2

Wastewater treatment in WSP

2.1 TYPES OF WSP AND THEIR FUNCTION

WSP systems comprise a single series of anaerobic, facultative and maturation ponds, or several such series in parallel. In essence, anaerobic and facultative ponds are designed for BOD removal and maturation ponds for pathogen removal, although some BOD removal occurs in maturation ponds and some pathogen removal in anaerobic and facultative ponds. In many instances only anaerobic and facultative ponds will be required: for example, prior to restricted crop irrigation (Section 12.1) and fishpond fertilization (Section 12.4), and also when a relatively weak wastewater (up to 150 mg BOD/l) is to be treated prior to surface water discharge. In general maturation ponds will be required only when the treated wastewater is to be used for unrestricted irrigation and has to comply therefore with the WHO guideline of $\ngtr$1000 faecal coliforms per 100 ml, and when stronger wastewaters (BOD >150 mg/l) are to be treated prior to surface water discharge. (Restricted irrigation refers to the irrigation of industrial crops, such as cotton and sunflower, and food crops that are processed or cooked prior to consumption, such as wheat, potatoes and many other vegetables. Unrestricted irrigation covers food crops eaten uncooked, such as salad crops.)

Designers should not be afraid of including anaerobic ponds. Their principal perceived disadvantage – odour release – can be eliminated at the design stage (Section 6.3), and they are so efficient at removing BOD that their inclusion substantially reduces the land area required (see Design Example No. 1 in Annex I).

2.1.1 Anaerobic ponds

Anaerobic ponds are commonly 2-5 m deep (see Section 7.5) and receive such a high organic loading (usually >100 g BOD/m^3 d, equivalent to >3000 kg/ha d for a depth of 3 m) that they contain no dissolved oxygen and no algae, although occasionally a thin film of mainly C*hlamydomonas* can be seen at the surface. They function much like open septic tanks, and their primary function is BOD removal (see Section 2.2). Anaerobic ponds work extremely well: a properly designed and not significantly underloaded anaerobic pond will achieve around 40 percent BOD removal at 10ºC and over 60 per cent at 20ºC. Retention times are short: for wastewater with a BOD of 300 mg/l, for example, 1.5 days is sufficient at a temperature of 15°C (see Section 6.3).

Designers have in the past been afraid to incorporate anaerobic ponds in case they cause odour. Hydrogen sulphide, formed mainly by the anaerobic reduction of sulphate by sulphate-reducing bacteria such as *Desulfovibrio*, is the principal potential source of odour. However in aqueous solution hydrogen sulphide is present as either dissolved hydrogen sulphide gas (H_2S) or the bisulphide ion (HS^-), with the sulphide ion (S^{2-}) only being formed in significant quantities at high pH. Figure 2.1 shows how the distribution of H_2S, HS^- and S^{2-} changes with pH. At the pH values normally found in well designed anaerobic ponds (around 7.5), most of the sulphide is present as the odourless bisulphide ion. Odour is only caused by escaping hydrogen sulphide molecules as they seek to achieve a partial pressure in the air above the pond which is in equilibrium with their concentration in it (Henry's law). Thus, for any given total sulphide concentration, the greater the proportion of sulphide present as HS^-, the lower the release of H_2S. Odour is *not* a problem if the recommended design loadings (Table 6.1) are not exceeded and if the sulphate concentration in the raw wastewater is less than 500 mg SO_4/l (Gloyna and Espino, 1969). A small amount of sulphide is beneficial as it reacts with heavy metals to form insoluble metal sulphides which precipitate out, but concentrations of 50-150 mg/l can inhibit methanogenesis (Pfeffer, 1970). A further important advantage of small concentrations (>3 mg/l) of sulphide in anaerobic ponds is that they are rapidly lethal to *Vibrio cholerae*, the causative agent of cholera (Oragui *et al.*, 1993; Arridge *et al.*, 1995).

Designs now exist for covering anaerobic ponds to facilitate methane recovery (Green *et al.*, 1995*a*; Hodgson and Paspaliaris, 1996). This also provides additional security against odour release since, even if the methane is not to be collected, the gases can be flared off.

