3

CONSTRUCTED WETLANDS

3.1 TYPES OF CONSTRUCTED WETLANDS

There are five main types of constructed wetlands (CW) (also often called reed beds after the plant most commonly grown in them: *Phragmites australis*, the common reed):

(a) free-water-surface CW,
(b) subsurface horizontal-flow CW,
(c) vertical-flow CW,
(d) raw-wastewater vertical-flow CW, and
(e) sludge-drying CW.

The first three types provide secondary or tertiary treatment and thus the wastewater is pretreated in a septic tank (Chapter 2) (or other simple solids/liquid separator) or, for example (and as routinely used by Severn Trent Water; Griffin, 2003), a rotating biological contactor (RBC). The fourth is a recent development in France; at present there is only one small system serving 2 p.e. in the UK. The last type is not considered in this Manual as it is described in the CIWEM Manual of Practice on Sludge Treatment and Disposal (forthcoming).

Detailed information on CW is given by IWA Specialist Group (2000) and Berland and Cooper (2001), and in the issues of *Water Science and Technology* which contain the proceedings of the IWA international conferences on CW.[1] Cooper (2001b, 2003), Cooper *et al*. (1996), Green and Upton (1995), Griffin (2003), Griffin and Pamplin

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[1] Issues available on-line at www.iwaponline.com/wst/toc.htm are: vol. 32, no. 3 (1995); vol. 35, no. 5 (1997); vol. 40, no. 3 (1999); vol. 44, no 11−12 (2001); vol. 48, no. 5 (2003); and vol. 51, no. 9 (2005).

(1998), Nuttal *et al*. (1997) and Upton *et al*. (1995) detail CW practice and design in the UK (a less positive view is given by Hiley, 1995). There is also a CIWEM Factsheet on Reed Bed Wastewater Treatment[2] and the UK-based Constructed Wetland Association.[3]

3.2 FREE-WATER-SURFACE CW

These CW are the most common type of CW used in the United States for domestic wastewater treatment (US Environmental Protection Agency, 1993), but they are not used for this purpose to any extent in the UK. In the US they are used for the tertiary treatment of high-quality secondary effluents from large populations (up to 500 000 p.e.) and hence require very large areas of land (which would not be available for this purpose in the UK).

Another disadvantage of the system is that the open water, which is shaded by the plants, encourages mosquito breeding, often to the extent of major nuisance. [In France, when waste stabilization ponds (Chapter 4) were introduced in the 1970s, it was then common practice to plant the downstream half of the second maturation pond with reeds (in an attempt to shade out the pond algae and so reduce effluent BOD and suspended solids), but mosquito breeding was such a problem that the practice was discontinued.]

3.2.1 Mine drainage waters

FWS-CW planted with *Phragmites* have been successfully used in the UK to treat mine drainage waters (Jarvis and Younger, 1999; Batty and Younger, 2002; Coal Authority, 2005). Currently the largest example is at Morlais in the county of Swansea (Figure 3.1), which was designed for a maximum flow of 300 l/s and commissioned in 2003. The water is first settled in two sedimentation lagoons (total area of 1 ha) and then in the FWS-CW (3 ha). The iron concentration is reduced from ~30 mg Fe/l to <1 mg Fe/l (and usually to <0.2 mg Fe/l).[4]

3.3 SUBSURFACE HORIZONTAL-FLOW CW

3.3.1 Description

Subsurface horizontal-flow CW (SSHF-CW) are the type of CW most commonly used for domestic wastewater treatment in the UK, to where they were introduced from Germany in 1985 (Cooper *et al*., 1989, 1990). Secondary SSHF-CW receive settled wastewater (e.g., septic tank effluent) and tertiary SSHF-CW receive secondary effluents (RBC effluents). The current design used by Severn Trent Water, which has ~400 SSHF-CW, is given in Figure 3.2 (Griffin, 2003). A typical SSHF-CW is shown in Figure 3.3. The bed medium (soil in the original German reed beds) is now most commonly 5−10-

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[2] www.ciwem.org.uk/policy/factsheets/fs3.asp

