reactor. Oxygen is supplied to the attached bio film from the air when the film is out of the water and from the liquid when submerged, since oxygen is transferred to the wastewater by surface turbulence created by the discs' rotation. Sloughed pieces of bio film are removed in the same manner described for bio filters.

High-rate biological treatment processes, in combination with primary sedimentation, typically remove 85 % of the BOD_5 and SS originally present in the raw wastewater and some of the heavy metals. Activated sludge generally produces an effluent of slightly higher quality, in terms of these constituents, than biofilters or RBCs. When coupled with a disinfection step, these processes can provide substantial but not complete removal of bacteria and virus. However, they remove very little phosphorus, nitrogen, non-biodegradable organics, or dissolved minerals. Data on effluent quality from selected secondary treatment plants in California are presented in Table 13.

<u>Table 13:</u> QUALITY OF SECONDARY EFFLUENT AT SELECTED WASTEWATER TREATMENT PLANTS IN CALIFORNIA

Quality parameter (mg/l except as otherwise indicated)	Plant location	
	Trickling filters	Activated sludge

	Chino Basin MWD (No. 1)	Chino Basin MWD (No. 2)	Santa Rosa Laguna	Montecito Sanitary District
Biochemical oxygen demand, BOD_5	21	8	-	11
Chemical oxygen demand	-	-	27	-
Suspended solids	18	26	-	13
Total nitrogen	-	-	-	-
NH_3-N	25	11	10	1.4
NO_3-N	0.7	19	8	5
Org-N	-	-	1.7	-
Total phosphorus	-	-	12.5	-
Ortho-P	-	-	3.4	-
pH (unit)	-	-	-	7.6
Cations:				
Ca	43	55	41	82
Mg	12	18	18	33
Na	83	102	94	-
K	17	20	11	-
Anions:				
HCO_3	293	192	165	-
SO_4	85	143	66	192
Cl	81	90	121	245
Electrical conductivity dS/m	-	-	-	1.39
Total dissolved solids	476	591	484	940
Sodium adsorption ratio	2.9	3.1	3.9	3.7
Boron (B)	0.7	0.6	0.6	0.7
Alkalinity ($CaCO_3$)	-	-	-	226
Total Hardness ($CaCO_3$)	156	200	175	265

Source: Asano and Tchobanoglous (1987)

3.2.4 Tertiary and/or advanced treatment

Tertiary and/or advanced wastewater treatment is employed when specific wastewater constituents which cannot be removed by secondary treatment must be removed. Individual treatment processes are necessary to remove nitrogen, phosphorus, additional suspended solids, refractory organics, and heavy metals and dissolved solids. Because advanced treatment usually follows high-rate secondary treatment, it is sometimes referred to as tertiary treatment. However, advanced treatment processes are sometimes combined with primary or secondary treatment (e.g., chemical addition to primary clarifiers or aeration basins to remove phosphorus) or used in place of secondary treatment (e.g., overland flow treatment of primary effluent).

An adaptation of the activated sludge process is often used to remove nitrogen and phosphorus and an example of this approach is the 23 Ml/d treatment plant commissioned in 1982 in British Columbia, Canada (World Water 1987). The Bardenpho Process adopted is shown in simplified form in Figure 6. Effluent from primary clarifiers flows to the biological reactor, which is physically divided into five zones by baffles and weirs. In sequence these zones are: (i) anaerobic fermentation zone (characterized by very low dissolved oxygen levels and the absence of nitrates); (ii) anoxic zone (low dissolved oxygen levels but nitrates present); (iii) aerobic zone (aerated); (iv) secondary anoxic zone; and (v) final aeration zone. The function of the first zone is to condition the group of bacteria responsible for phosphorus removal by stressing them under low oxidation-reduction conditions, which results in a release of phosphorus equilibrium in the cells of the bacteria. On subsequent exposure to an adequate supply of oxygen and phosphorus in the aerated zones, these cells rapidly accumulate phosphorus considerably in excess of their normal metabolic requirements. Phosphorus is removed from the system with the waste activated sludge.

Figure 6: Simplified flow diagram of Bardenpho-plant (World Water 1987)

Most of the nitrogen in the influent is in the ammonia form, and this passes through the first two zones virtually unaltered. In the third aerobic zone, the sludge age is such that almost complete nitrification takes place, and the ammonia nitrogen is converted to nitrites and then to nitrates. The nitrate-rich mixed liquor is then recycled from the aerobic zone back to the first anoxic zone. Here denitrification occurs, where the recycled nitrates, in the absence of dissolved oxygen, are reduced by facultative bacteria to nitrogen gas, using the influent organic carbon compounds as hydrogen donors. The nitrogen gas merely escapes to atmosphere. In the second anoxic zone, those nitrates which were not recycled are reduced by the endogenous respiration of bacteria. In the final re-aeration zone, dissolved oxygen levels are again raised to prevent further denitrification, which would impair settling in the secondary clarifiers to which the mixed liquor then flows.

An experimentation programme on this plant demonstrated the importance of the addition of volatile fatty acids to the anaerobic fermentation zone to achieve good phosphorus removal. These essential short-chain organics (mainly acetates) are produced by the controlled fermentation of primary sludge in a gravity thickener and are released into the thickener supernatent, which can be fed to the head of the biological reactor. Without this supernatent return flow, overall phosphorus removal quickly dropped to levels found in conventional activated sludge plants. Performance data over three years have proved that, with thickener supernatent recycle, effluent quality median values of 0.5-1.38 mg/l Ortho-P, 1.4-1.6 mg/l

Total nitrogen and 1.4-2.0 mg/l nitrate-N are achievable. This advanced biological wastewater treatment plant cost only marginally more than a conventional activated sludge plant but nevertheless involved considerable investment. Furthermore, the complexity of the process and the skilled operation required to achieve consistent results make this approach unsuitable for developing countries.

In many situations, where the risk of public exposure to the reclaimed water or residual constituents is high, the intent of the treatment is to minimize the probability of human exposure to enteric viruses and other pathogens. Effective disinfection of viruses is believed to be inhibited by suspended and colloidal solids in the water, therefore these solids must be removed by advanced treatment before the disinfection step. The sequence of treatment often specified in the United States is: secondary treatment followed by chemical coagulation, sedimentation, filtration, and disinfection. This level of treatment is assumed to produce an effluent free from detectable viruses. Effluent quality data from selected advanced wastewater treatment plants in California are reported in Table 14. In Near East countries adopting tertiary treatment, the tendency has been to introduce pre-chlorination before rapid-gravity sand filtration and post-chlorination afterwards. A final ozonation treatment after this sequence has been considered in at least one country.