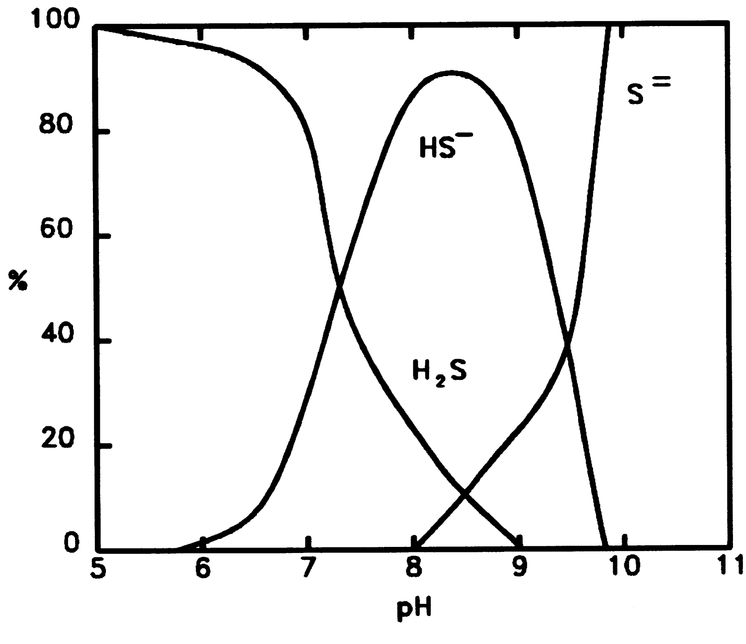

Figure 2.1 Effect of pH on hydrogen sulphide – bisulphide – sulphide equilibrium (Sawyer *et al.*, 1994).

2.1.2 Facultative ponds

Facultative ponds (1-2 m deep) are of two types: primary facultative ponds which receive raw wastewater, and secondary facultative ponds which receive settled wastewater (usually the effluent from anaerobic ponds). They are designed for BOD removal on the basis of a relatively low surface loading (100 -400 kg BOD/ha d) to permit the development of a healthy algal population as the oxygen for BOD removal by the pond bacteria is mostly generated by algal photosynthesis (see Sections 2.2 and 6.4). Due to the algae facultative ponds are coloured dark green, although they may occasionally appear red or pink (especially when slightly overloaded) due to the presence of anaerobic purple sulphide-oxidising photosynthetic bacteria. The algae that tend to predominate in the turbid waters of facultative ponds (see Table 2.1) are the motile genera (such as *Chlamydomonas, Pyrobotrys* and *Euglena*) as these can optimise their vertical position in the pond water column in relation to incident light intensity and temperature more easily than non-motile forms (such as *Chlorella*, although this is also fairly common in facultative ponds). The concentration of algae in a facultative pond depends on loading and temperature, but is usually in the range 500-2000 μg chlorophyll *a* per litre.

As a result of the photosynthetic activities of the pond algae, there is a diurnal variation in the concentration of dissolved oxygen. After sunrise, the dissolved oxygen level gradually rises, in response to photosynthetic activity, to a maximum in the mid-afternoon, after which it falls to a minimum during the night when photosynthesis ceases and respiratory activity consumes oxygen. The position of the oxypause (the depth at which the dissolved oxygen concentration reaches zero) similarly changes, as does the pH since at peak algal activity carbonate and bicarbonate ions react to provide more carbon dioxide for the algae, so leaving an excess of hydroxyl ions with the result that the pH can rise to above 9 which kills faecal bacteria (see Section 2.3.1).

Table 2.1 Examples of algal genera present in waste stabilisation ponds

Algae	Facultative Ponds	Maturation Ponds
Euglenophyta		
Euglena	+	+
Phacus	+	+
Chlorophyta		
Chlamydomonas	+	+
Chlorogonium	+	+
Eudorina	+	+
Pandorina	+	+
Pyrobotrys	+	+
Ankistrodesmus	⊗	+
Chlorella	+	+
Micractinium	⊗	+
Scenedesmus	⊗	+
Selenastrum	⊗	+
Carteria	+	+
Coelastrum	⊗	+
Dictyosphaerium	⊗	+
Oocystis	⊗	+
Rhodomonas	⊗	+
Volvox	+	⊗
Chrysophyta		
Navicula	+	+
Cyclotella	⊗	+
Cyanophyta		
Ocsillatoria	+	+
Anabaena	+	+

+ = present; ⊗ = absent

The wind has an important effect on the behaviour of facultative ponds, as it induces vertical mixing of the pond liquid. Good mixing within the upper aerobic layer ensures a more uniform distribution of BOD, dissolved oxygen, bacteria and algae and hence a better degree of waste stabilisation. In the absence of wind-induced mixing, the algal population tends to stratify in a narrow band, some 20 cm thick, during daylight hours. This concentrated band of algae moves up and down through the top 50 cm of the pond in response to changes in incident light intensity, and causes large fluctuations in effluent quality (especially BOD and suspended solids) if the effluent take-off point is within this zone (see Section 7).