[3] www.constructedwetland.org

[4] Information kindly provided by Parsons Brinckerhoff Ltd, Bristol. See also:
www.coal.gov.uk/resources/environment/morlaisminewatertreatmentscheme.cfm

Figure 3.1. Free-water-surface constructed wetlands treating acid mine drainage water at Morlais, Swansea.
Photograph courtesy of Parsons Brinckerhoff Ltd.

mm gravel, although coarse sands are sometimes used. The bed depth is usually 0.6 m (this is the maximum depth to which *Phragmites* roots grow) and the medium extends above the water surface by ~0.1 m. The bed is usually lined with a 0.5−0.6-mm thick impermeable LDPE or butyl rubber geomembrane.

Although reeds are the plants by far most commonly grown in CW, a variety of other aquatic macrophytes are used − for example, rushes: *Typha latifolia* (bulrush), *Schoenoplectus lacustris* (club rush), and *Juncus effusus* (soft rush). Ornamental flowers can also be grown in CW: for example, yellow flag iris (*Iris pseudacorus*), canna lilies (*Canna* spp.), and arum or calla lilies (*Zantedeschia* spp.) (Belmont *et al*., 2005). In principle, any plant that can be grown hydroponically can be grown in SSHF-CW (this includes non-root food crops, although clearly UK water authorities and companies are unlikely to become food producers; however, owners of private CW may see this as an advantage. The health risks from consuming foods produced in this way are minimal; WHO, 2006).

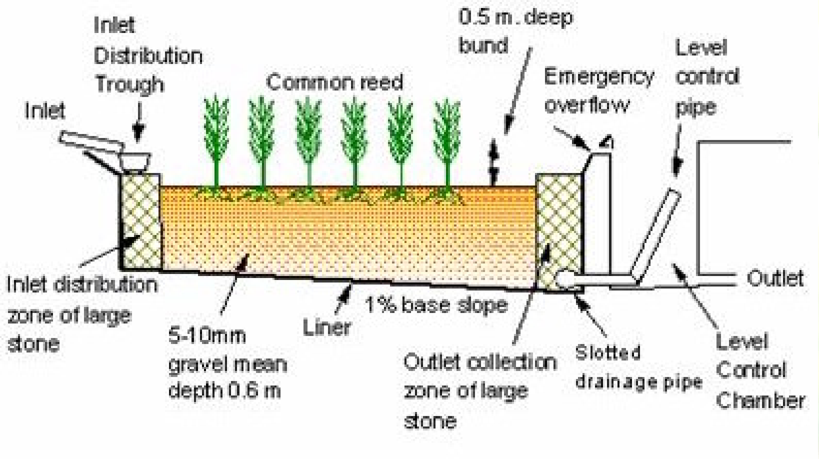

Figure 3.2. Longitudinal section of a subsurface horizontal-flow constructed wetland. Figure courtesy of Severn Trent Water (Griffin, 2003).

Figure 3.3. Subsurface horizontal-flow constructed wetland at Airton, North Yorkshire in winter (Figure 1.1 shows this CW in summer).

3.3.2 Design

SSHF-CW are designed for BOD removal as plug-flow reactors, as follows:

$$L_e = L_i e^{-k_1\theta} \tag{3.1}$$

where L_e and L_i are the mean effluent and influent BOD (mg/l), respectively; k_1 is the first-order rate constant for BOD removal (day^{-1}); θ is the mean hydraulic retention time (days); and e is the base of Naperian logarithms. The value of k_1 depends on temperature (T, °C):

$$k_{1(T)} = k_{1(20)}\varphi^{T-20} \tag{3.2}$$

where φ is an Arrhenius constant.

The retention time is volume/flow, and the flow is the mean of the inflow and outflow; therefore:

$$\theta = \frac{\varepsilon AD}{0.5(Q_\mathrm{i} + Q_\mathrm{e})} \tag{3.3}$$

where ε is the porosity of the bed medium (~0.35−0.4 for pea gravel); A, the CW area (m^2); D, the CW depth (m); and Q_i and Q_e are the inflow and outflow, respectively (m^3/d).