3.2.5 Disinfection

Disinfection normally involves the injection of a chlorine solution at the head end of a chlorine contact basin. The chlorine dosage depends upon the strength of the wastewater and other factors, but dosages of 5 to 15 mg/l are common. Ozone and ultra violet (uv) irradiation can also be used for disinfection but these methods of disinfection are not in common use. Chlorine contact basins are usually rectangular channels, with baffles to prevent short-circuiting, designed to provide a contact time of about 30 minutes. However, to meet advanced wastewater treatment requirements, a chlorine contact time of as long as 120 minutes is sometimes required for specific irrigation uses of reclaimed wastewater. The bactericidal effects of chlorine and other disinfectants are dependent upon pH, contact time, organic content, and effluent temperature.

3.2.6 Effluent storage

Although not considered a step in the treatment process, a storage facility is, in most cases, a critical link between the wastewater treatment plant and the irrigation system. Storage is needed for the following reasons:

i. To equalize daily variations in flow from the treatment plant and to store excess when average wastwater flow exceeds irrigation demands; includes winter storage.

ii. To meet peak irrigation demands in excess of the average wastewater flow.

iii. To minimize the effects of disruptions in the operations of the treatment plant and irrigation system. Storage is used to provide insurance against the possibility of unsuitable reclaimed wastewater entering the irrigation system and to provide additional time to resolve temporary water quality problems.

Table 14: EFFLUENT QUALITY DATA FROM SELECTED ADVANCED WASTEWATER TREATMENT PLANTS IN CALIFORNIA[1]

Quality parameter (mg/l except as otherwise indicated)	Plant location					
	Long Beach	Los Coyotes	Pomona	Dublin San Ramon	City of Livermore	Simi Valley CSD
Biochemical oxygen demand, BOD_5	5	9	4	2	3	4
Suspended solids	-	5	-	1	-	-
Total nitrogen	-	-	-	-	-	19
NH_3-N	3.3	13.6	11.4	0.1	1.0	16.6
NO_3-N	15.4	1.1	3	19.0	21.3	0.4
Org-N	2.2	2.5	1.3	0.2	2.6	2.3
Total phosphorus	-	-	-	-	-	-
Ortho-P	30.8	23.9	21.7	28.5	16.5	-
pH (unit)	-	-	-	6.8	7.1	-
Oil and grease	-	-	-	-	-	3.1
Total coliform bacteria, MPN/100 ml	-	-	-	2	4	-
Cations:						
Ca	54	65	58	-	-	-
Mg	17	18	14	-	-	-
Na	186	177	109	168	178	-
K	16	18	12	-	-	-
Anions:						
SO_4	212	181	123	-	-	202
Cl	155	184	105	147	178	110
Electrical conductivity, dS/m	1.35	1.44	1.02	1.27	1.25	-
Total dissolved solids	867	827	570	-	-	585
Soluble sodium, %	63.2	59.2	51.7	-	-	-
Sodium adsorption ratio	5.53	4.94	3.37	4.6	5.7	-
Boron (B)	0.95	0.95	0.66	-	1.33	0.6
Alkalinity ($CaCO_3$)	-	256	197	150	-	-
Total Hardness ($CaCO_3$)	212	242	206	254	184	-

[1]Advanced wastewater treatment in these plants follows high rate secondary treatment and includes addition of chemical coagulants (alum + polymer) as necessary followed by filtration through sand or activated carbon granular medium filters.

iv. To provide additional treatment. Oxygen demand, suspended solids, nitrogen, and microorganisms are further reduced during storage.

3.2.7 Reliability of conventional and advanced wastewater treatment

Wastewater reclamation and reuse systems should contain both design and operational requirements necessary to ensure reliability of treatment. Reliability features such as alarm systems, standby power supplies, treatment process duplications, emergency storage or disposal of inadequately treated wastewater, monitoring devices, and automatic controllers are important. From a public health standpoint, provisions for adequate and reliabile disinfection are the most essential features of the advanced wastewater treatment process. Where disinfection is required, several reliability features must be incorporated into the system to ensure uninterrupted chlorine feed.

3.3 Natural biological treatment systems

Natural low-rate biological treatment systems are available for the treatment of organic wastewaters such as municipal sewage and tend to be lower in cost and less sophisticated in operation and maintenance. Although such processes tend to be land intensive by comparison with the conventional high-rate biological processes already described, they are often more effective in removing pathogens and do so reliably and continuously if properly designed and not overloaded. Among the natural biological treatment systems available, stabilization ponds and land treatment have been used widely around the world and a considerable record of experience and design practice has been documented. The nutrient film technique is a fairly recent development of the hydroponic plant growth system with application in the treatment and use of wastewater.

3.3.1 Wastewater stabilization ponds

A recent World Bank Report (Shuval *et al.* 1986) came out strongly in favour of stabilization ponds as the most suitable wastewater treatment system for effluent use in agriculture. Table 15 provides a comparison of the advantages and disadvantages of ponds with those of high-rate biological wastewater treatment processes. Stabilization ponds are the preferred wastewater treatment process in developing countries, where land is often available at reasonable opportunity cost and skilled labour is in short supply.

Table 15: ADVANTAGES AND DISADVANTAGES OF VARIOUS SEWAGE TREATMENT SYSTEMS

	Criteria	Package plant	Activated sludge plant	Extended aeration activated sludge	Biological filter	Oxidation ditch	Aerated lagoon	Waste stabilization pond system
Plant performance	BOD removal	F	F	F	F	G	G	G
	FC removal	P	P	F	P	F	G	G
	SS removal	F	G	G	G	G	F	F
	Helminth removal	P	F	P	P	F	F	G
	Virus removal	P	F	P	P	F	G	G
Economic factors	Simple and cheap construction	P	P	P	P	F	F	G
	Simple operation	P	P	P	F	F	P	G
	Land requirement	G	G	G	G	G	F	P
	Maintenance costs	P	P	P	F	P	P	G
	Energy demand	P	P	P	F	P	P	G
	Sludge removal costs	P	F	F	F	P	F	G