2.1.3 Maturation ponds

A series of maturation ponds (1-1.5m deep) receives the effluent from a facultative pond, and the size and number of maturation ponds is governed mainly by the required bacteriological quality of the final effluent (see Sections 6.1 and 6.5). Maturation ponds usually show less vertical biological and physicochemical stratification and are well oxygenated throughout the day. Their algal population is more diverse than that of facultative ponds (Table 2.1) with non-motile genera tending to be more common; algal diversity increases progressively along the pond series.

The primary function of maturation ponds is the removal of excreted pathogens, and this is extremely efficient in a properly designed series of ponds (Table 2.2). Maturation ponds achieve only a small removal of BOD, but their contribution to nutrient (nitrogen and phosphorus) removal can also be significant (see Sections 2.4 and 6.5.4).

2.2 BOD REMOVAL

In anaerobic ponds BOD removal is achieved (as in septic tanks) by sedimentation of settleable solids and subsequent anaerobic digestion in the resulting sludge layer: this is particularly intense at temperatures above 15°C when the pond surface literally bubbles with the release of biogas (around 70 percent methane and 30 percent carbon dioxide).

The bacterial groups involved are the same as those in any anaerobic reactor – the anaerobic acidogens and the methanogens, and those in anaerobic ponds are equally sensitive to the same toxicants, one of which is low pH (< 6.2). Acidic wastewaters thus require neutralising prior to treatment in anaerobic ponds.

In secondary facultative ponds that receive settled wastewater (usually anaerobic pond effluent), the remaining non-settleable BOD is oxidised by the normal heterotrophic bacteria of wastewater treatment (*Pseudomonas, Flavobacterium, Archromobacter* and *Alcaligenes* spp.), but with one important difference: these bacteria obtain the oxygen they need not from mechanical aeration (as they do in aerated lagoons, oxidation ditches and activated sludge tanks), but from the photosynthetic activities of the micro-algae which grow naturally and profusely in facultative ponds, giving them their characteristic dark green colour. The algae, in turn, depend largely on the bacteria for the carbon dioxide which they photosynthetically convert into sugars:

$$6CO_2 + 12H_2O \rightarrow C_6H_{12}O_6 + 6H_2O + 6O_2$$

Table 2.2 Geometric mean bacterial and viral numbers[a] and percentage removals in raw wastewater (RW) and the effluents of five waste stabilisation ponds in series (P1-P5[b]) at a mean mid-depth pond temperature of 26°C.

Organism	RW	P1	P2	P3	P4	P5	Percentage removal
Faecal coliforms	2×10^7	4×10^6	8×10^5	2×10^5	3×10^4	7×10^3	99.97
Faecal streptococci	3×10^6	9×10^5	1×10^5	1×10^4	2×10^3	300	99.99
Clostridium perfringens	5×10^4	2×10^4	6×10^3	2×10^3	1×10^3	300	99.40
Campylobacters	70	20	0.2	0	0	0	100.00
Salmonellae	20	8	0.1	0.02	0.01	0	100.00
Enteroviruses	1×10^4	6×10^3	1×10^3	400	50	9	99.91
Rotaviruses	800	200	70	30	10	3	99.63
BOD (mg/l)	215	36	41	21	21	18	92

[a] Bacterial numbers per 100 ml, viral numbers per 10 litres.
[b] Pl was an anaerobic pond with a mean hydraulic retention time of 1 day; P2 and P3-P5 were secondary facultative and maturation ponds respectively, each with a retention time of 5 days.
Source: Oragui *et al*. (1987).