The outflow is the inflow less the loss due to evapotranspiration:

$$Q_\mathrm{e} = Q_\mathrm{i} - 0.001eA \tag{3.4}$$

where e is the net evapotranspiration (i.e., evapotranspiration − rainfall) (mm/d). Thus:

$$\theta = \frac{2\varepsilon AD}{2Q_\mathrm{i} - 0.001eA} \tag{3.5}$$

A can now be calculated from known (and/or assumed) values of the parameters in the above equations.

A simpler approach, but still one based on equation 3.1, is typically used in the UK: evapotranspiration is ignored,[5] temperature and depth are not considered explicitly, and, rather than using k_1 as defined above, an area-based k value (k_A, m/d) is used, as follows (Cooper, 2001):

$$A = \frac{Q_\mathrm{i}\,(\ln L_\mathrm{i} - \ln L_\mathrm{e})}{k_\mathrm{A}} \tag{3.6}$$

For secondary SSHF-CW the design value of k_A is 0.06 m/d and A is typically 5 m^2 per person; effluent BOD and SS are both ~20 mg/l, but ammonia removal is negligible; for tertiary SSHF-CW k_A is taken as 0.31 m/d and A is typically 0.5−0.7 m^2 per person; ammonia is removed by nitrification (Cooper, 2001). Severn Trent Water uses a tertiary SSHF-CW area of 0.7 m^2 per person (Griffin, 2003).

The values of L_e used in the above equations are mean (50-percentile) values as the equations were developed before it became the practice to specify effluent quality parameters as 95-percentile values. In very general terms a 50-percentile value (used in these equations) is about half the required 95-percentile value.

3.3.3 Ammonia removal

Ammonia is nitrified in the micro-aerobic zones around the roots of the plants and then some of resultant nitrate (~35−40 percent, although there is considerable variation from

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[5] This is of course an acceptable assumption in winter; however, in summer a significant proportion of the influent water may be lost through evapotranspiration. Widdas (2005) reports rates of up to 25 mm/day in summer and ~1400 mm/year in Europe. This has consequences for effluent quality when expressed in concentration terms (see the design example in Section 3.7).

site to site) is denitrified in the bulk anoxic zone of the gravel bed (Tanner, 2001).[6] Ammonia removal is modelled by equation 3.1 rewritten as follows (Huang *et al*., 2000):

$$C_e = C_i e^{-k_N \theta} \qquad (3.7)$$

where C_e and C_i are the mean ammonia concentrations in the CW effluent and influent respectively (mg N/l); and k_N is the first-order rate constant for ammonia removal at T °C (m/d); θ is given by equation 3.5. For secondary SSHF-CW the variation of k_N with temperature in the range 6−20°C is given by:

$$k_{N(T)} = 0.126(1.008)^{T-20} \qquad (3.8)$$

According to Griffin (2005), tertiary SSHF-CW remove ~1−3 mg N/l, although there is some evidence that this increases as the bed matures. Severn Trent Water therefore designs the secondary treatment process for nitrification and does not rely on the tertiary SSHF-CW for any additional removal.

3.3.4 Phosphorus removal

Phosphorus is removed principally by two mechanisms: adsorption on to the bed medium, and precipitation (mainly as apatite $[Ca_5(PO_4)_3(F, Cl, OH)]$) followed by crystallization (Brix *et al*., 2001; Molle *et al*., 2003). Use of media with high P-adsorptivities (e.g., calcite, crushed marble, blast furnace slag) in the bed of a SSHF-CW improves P removal; however, removal is limited and in some cases the P is desorbed after a few weeks or months and appears in the effluent as a high-P pulse. In general vertical-flow CW are better at removing P than SSHF-CW (see below).

3.3.5 Role of plants

A review of the CW literature (Mara, 2004b) revealed consistent evidence that the plants in SSHF-CW play no role in the removals of BOD, SS, P and faecal bacteria − i.e., there are no significant differences in the percentage removals achieved in planted CW and unplanted controls (as found, for example, by Gersberg *et al*., 1985; Hiley, 1995; Wood, 1995; Mæhlum and Stålnacke, 1999; Ayaz and Akça, 2001; Coleman *et al*., 2001; Tanner, 2001; Baptista *et al*., 2003; and Regmi *et al*., 2003).