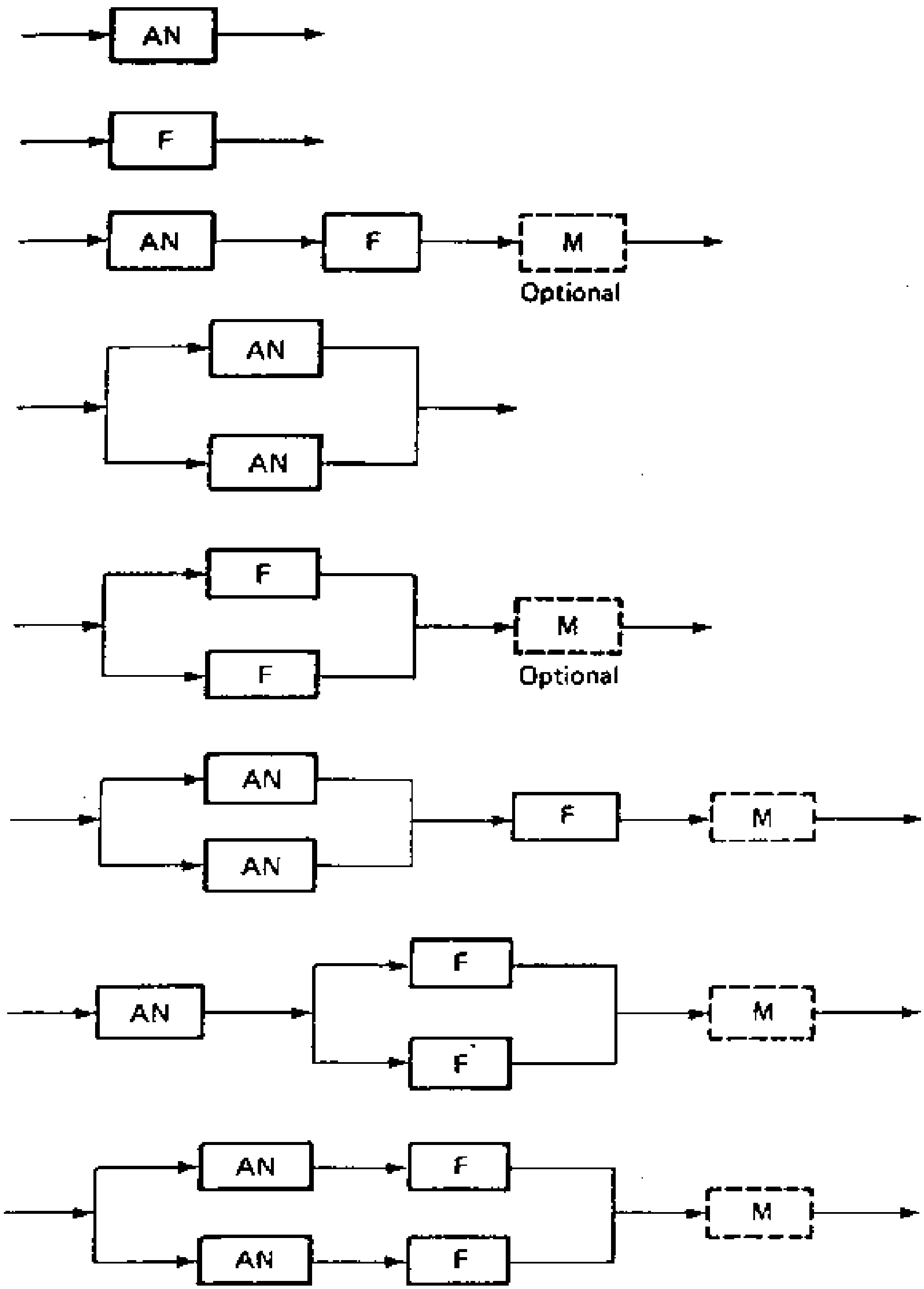
Key:

FC = Faecal coliforms;
SS = Suspended slids;
G = Good;
F = Fair;
P = Poor.

Source: Arthur (1983)

Wastewater stabilization pond systems are designed to achieve different forms of treatment in up to three stages in series, depending on the organic strength of the input waste and the effluent quality objectives. For ease of maintenance and flexibility of operation, at least two trains of ponds in parallel are incorporated in any design. Strong wastewaters, with BOD_5 concentration in excess of about 300 mg/l, will frequently be introduced into first-stage anaerobic ponds, which achieve a high volumetric rate of removal. Weaker wastes or, where anaerobic ponds are environmentally unacceptable, even stronger wastes (say up to 1000 mg/l BOD_5) may be discharged directly into primary facultative ponds. Effluent from first-stage anaerobic ponds will overflow into secondary facultative ponds which comprise the second-stage of biological treatment. Following primary or secondary facultative ponds, if further pathogen reduction is necessary maturation ponds will be introduced to provide tertiary treatment. Typical pond system configurations are given in Figure 7.

Figure 7: Stabilization pond configurations AN = anaerobic pond; F = facultative pond; M = maturation pond (Pescod and Mara 1988)



i. *Anaerobic Ponds*

Anaerobic ponds are very cost effective for the removal of BOD, when it is present in high concentration. Normally, a single, anaerobic pond in each treatment train is sufficient if the strength of the influent wastewater, L_i is less than 1000 mg/l BOD_5. For high strength industrial wastes, up to three anaerobic ponds in series might be justifiable but the retention time t_{an}, in any of these ponds should not be less than 1 day (McGarry and Pescod, 1970).

Anaerobic conditions in first-stage stabilization ponds are created by maintaining a high volumetric organic loading, certainly greater than 100g BOD_5/m^3 d. Volumetric loading, l_v, is given by:

(2)

$$\lambda = \frac{L_i Q}{V}$$

where:

L_i = Influent BOD_5, mg/l,
Q = Influent flow rate, m^3/d, and
V = Pond volume, m^3

or, since V/Q = t_{an}, the retention time:

(3)

$$\lambda_v = \frac{L_i}{t_{an}}$$

Very high loadings, up to 1000g BOD_5/m^3d, achieve efficient utilization of anaerobic pond volume but, with wastewater containing sulphate concentrations in excess of 100 mg/l, the production of H_2S is likely to cause odour problems. In the case of typical municipal sewage, it is generally accepted that a maximum anaerobic pond loading of 400g BOD_5/m^3d will prevent odour nuisance (Meiring et al. 1968).