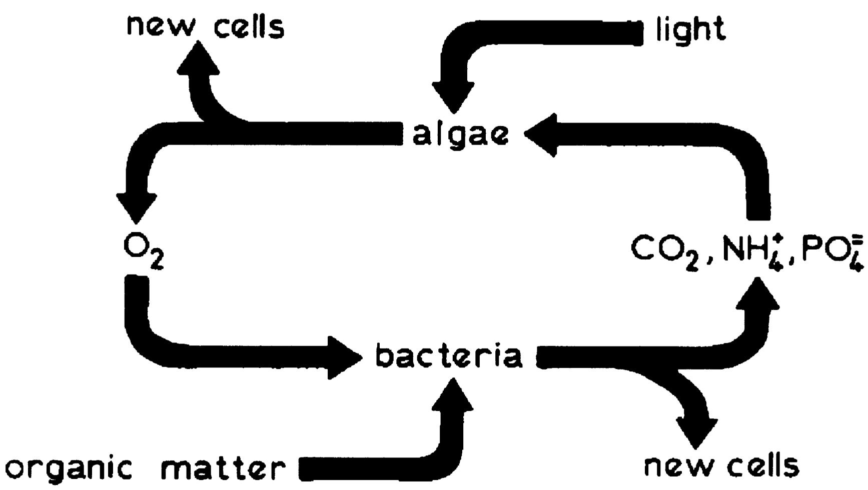

Figure 2.2 Mutualistic relationship between pond algae and pond bacteria.

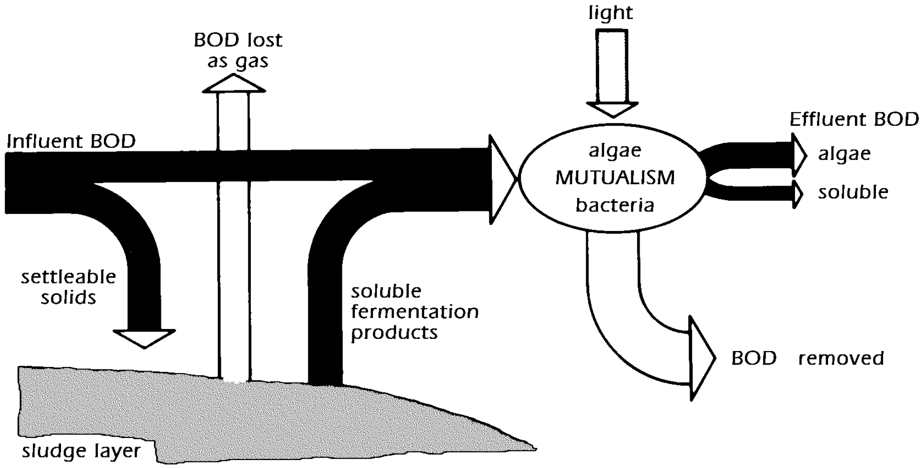

Figure 2.3
Pathways of BOD removal in primary facultative ponds (after Marais, 1970).

So there exists a *mutualistic* relationship between the pond algae and the pond bacteria: the algae provide the bacteria with oxygen and the bacteria provide the algae with carbon dioxide (Figure 2.2). Of course some oxygen and carbon dioxide comes from the atmosphere by mass transfer, but the bulk is supplied by algal-bacterial mutualism.

In primary facultative ponds (those that receive raw wastewater) the above functions of anaerobic and secondary facultative ponds are combined, as shown in Figure 2.3. Around 30 percent of the influent BOD leaves a primary facultative pond in the form of methane (Marais, 1970).

As a result of these algal-bacterial activities, a high proportion of the BOD that does not leave the pond as methane and carbon dioxide ends up as algal cells. Thus in facultative ponds "sewage BOD" is converted into "algal BOD" and this has important implications for effluent quality requirements (see Section 6.1).

In maturation ponds only a small amount of BOD removal occurs. While there is some removal of soluble BOD, this is principally as a result of lower algal concentrations (and hence lower "algal BOD") which, in turn, result from a decreased supply of nutrients and predation by protozoa and micro-invertebrates such as *Daphnia* or by fish such as carp if these are present. Around 70-90 percent of the BOD of a maturation pond effluent is due to the algae it contains.

2.3 PATHOGEN REMOVAL

2.3.1 Bacteria

Faecal bacteria are partially removed in facultative but especially in maturation ponds whose size and number determine the numbers of faecal bacteria (usually modelled in terms of faecal coliforms) in the final effluent (Section 6.2.4.). There is some removal in anaerobic ponds principally by sedimentation of solids-associated bacteria.