As noted above, the plants have a crucial role in nitrogen removal by providing aerobic conditions adjacent to their roots for nitrification to occur; some of the nitrate so formed is then denitrified in the bulk anoxic zone of the bed. This suggests that the plants are only needed for treatment (as opposed to, for example, aesthetics) when the environmental regulator has specified a discharge consent for ammonia-nitrogen; otherwise it may be better to leave the bed unplanted and to increase the size of the bed medium − i.e., to have a rock filter (Chapter 5). However, the plants are not active in winter (they transport only enough oxygen to their roots to prevent them from rotting) and the removal of ammonia is lower in winter than in summer (Figure 3.4); indeed it

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[6] In the absence of nitrate, sulphate is used as a source of oxygen and this can lead to odour from H_2S, especially in summer.

may often be close to zero [Andersson *et al*. (2005) reported a variation in total N removal over a 4-year period in a free-water-surface CW in southern Sweden from ~63 percent in July to ~1 percent in December; see also IWA Specialist Group (2000)].

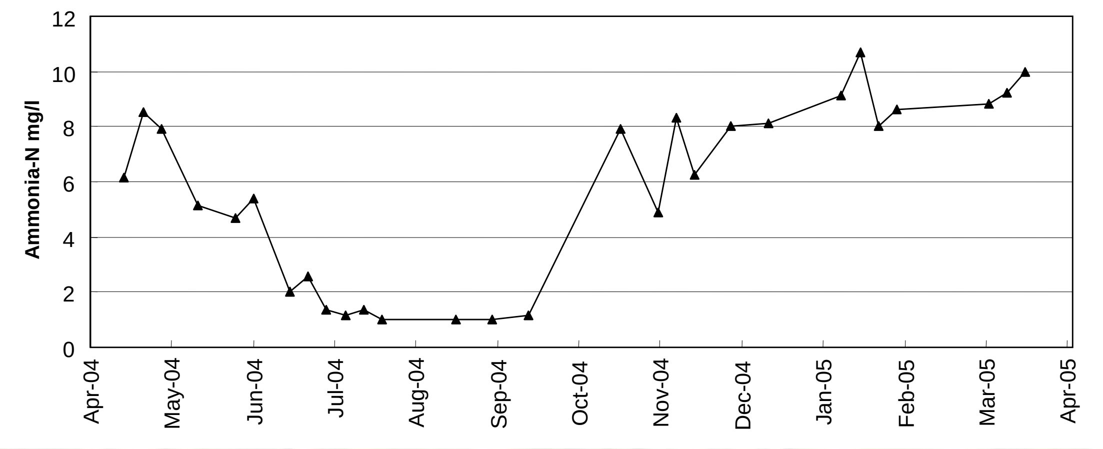

Figure 3.4. Ammonia concentrations in the effluent of a tertiary SSHF-CW planted with *Typha* at Esholt, Bradford, during April 2004 − April 2005.

Figure courtesy of Ms Michelle Johnson, School of Civil Engineering, University of Leeds.

Despite not contributing to performance (other than ammonia removal in summer), the plants do nevertheless have an important role in SSHF-CW: they prevent the bed from clogging (the bed medium is 5−10-mm gravel, as opposed to the 40−200-rock used in rock filters; see Chapter 5). The major function of the plants is associated with their roots and rhizomes which provide hydraulic pathways through the bed and maintain its hydraulic conductivity at higher rates than those occurring in unplanted beds (the roots and rhizomes expand the bed surface by several cm when the root zone is fully developed, so demonstrating the power of the growing roots). Another important factor is ‘wind rock’: when the wind blows, the plants sway and this creates small gaps between the base of the stems and the surface of the bed; this punctures the surface and so helps to maintain the bed conductivity.

3.3.6 Storm sewage overflow

At some of its small treatment works Severn Trent Water treats 6×DWF in an RBC and the RBC effluent, together with any storm flow >6×DWF, is treated in a combined tertiary/stormwater SSHF-CW sized at 1 m^2 per person. The company has agreed a framework for the relaxation of consent conditions during storm events with the Environment Agency (Table 3.1).