Table 16: BOD REMOVALS IN ANAEROBIC PONDS LOADED AT 250 g BOD_5/m^3d

Retention t_{an} days	BOD_5 removal %
1	50
2.5	60
5	70

Source: Mara (1976)

Anaerobic ponds normally have a depth between 2m and 5m and function as open septic tanks with gas release to the atmosphere. The biochemical reactions which take place in anaerobic ponds are the same as those occurring in anaerobic digesters, with a first phase of acidogenesis and a second slower-rate of methanogenesis (see Example 3). Ambient temperatures in hot-climate countries are conducive to these anaerobic reactions and expected BOD_5 removals for different retention times in treating sewage have been given by Mara (1976) as shown in Table 16. More recently, Gambrillet al. (1986) have suggested conservative removals of BOD_5 in anaerobic ponds as 40% below 10°C, at a design loading, l_v,of 100 g/m³d, and 60% above 20°C, at a design loading of 300 g/m³d, with linear interpolation for operating temperature between 10 and 20°C. Higher removal rates are possible with industrial wastes, particularly those containing significant quantities of organic settleable solids. Of course, other environmental conditions in the ponds, particularly pH, must be suitable for the anaerobic microorganisms bringing about the breakdown of BOD.

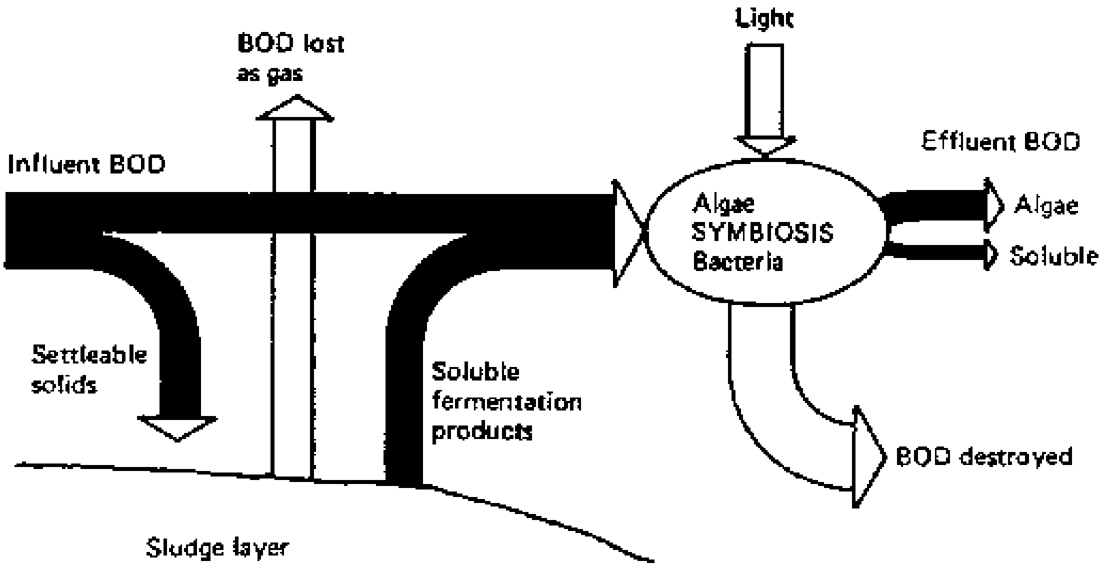
In certain instances, anaerobic ponds become covered with a thick scum layer, which is thought to be beneficial but not essential, and may give rise to increased fly breeding. Solids in the raw wastewater, as well as biomass produced, will settle out in first-stage anaerobic ponds and it is common to remove sludge when it has reached half depth in the pond. This usually occurs after two years of operation at design flow in the case of municipal sewage treatment.

ii. *Facultative Ponds*

The effluent from anaerobic ponds will require some form of aerobic treatment before discharge or use and facultative ponds will often be more appropriate than conventional forms of secondary biological treatment for application in developing countries. Primary facultative ponds will be designed for the treatment of weaker wastes and in sensitive locations where anaerobic pond odours would be unacceptable. Solids in the influent to a facultative pond and excess biomass produced in the pond will settle out forming a sludge layer at the bottom. The benthic layer will be anaerobic and, as a result of anaerobic breakdown of organics, will release soluble organic products to the water column above.

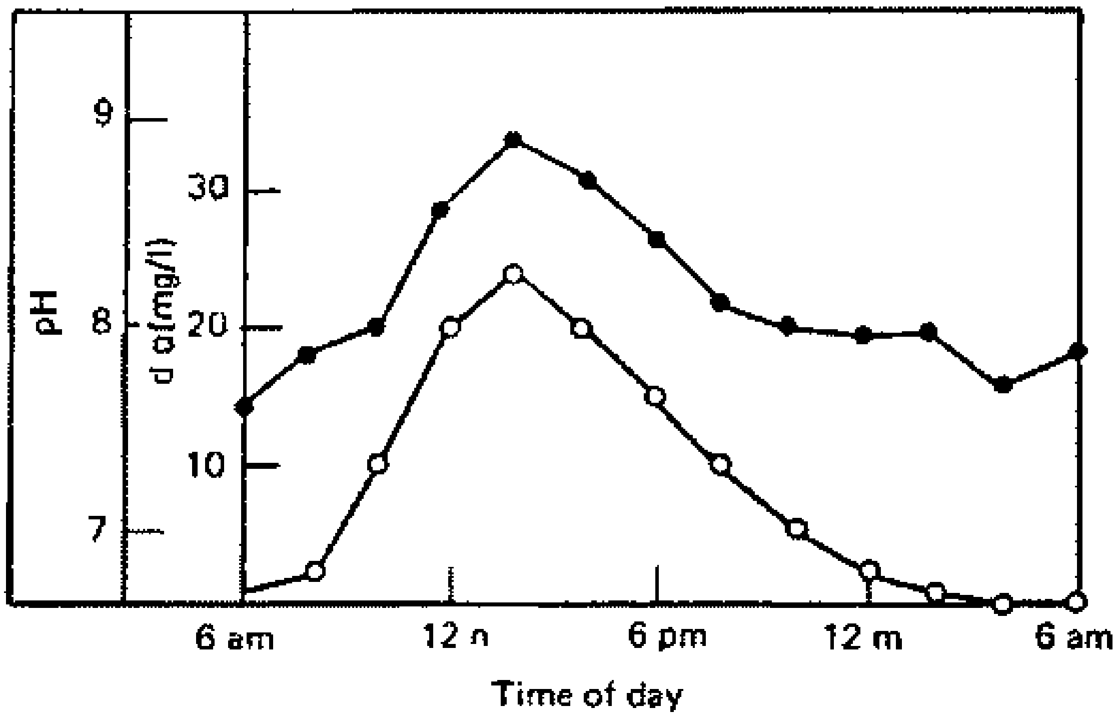
Organic matter dissolved or suspended in the water column will be metabolized by heterotrophic bacteria, with the uptake of oxygen, as in convential aerobic biological wastewater treatment processes. However, unlike in convential processes, the dissolved oxygen utilized by the bacteria in facultative ponds is replaced through photosynthetic oxygen production by microalgae, rather than by aeration equipment. Especially intreating municipal sewage in hot climates, the environment in facultative ponds is ideal for the proliferation of microalgae. High temperature and ample sunlight create conditions which encourage algae to utilize the carbon dioxide (CO_2) released by bacteria in breaking down the organic components of the wastewater and take up nutrients (mainly nitrogen and phosphorus) contained in the wastewater. This symbiotic relationship contributes to the overall removal of BOD in facultative ponds, described diagrammatically by Marais (1970) as in Figure 8.