The principal mechanisms for faecal bacterial removal in facultative and maturation ponds are now known to be:

(a) time and temperature,
(b) high pH (> 9), and
(c) high light intensity together with high dissolved oxygen concentration.

Time and temperature are the two principal parameters used in maturation pond design (Section 6.2.4.): faecal bacterial die-off in ponds increases with both time and temperature (Feachem *et al.,* 1983). High pH values above 9 occur in ponds due to rapid photosynthesis by the pond algae which consumes CO_2 faster than it can be replaced by bacterial respiration; as a result carbonate and bicarbonate ions dissociate:

$$2HCO^-_3 \rightarrow CO^{2-}_3 + H_2O + CO_2$$

$$CO^{2-}_3 + H_2O\ 2 \rightarrow 2OH^- + CO_2$$

The resulting CO_2 is fixed by the algae and the hydroxyl ions accumulate so raising the pH, often to above 10. Faecal bacteria (with the notable exception of *Vibrio cholerae*) die very quickly at pH > 9 (Pearson *et al.,* 1987*c*).

The role of high light intensity and high dissolved oxygen concentration has recently been elucidated (Curtis *et al.,* 1992). Light of wavelengths 425 – 700 nm can damage faecal bacteria by being absorbed by the humic substances ubiquitous in wastewater: these then enter an excited state for long enough to damage the cell. Light-mediated die-off is completely dependent on the presence of oxygen, and it is considerably enhanced at high pH. The sun thus plays a threefold role in promoting faecal bacterial removal in WSP (Figure 2.4): directly, by increasing the pond temperature ; and more indirectly, by providing the energy for rapid algal photosynthesis which not only raises the pond pH above 9 but also results in high dissolved oxygen concentrations which are necessary for its third role, that in promoting photo-oxidative damage.

2.3.2 Viruses

Little is definitely known about the mechanisms of viral removal in WSP, but it is generally recognised that it occurs by adsorption on to settleable solids (including the pond algae) and consequent sedimentation.

2.3.3 Parasites

Protozoan cysts and helminth eggs are removed by sedimentation. Their settling velocities are quite high (for example, 3.4×10^{-4} m/s in the case of *Ascaris lumbricoides)*, and consequently most removal takes place in the anaerobic and facultative ponds. It is possible to design WSP specifically for helminth egg removal (Ayres *et al.,* 1992*a*; see Section 6.5.2. and Design Example No. 2 in Annex I); this is necessary if the effluent is to be used for restricted crop irrigation (Section 12.1).

2.4 NUTRIENT REMOVAL

2.4.1 Nitrogen

In WSP systems the nitrogen cycle is at work. In anaerobic ponds organic nitrogen is hydrolysed to ammonia, so ammonia concentrations in anaerobic pond effluents are generally higher than in the raw wastewater (unless the time of travel in the sewer is so long that all the organic nitrogen has been converted before reaching the WSP). In facultative and maturation ponds, ammonia is