3.3.7 Surface water run-off

Constructed wetlands, mainly FWS-CW and SSHF-CW, are used in the UK for surface water run-off from some urban areas, highways and airports; they are ‘sustainable drainage systems’ (SUDS) which provide a storage and treatment function (Figure 3.5).

Table 3.1. Consent conditions in dry weather and during storm events.

Consent in dry weather (BOD/SS/Ammonia-N, mg/l)	Consent during storm events[a] (BOD/SS/Ammonia-N, mg/l)
25/45/15	40/60/15
20/30/10	30/50/15
15/25/5	25/45/10

[a] When the storm overflow is in operation (>6×DWF).
Source: Griffin (2003).

Shutes *et al*. (2005) give a comprehensive review which should be consulted for further details

3.4 VERTICAL-FLOW CW

The original concept of vertical-flow constructed wetlands (VF-CW), which are downward-flow systems usually planted with *Phragmites*, was that they were used for tertiary treatment, principally for the removal of ammonia-nitrogen, in a cycle over a few days of load and rest; their action was that of a very simple, discontinuous form of nitrifying trickling filter. However, their role has been reappraised over the last 15 years and now, as reviewed by Cooper (2003, 2005a) (on which much of the following text is based), they continuously receive settled wastewater[7] and are sometimes followed by a tertiary SSHF-CW to reduce effluent SS, so forming a ‘hybrid’ system. Their design has become much more sophisticated and these recent (or ‘second generation’) VF-CW are often now referred to as ‘compact’ vertical-flow constructed wetlands (CVF-CW, Figure 3.6) (Weedon, 2003). The most usual sizing of CVF-CW is 2 m^2 per person.

The hydraulic loading rate (HLR, litres of settled wastewater per m^2 of filter surface area per day, equivalent to mm/day) and the oxygen transfer rate (OTR, g O_2 per m^2 of filter surface area per day), and the size grading of the bed medium are the three critical parameters which control CVF-CW performance (effluent quality, no surface flooding). Surface flooding of the filter does not occur at HLR of <800 mm/day. The minimum value found for OTR is ~28 g O_2/m^2 day. Bed depths are 0.5−1 m; the bed medium grading is typically as follows for a bed depth of 0.7 m:

(a) top 50 mm: 1-mm sand,
(b) next 350 mm: 5−10-mm gravel,
(c) bottom 300 mm: 30−60-mm rounded stones.

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[7] Including wastewater separated in an Aquatron (www.aquatron.se), as used by Weedon (2003).

Figure 3.5. Free-water-surface constructed SUDS wetland at Appleton Court, Wakefield, West Yorkshire

Photograph courtesy of Dr Nigel Horan, School of Civil Engineering, University of Leeds

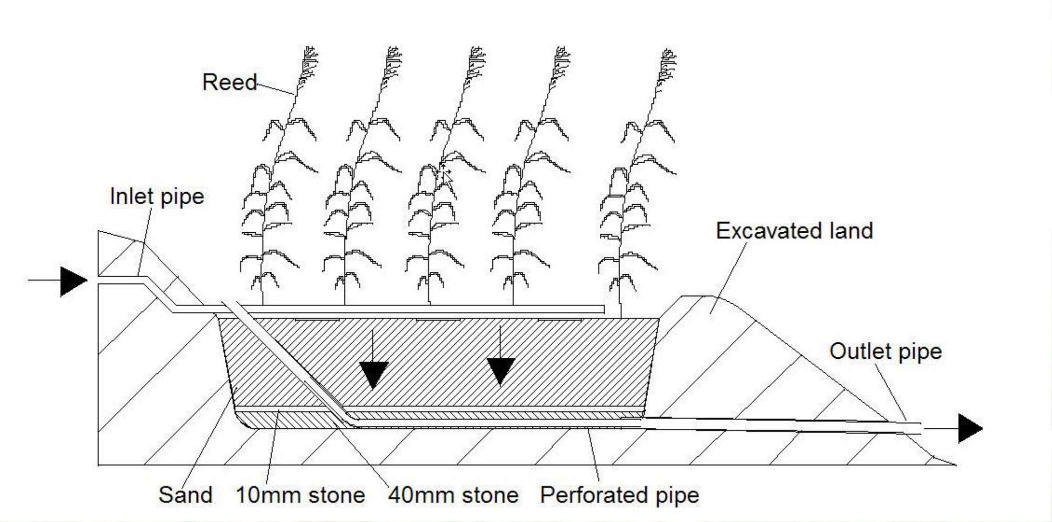

Figure 3.6. Longitudinal section of a compact vertical-flow constructed wetland.
Source: Weedon (2003).