Figure 8: Energy flows in facultative stabilization ponds (Marais 1970)



To maintain the balance necessary to allow this symbiosis to persist, the organic loading on a facultative pond must be strictly limited. Even under satisfactory operating conditions, the dissolved oxygen concentration (DO) in a facultative pond will vary diurnally as well as over the depth. Maximum DO will occur at the surface of the pond and will usually reach supersaturation in tropical regions at the time of maximum radiation intensity, as shown in Figure 9. From that time until sunrise, DO will decline and may well disappear completely for a short period. For a typical facultative pond depth, D_f, of 1.5m the water column will be predominantly aerobic at the time of peak radiation and predominantly anaerobic at sunrise. As illustrated in Figure 9, the pH of the pond contents will also vary diurnally as algae utilize CO_2 throughout daylight hours and respire, along with bacteria and other organisms, releasing CO_2 during the night.

Figure 9: Diurnal variation of dissolved oxygen and pH in facultative pond, pH: ·, dissolved oxygen: o (Pescod and Mara 1988)



Wind is considered important to the satisfactory operation of facultative ponds by mixing the contents and helping to prevent short-circuiting. Intimate mixing of organic substrate and the degrading organisms is important in any biological reactor but in facultative ponds wind mixing is considered essential to prevent thermal stratification causing anaerobiosis and failure. Facultative ponds should be orientated with the longest dimension in the direction of the prevailing wind.

Although completely-mixed reactor theory with the assumption of first-order kinetics for BOD removal can be adopted for facultative pond design (Marais and Shaw, 1961), such a fundamental approach is rarely adopted in practice. Instead, an empirical procedure based on operational experience is more common. The most widely adopted design method currently being applied wherever local experience is limited is that introduced by McGarry and Pescod (1970).

A regression analysis of operating data on ponds around the world relating maximum surface organic loading, in lb/acre d, to the mean ambient air temperature, in °F, of the coldest month resulted in the following equation (now converted to metric units):

(4)

$$\lambda_{s(max)} = 60.3\,(1.099)^{T}$$

where:

l_s = surface or arael organic loading, kg BOD_5/ha.d
T = mean ambient air temperature of coldest month, °C

Subsequently, Arthur (1983) modified this formula and suggested that best agreement with available operating data, including a factor of safety of about 1.5, is represented by the relationship:

(5)

$$\lambda_s = 20T - 60$$

This surface (or areal) BOD_5 loading can be translated into a mid-depth facultative pond area requirement (A_f in m^2) using the formula:

(6)

$$A_f = \frac{10 L_i Q}{\lambda_s}$$

Thus:

(7)

$$A_f = \frac{L_i Q}{2T - 6}$$

and the mean hydraulic retention time in the facultative pond (t_f in days) is given by:

(8)

$$t_f = \frac{A_f D_f}{Q}$$

The removal of BOD_5 in facultative ponds (l_r in kg/ha d) is related to BOD_5 loading and usually averages 70-80% of l_s. Retention time in a properly designed facultative pond will normally be 20-40 days and, with a depth of about 1.5m, the area required will be signficantly greater than for an anaerobic pond. The effluent from a facultative pond treating municipal sewage in the tropics will normally have a BOD_5 between 50 and 70 mg/l as a result of the suspended algae. On discharge to a surface water, this effluent will not cause problems downstream if the dilution is of the order of 8:1 and any live algae in the effluent might well be beneficial as a result of photo synthetic oxygen production during daylight hours.

Efficiently operating facultative ponds treating wastewater will contain a mixed population of flora but flagellate algal genera such as Chlamydomonas, Euglena, Phacus and Pyrobotrys will predominate. Non-motile forms such as Chlorella, Scenedesmus and various diatom species will be present in low concentrations unless the pond is underloaded. Algal stratification often occurs in facultative ponds, particularly in the absence of wind-induced mixing, as motile forms respond to changes in light intensity and move in a band up and down the water column. The relative numbers of different genera and their dominance in a facultative pond vary from season to season throughout the year but species diversity generally decreases with increase in loading. Sometimes, mobile purple sulphur bacteria appear when facultative ponds are overloaded and sulphide concentration increases, with the danger of odour production. High ammonia concentrations also bring on the same problem and are toxic to algae, especially above pH 8.0.

Maintenance of properly designed facultative ponds will be limited to the removal of scum mats, which tend to accumulate in downwind corners, and the cutting of grass on embankments. To ensure efficient operation, facultative ponds should be regularly monitored but, even where this is not possible, they have the reputation of being relatively trouble-free.

iii. *Maturation Ponds*

The effluent from facultative ponds treating municipal sewage or equivalent input wastewater will normally contain at least 50 mg/l BOD_5 and if an effluent with lower BOD_5 concentration is required it will be necessary to use maturation ponds. For sewage treatment, two maturation ponds in series, each with a retention time of 7 days, have been found necessary to produce a final effluent with $BOD_5 < 25$ mg/l when the facultative pond effluent had a $BOD_5 < 75$ mg/l.