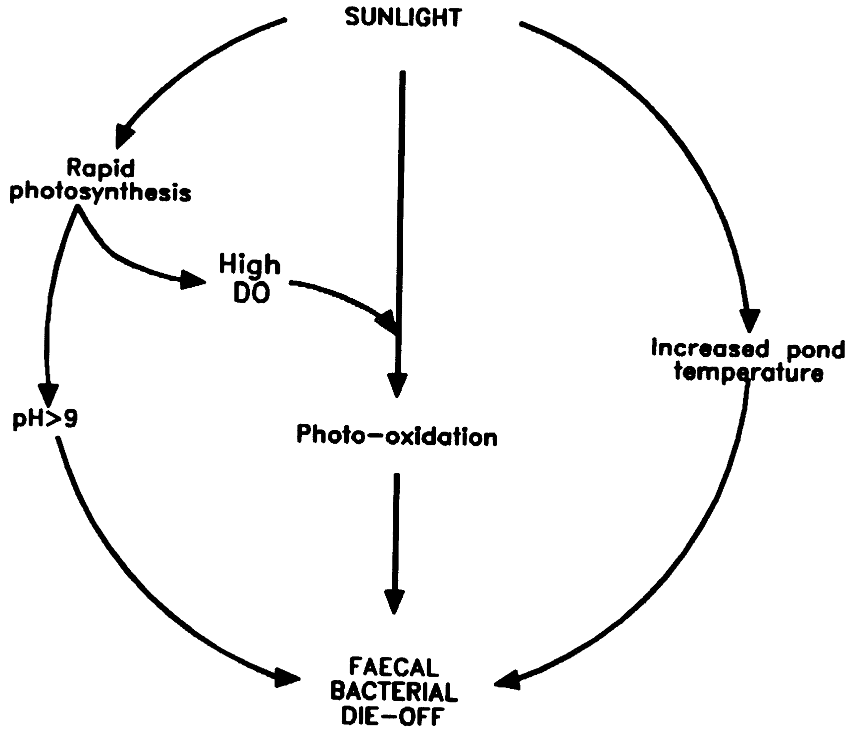

Figure 2.4 Conceptual mechanisms for faecal coliform die-off in ponds.

incorporated into new algal biomass. Eventually the algae become moribund and settle to the bottom of the pond; around 20 percent of the algal cell mass is non-biodegradable and the nitrogen associated with this fraction remains immobilised in the pond sediment. That associated with the biodegradable fraction eventually diffuses back into the pond liquid and is recycled back into algal cells to start the process again. At high pH, some of the ammonia will leave the pond by volatilization.

There is little evidence for nitrification (and hence denitrification, unless the wastewater is high in nitrates). The populations of nitrifying bacteria are apparently very low in WSP possibly due to the absence of physical attachment sites in the aerobic zone, although inhibition by the pond algae may also occur.

Total nitrogen removal in WSP systems can reach 80 percent or more, and ammonia removal can be as high as 95 percent. Equations for estimating total and ammoniacal nitrogen removals are given in Section 6.5.4.

2.4.2 Phosphorus

The efficiency of total phosphorus removal in WSP depends on how much leaves the pond water column and enters the pond sediments – this occurs due to sedimentation as organic P in the algal biomass and precipitation as inorganic P (principally as hydroxyapatite at pH levels above 9.5) – compared to the quantity that returns through mineralization and resolubilization. As with nitrogen, the phosphorus associated with the non-biodegradable fraction of the algal cells remains in the sediments. Thus the best way of increasing phosphorus removal in WSP is to increase the number of maturation ponds, so that progressively more and more phosphorus becomes immobilized in the sediments. A first order plug flow model for phosphorus removal has been developed, (Huang and Gloyna, 1984), but it is not in a form useful for design. The model shows that, if the BOD removal is 90 percent, then phosphorus removal is around 45 percent.

2.5 ENVIRONMENTAL IMPACT OF WSP SYSTEMS

The environmental impacts resulting from the installation of a waste stabilisation pond system would normally be expected to be positive. Nevertheless, environmental impact assessments (EIA) are now recognised as an essential component in any development project and as an important decision-making tool, and the appropriate procedures should be followed (Council of the European Communities, 1985). Annex III outlines the guidelines recommended by UNEP (1990) for the preparation of an EIA document for a sewage treatment plant for cities with populations of 10,000 – 100,000 and 100,000 – 1,000,000. Reference may also be made to the *Environmental Assessment Sourcebook* published by the World Bank (1991).

2.6 PERCEIVED DISADVANTAGES OF WSP

It is not uncommon to come across gross misconceptions about the performance and efficiency of WSP. Often this is due to a simple lack of knowledge, but occasionally there is prejudice against them generally from those who favour electromechanical treatment or other processes such as UASB reactors or constructed wetlands.

The principal gross misconceptions concerning WSP are: odour, insect (especially mosquito) breeding, high effluent suspended solids, high land take, high water loss due to evaporation, and groundwater contamination.

Odour. Well-designed, well-maintained and not overloaded WSP do not give rise to odour nuisance. Odour from anaerobic ponds can be prevented at the design stage (Section 2.1.1). Odour does occur with overloaded WSP, but not to a greater extent than with other forms of treatment.

Mosquito breeding does not occur in well-maintained ponds. Mosquitoes need both water and shade for breeding, and shade is only provided in WSP by emergent vegetation or grass growing down the embankment into the pond. This does not occur if the WSP are properly maintained (Section 8.2).

High effluent suspended solids. The EU Directive on urban wastewater treatment (Council of the European Communities, 1991*a*) permits WSP effluents to contain up to 150 mg suspended solids per litre, since it is recognised that most (70-90 percent) of the suspended solids are algae and hence environmentally less damaging (see Section 6.1).