A more important function of maturation ponds, however, is the removal of excreted pathogens to achieve an effluent quality which is suitable for its downstream reuse. Although the longer retention in anaerobic and facultative pond systems will make them more efficient than conventional wastewater treatment processes in removing pathogens, the effluent from a facultative pond treating municipal sewage will generally require further treatment in maturation ponds to reach effluent standards imposed for reuse in unrestricted irrigation. Faecal coliform bacteria are commonly used as indicators of excreted pathogens and maturation ponds can be designed to achieve a given reduction of faecal coliforms (FC). Protozoan cysts and helminth ova are removed by sedimentation in stabilization ponds and a series of ponds with overall retention of 20 days or more will produce an effluent totally free of cysts and ova (Feachem*et al.* 1983).

Reduction of faecal coliform bacteria in any stabilization pond (anaerobic, facultative and maturation) is generally taken as following first-order kinetics:

(9)

$$N_e = \frac{N_i}{1 + K_b t}$$

where:

N_e = Number of faecal coliforms/100 ml of effluent
N_i = Number of faecal coliforms/100 ml of influent
K_b = First-order rate constant for FC removal, d^{-1}
t = Retention time in any pond, d

For n ponds in series, Eq 8 becomes:

(10)

$$N_e = \frac{N_i}{(1 + K_b t_{an})(1 + K_b t_f)(1 + k_b t_{m_1}) \cdots (1 + k_b t_{m_n})}$$

Where:

$t_{m\,n}$ = Retention time in the nth maturation pond.

The value of KB is extremely sensitive to temperature and was shown by Marais (1974) to be given by:

(11)

$$K_{b(T)} = 2.6\,(1.19)^{T-20}$$

where:

$K_{b(T)}$ = value of KB at T°C

A suitable design value of N_i in the case of municipal sewage treatment is 1 x 10^8 faecal coliforms/100ml, which is slightly higher than average practical levels.

The value of N_e should be obtained by substituting the appropriate levels of variables in Eq 10 assuming a retention time of 7 days in each of two maturation lagoons (for sewage). If the calculated value of N_e does not meet the reuse effluent standard, the number of maturation ponds should be increased, say to three or more each with retention time 5 days, and N_e recalculated. A more systematic approach is now available whereby the optimum design for maturation ponds can be obtained using a simple computer programme (Gambrill*et al.* 1986).

Polprasert*et al.* (1983) have published an approach to the assessment of bacterial die-off which attempts to take into account the complex physical characteristics of ponds and biochemical reactions taking place in them. A multiple-regression equation involving parameters such as retention time, organic loading, algal concentration and ultra-violet light exposure has been suggested. The Wehner and Wilhelm (1956) non-ideal flow equation, including the pond dispersion number, was adopted to predict bacterial survival, in preference to the first order rate equation (Eq 9 and 10).

Maturation ponds will be aerobic throughout the water column during daylight hours and the pH will rise above 9.0. The algal population of many species of non-flagellate unicellular and colonial forms will be distributed over the full depth of a maturation pond. Large numbers of filamentous algae, particularly blue-greens, will emerge under very low BOD loading conditions. Very low concentrations of algae in a maturation pond will indicate excessive algal predation by zooplankton, such as Daphnia sp, and this will have a deleterious effect on pathogen die-off, which is linked to algal activity.

Saqqar (1988), in his analysis of the performance of the Al Samra stabilization ponds in Amman, Jordan, has shown that the coliform and faecal coliform die-off coefficients varied with retention time, water temperature, organic loading, total BOD_5 concentration, pH and pond depth. Total coliform die-off was less than the rate of faecal coliform die-off, except during the cold season. For the series of ten ponds, including at least the first five totally anaerobic, the faecal coliform die-off coefficient, k, for the temperature range 12 - 15°C increased through the pond sequence from 0.11 per day in the first anaerobic pond to 0.68 per day in the final two ponds, which operated as facultative ponds.

3.3.2 Overland treatment of wastewater

Apart from the use of effluent for irrigation of crops, termed 'slow rate' land treatment in the US Environmental Protection Agency's Process Design Manual for Land Treatment of Municipal Wastewaters (EPA 1977), and 'rapid infiltration' or 'infiltration percolation' of effluent discussed as soil-aquifer treatment in a later section of this document, the EPA manual deals with 'overland flow' as a wastewater treatment method. In overland flow treatment, effluent is distributed over gently sloping grassland on fairly impermeable soils. Ideally, the wastewater moves evenly down the slope to collecting ditches at the bottom edge of the area and water-tolerant grasses are an essential component of the system.

This form of land treatment requires alternating applications of effluent (usually treated) and resting of the land, to allow soil reaction and grass cutting. The total area utilized is normally broken up into small plots to allow this form of intermittent operation and yet achieve continuous treatment of the flow of wastewater. Although this type of land treatment has been widely adopted in Australia, New Zealand and the UK for tertiary upgrading of secondary effluents, it has been used for the treatment of primary effluent in Werribee, Australia and is being considered for the treatment of raw sewage in Karachi, Pakistan.

Table 17: SITE CHARACTERISTICS AND DESIGN FEATURES FOR OVERLAND FLOW TREATMENT OF WASTEWATER

Grade	Finished slope 2-8%
Field area required (ha)	6.55-44
Soil permeability	Slow (clays, silts and soils with impermeable barriers)
Annual application rate (m)	3-20
Typical weekly application rate (cm)	6-40

Source: EPA (1977)

Basic site characteristics and design features for overland flow treatment have been suggested by EPA (1977) as shown in Table 17. It was pointed out that steeper land slopes might be feasible at reduced hydraulic loadings. The ranges given for field area required and application rates cover the wastewater quality from raw sewage to secondary effluent, with higher application rates and lower land area requirements being associated with higher levels of preapplication treatment. Although soil permeability is not critical with this form of land treatment, the impact on groundwater should not be overlooked in the case of highly permeable soils.

The application rate for wastewaters will depend principally on the type of soil, the quality of wastewater effluent and the physical and biochemical activity in the near-surface environment. Rational design procedures, based on the kinetics of BOD removal, have been developed for overland flow systems by Middlebrooks *et al.* (1982). Slope lengths from 30 - 60 m are common in the US for overland flow systems.

The cover crop is an important component of the overland flow system since it prevents soil erosion, provides nutrient uptake and serves as a fixed-film medium for biological treatment. Crops best suited to overland flow treatment are grasses with a long growing season, high moisture tolerance and extensive root formation. Reed canary grass has a very high nutrient uptake capacity and yields a good quality hay; other suitable grasses include rye grass and tall fescue.

Suspended and colloidal organic materials in the wastewater are removed by sedimentation and filtration through surface grass and organic layers. Removal of total nitrogen and ammonia is inversely related to application rate, slope length and soil temperature. Phosphorus and trace elements removal is by sorption on soil clay colloids and precipitation as insoluble complexes of calcium, iron and aluminium. Overland flow systems also remove pathogens from sewage effluent at levels comparable with conventional secondary treatment systems, without chlorination. A monitoring programme should always be incorporated into the design of overland flow projects both for wastewater and effluent quality and for application rates.

3.3.3 Macrophyte treatment

Maturation ponds which incorporate floating, submerged or emergent aquatic plant species are termed *macrophyte ponds* and these have been used in recent years for upgrading effluents from stabilization ponds. Macrophytes take up large amounts of inorganic nutrients (especially N and P) and heavy metals (such as Cd, Cu, Hg and Zn) as a consequnce of the growth requirements and decrease the concentration of algal cells through light shading by the leaf canopy and, possibly, adherence to gelatinous biomass which grows on the roots.

Floating macrophyte systems utilizing water hyacinth and receiving primary sewage effluent in Florida have achieved secondary treatment effluent quality with a 6 day hydraulic retention time, water depth of 60 cm and hydraulic loading 1860 m^3/ha d (Reddy and Debusk 1987). The same authors suggested that similar results had also been observed for artificial wetlands using emergent macrophytes. In Europe, the land area considered to be necessary for treatment of preliminary-treated sewage is estimated at 2-5 m^2 per population equivalent to achieve a secondary effluent quality (Cooper et al. 1988).

i. *Floating Aquatic Macrophyte Systems*

Floating macrophyte species, with their large root systems, are very efficient at nutrient stripping. Although several genera have been used in pilot schemes, including *Salvinia, Spirodella, Lemna* and *Eichornia* (O'Brien 1981), *Eichorniacrassipes* (water hyacinth) has been studied in much greater detail. In tropical regions, water hyacinth doubles in mass about every 6 days and a macrophyte pond can produce more than 250 kg/ha d (dry weight). Nitrogen and phosphorus reductions up to 80% and 50% have been achieved. In Tamil Nadu, India, studies have indicated that the coontail, *Ceratophyllumdemersum,* a submerged macrophyte, is very efficient at removing ammonia (97%) and phosphorus (96%) from raw sewage and also removes 95% of the BOD_5. It has a lower growth rate than *Eichorniacrassipes,* which allows less frequent harvesting.

In such macrophyte pond systems, apart from any physical removal processes which might occur (especially sedimentation) the aquatic vascular plants serve as living substrates for microbial activity, which removes BOD and nitrogen, and achieves reductions in phosphorus, heavy metals and some organics through plant uptake. The basic function of the macrophytes in the latter mechanism is to assimilate, concentrate and store contaminants on a short-term basis. Subsequent harvest of the plant biomass results in permanent removal of stored contaminents from the pond treatment system. Potential growth rates of selected aquatic macrophytes cultured in nutrient water are given in Table 18.

The nutrient assimilation capacity of aquatic macrophytes is directly related to growth rate, standing crop and tissue composition. The potential rate of pollutant storage by an aquatic plant is limited by the growth rate and standing crop of biomass per unit area. Water hyacinth, for example, was found to reach a standing crop level of 30 tonnes (dry weight)/ha in Florida, resulting in a maximum storage of 900 kg N/ha and 180 kg P/ha (Reddy and De Busk 1987).

Fly and mosquito breeding is a problem in floating macrophyte ponds but this can be partially alleviated by introducing larvae-eating fish species such as *Gambusia* and *Peocelia* into the ponds. It should be recognized that pathogen die-off is poor in macrophyte ponds as a result of light shading and the lower dissolved oxygen and pH compared with algal maturation ponds. In their favour, macrophyte ponds can serve a useful purpose in stripping pond effluents of nutrients and algae and at the same time produce a harvestable biomass. Floating macrophytes are fairly easily collected by floating harvesters. The harvested plants might be fed to cattle, used as a green manure in agriculture, composted aerobically to produce a fertilizer and soil conditioner, or can be converted into biogas in an anaerobic digester, in which case the residual sludge can then be applied as a fertilizer and soil conditioner (UN Economic and Social Commission for Asia and the Pacific 1981). Maximum removal by water hyacinth was 5850 kg N/ha year, compared with 1200 kg N/ha year by duckweed.

ii. *EmergentMacrophyte Treatment Systems*

In recent years, natural and artificial wetlands and marshes have been used to treat raw sewage and partially-treated effluents. Natural wetlands are usually unmanaged, whereas artificial systems are specially designed to maximize performance by providing the optimum conditions for emergent macrophyte growth. The key features of such reed bed treatment systems are:

- Rhizomes of the reeds grow vertically and horizontally in the soil or gravel bed, opening up 'hydraulic pathways'.

- Wastewater BOD and nitrogen are removed by bacterial activity; aerobic treatment takes place in the rhizosphere, with anoxic and anaerobic treatment taking place in the surrounding soil.

- Oxygen passes from the atmosphere to the rhizosphere via the leaves and stems of the reeds through the hollow rhizomes and out through the roots.

- Suspended solids in the sewage are aerobically composted in the above-ground layer of vegetation formed from dead leaves and stems.

- Nutrients and heavy metals are removed by plant uptake.

The growth rate and pollutant assimilative capacity of emergent macrophytes such as *Phragmitescommunis and Scirpuslacstris* are limited by the culture system, wastewater loading rate, plant density, climate and management factors.

Growth rates for emergent macrophytes are also provided in Table 18 as well as nutrient contents. High tissue N concentrations have been found in plants cultured in nutrient enriched (wastewater) systems and in plants analyzed in the early stages of growth. Maximum storage of nutrients by emergent macrophytes was found to be in the range 200-1560 kg N/ha and 40-375 kg P/ha in Florida (Reddy and DeBusk 1987). More than 50 percent of the nutrients were stored in below-ground portions of the plants, tissues difficult to harvest to achieve effective nutrient removal. However, because emergent macrophytes have more supportive tissue than floating macrophytes, they might have greater potential for storing the nutrients over a longer period. Consequently, frequent harvesting might not be so necessary to achieve maximum nutrient removal although harvesting above-ground biomass once a year should improve overall nutrient removal efficiency.