High land take. WSP do, of course, require more land than other treatment processes. However, as noted in Box 1, an honest economic or financial appraisal will indicate that WSP, even with a high land take, are often the cheapest option. The question generally is: do you pay for a large land area now, or for a continuously high consumption of electricity in the future? Land purchased for WSP can often be a real-estate investment (Section 1.2).

In member States of the European Union farmers are frequently paid not to farm part of their land. This so-called “set aside” land could clearly be leased by sewerage authorities for WSP.

High water loss. In the arid and semi-arid areas of the Region water is a valuable commodity, and a high evaporative loss from WSP reduces the quantity of treated wastewater available for crop irrigation (Section 12). However, this loss is rarely more than 10 percent even in desert areas (see Design Example No. 3 in Annex I). This lost water does, of course, have a value, but the proper question should be: is its value higher or lower than the energy costs of alternative electromechanical treatment?

Groundwater contamination is not a problem if the physical design of WSP has been properly done (Section 7). The key parameter is the coefficient of soil permeability as this determines whether or not the ponds need to be lined. As noted in Section 7.3, if the coefficient of permeability is $> 10^{-9}$ m/s and the groundwater is used as a source of potable supply, specialist hydrogeological advice should be obtained.

A further important perceived disadvantage of WSP is that they are sometimes considered inferior in some way to other treatment technologies – despite their clear advantages of simplicity, low cost and high efficiency (Section 1.2). Aerated lagoons used to be frequently promoted as a better alternative to WSP, but their energy costs are high (Section 1.2), and it is not uncommon for the aerators to be permanently switched off. The result is that the aerated lagoon then functions as an anaerobic pond. Provided this is recognised and the resulting anaerobic pond is not overloaded and regularly desludged (see Section 8.4), BOD removal efficiency can be as high as in the aerated lagoon but without, of course, its high energy costs.

A more recent technology which is being increasingly promoted is the upflow anaerobic sludge blanket (UASB) reactor (see, for example, van Haandel and Lettinga, 1994). This should really only be considered as an alternative to anaerobic ponds as some form of subsequent treatment is required (and WSP are noted as being especially suitable for this purpose – see van Haandel *et al.*, 1996). However, while UASB reactors have been found to be appropriate for the treatment of high strength industrial wastewaters, there is less experience of their treatment of domestic wastewaters, especially at temperatures below 20°C (van Haandel *et al.*, 1996). A two-stage UASB system has been recommended for the treatment of domestic and municipal wastewater below 20°C, but this is an even more complex technology and further research and development is needed before it can be considered a viable option (van Haandel *et al.*, 1996).

High-rate algal ponds (HRAP) hold considerable promise for their primary purpose, which is the production of large quantities of high-quality algal protein, rather than wastewater treatment *per se* (Oswald, 1995). However, despite many years of research, principally in California and Israel, HRAP are not yet at the stage of large-scale application. Little has changed since their review in the WHO *Waste Stabilization Pond Design Manual for Mediterranean Europe* (Mara and Pearson, 1987).

Similar arguments can be made in the case of the Advanced Integrated Pond System (AIPS) recently developed in California (Green *et al.*, 1995*b*). With AIPS the wastewater enters a 4-5 m deep facultative pond containing a "digester pit", which functions much like an anaerobic pond but, in this case, within the facultative pond, rather than preceding it. The facultative pond effluent is discharged into a stirred high-rate pond, then into a settling pond to remove most of the algae produced in the high-rate pond, and thence into maturation ponds for biological disinfection. Recirculation of some of the high-rate pond contents back to the surface layers of the facultative pond ensures odourless conditions in the latter. Operation and maintenance are thus greater than with conventional WSP, to which AIPS have not been shown to be superior.

The same is largely true of macrophyte ponds both floating and rooted (the latter sometimes being called gravel bed hydroponic systems – see Williams *et al.*, 1995) and also of constructed wetlands (which generally comprise a selection of both types of macrophytes). As shown in Table 1.1, reed beds are about twice as expensive as WSP. Their operation and maintenance requirements are significantly higher (Mara and Pearson, 1987) and mosquito (especially *Mansonia* spp.) breeding is a serious problem if there is a free water surface (Ringuelet, 1983).