Table 18: GROWTH AND NUTRIENT (N & P) CONTENTS OF SELECTED MACROPHYTES

	Biomass		Tissue composition	
	Standing crop	Growth rates	N	P
	t (dw) ha^{-1}	t ha^{-1} yr^{-1}	--- g kg^{-1} ---	
FLOATING MACROPHYTES:				
Eichhorniacrasspipes (water hyacinth)	20.0-24.0	60-110	10-40	1.4-12.0
Pistiastratiotes (water lettuce)	6.0-10.5	50-80	12-40	1.5-11.5
Hydrocotyle spp. (pennywort)	7.0-11.0	30-60	15-45	2.0-12.5
Alternanthera spp. (alligator weed)	18.0	78	15-35	2.0-9.0
Lemna spp. (duckweed)	1.3	6-26	25	4.0-15.0
Salvinia spp.	2.4-3.2	9-45		1.8-9.0
EMERGENT MACROPHYTES:				
Typha (cattail)	4.3-22.5	8-61	5-24	0.5-4.0
Juncus (rush)	22.0	53	15	2.0
Scirpus (bulrush)			8-27	1.0-3.0
Phragmites (reed)	6.0-35.0	10-60	18-21	2.0-3.0
Eleocharis (spike rush)	8.8	26	9-18	1.0-3.0
Saururuscernuus (lizardis tail)	4.5-22.5	-	15-25	1.0-5.0

Source: Reddy and De Busk (1987)

3.3.4 Nutrient film technique

The nutrient film technique (NFT) is a modification of the hydroponic plant growth system in which plants are grown directly on an impermeable surface to which a thin film of wastewater is continuously applied (Figure 10). Root production on the impermeable surface is high and the large surface area traps and accumulates matter. Plant top-growth provides nutrient uptake, shade for protection against algal growth and water removal in the form of transpiration, while the large mass of self-generating root systems and accumulated material serve as living filters. Jewell et al. (1983) have hypothesized the following mechanisms, taking place in three plant sections:

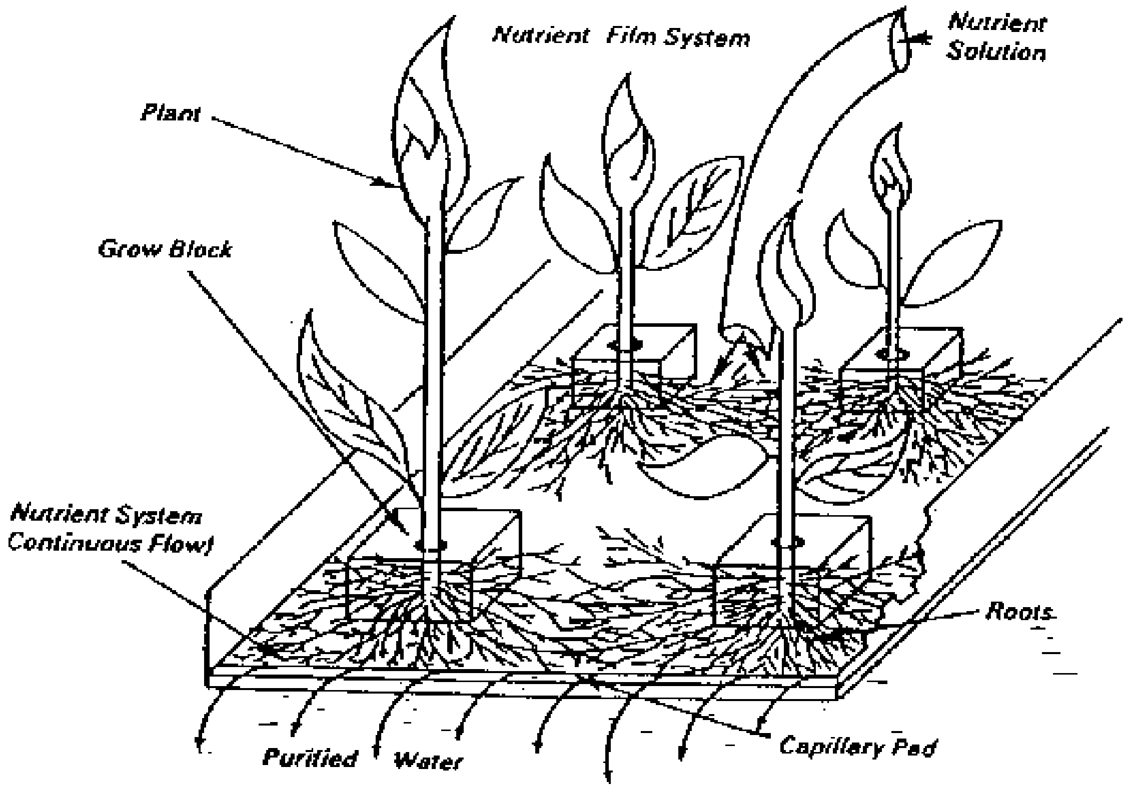
- Roughing or preliminary treatment by plant species with large root systems capable of surviving and growing in a grossly polluted condition. Large sludge accumulations, anaerobic conditions and trace metal precipitation and entrapment characterize this mechanism and a large portion of wastewater BOD and suspended solids would thereby be removed.

- Nutrient conversion and recovery due to high biomass production.

- Wastewater polishing during nutrient-limited plant production, depending on the required effluent quality.

A three year pilot-scale study by Jewell et al. (1983) proved this to be a viable alternative for sewage treatment. Reed canary grass was used as the main test species and resulted in the production of better than secondary effluent quality at an application rate of 10 cm/d of settled domestic sewage and synthetic wastewater. The highest loading rates achieved were equivalent to treating the sewage generated by a population of 10,000 on an area of 2 ha. Plants other than reed canary grass were also tested and those that flourished best in the NFT system were: cattails, bulrush, strawflowers, Japanese millet, roses, Napier grass, marigolds, wheat and phragmites.

Figure 10: Nutrient film technique variation of hydroponic plant production systems (Jewell *et al.* 1983)



Nutrient Film System
Nutrient Solution
Plant
Grow Block
Nutrient System Continuous Flow!
Roots
Capillary Pad
Purified Water