Sand alone has been used in 1-m deep CVF-CW (Weedon, 2003; Brix and Arias, 2005); the sand grading is important: it should have a d_{10} between 0.25 and 1.2 mm, a d_{60} between 1 and 4 mm, with a coefficient of uniformity (= d_{60}/d_{10}) of <3.5 (the clay and silt fraction should be <0.5 percent). A recent innovation is the use of crushed waste glass (Figure 3.7).

Figure 3.7. Bed medium of recycled glass in the VF-CW at Bernard Matthew Ltd, Great Witchingham, Norfolk
Photograph courtesy of Dr Nigel Horan, School of Civil Engineering, University of Leeds

The oxygen supply is used for both BOD removal and nitrification. Thus OTR is given by:

$$\text{OTR} = \frac{Q[(L_\text{i} - L_\text{e}) + 4.3(C_\text{i} - C_\text{e})]}{A} \tag{3.9}$$

where 4.3 is the O_2 demand of nitrification (g O_2 per g ammonia-N nitrified).

This equation can be expressed in terms of C_e as follows:

$$C_\text{e} = C_\text{i} - \frac{(\text{OTR})(A/Q) - (L_\text{i} - L_\text{e})}{4.3} \tag{3.10}$$

OTR is likely to be a function of temperature, but no relationship has been established. Kayser *et al*. (2002) reported the following variation of nitrification performance (i.e., percentage of influent ammonia nitrified) with temperature in a tertiary VF-CW treating the effluent from a facultative waste stabilization pond in northern Germany:

$T < 5°\text{C}$	~50 percent
$5°\text{C} < T < 10°\text{C}$	~70 percent
$T > 10°\text{C}$	~90 percent

3.4.1 Phosphorus removal

Currently few small natural wastewater treatment plants in the UK have a discharge consent for phosphorus (one example is the Tigh Mor Trossachs waste stabilization ponds in Perthshire shown in Figure 4.1; the effluent, which discharges into the pristine Loch Achray, is required to have ≤3 mg P/l). Most of the research and development work on P removal in CW has been done by investigators in Europe and the United States (IWA Specialist Group, 2000).

The main mechanisms of P removal in VF-CW are precipitation, adsorption on to the bed medium and subsequent crystallization (Brix *et al*., 2001; Molle *et al*., 2003). There has been considerable effort made in identifying and evaluating suitable P-adsorbing media. Calcite, crushed marble, crushed waste concrete, sea-shell sand and blast furnace slag have all been investigated (Arias *et al*., 2003; Brix *et al*., 2001; Arias and Brix, 2005; Korkusuz *et al*., 2005; Kostura *et al*., 2005; Molle *et al*., 2003; Søvik and Kløve, 2005). Rather than adding these P-adsorbents to a VF-CW, it is better from an engineering perspective (for ease of replacing the medium when it is P-saturated) to have a separate filter for P removal. For example, Arias *et al*. (2003) used three upflow calcite filters in series between two VF-CW; P removal was ~2.3 kg P per m^3 of calcite filter. Blast furnace slag appears to be a particularly good P-adsorbent (Korkusuz *et al*., 2005; Kostura *et al*., 2005), although it may introduce high metal concentrations in the final effluent. However, more work is needed to develop design guidelines (e.g., upflow *vs* SSHF filters, number of filters, optimal medium selection, how best to replace the medium when exhausted, and so on). Alternatively, P removal could be achieved by chemical dosing of the CW influent with removal of the precipitates in the CW bed, although for small works this may not be wholly practical.

3.4.2 Effluent polishing

The tertiary SSHF-CW for SS removal which sometimes follows a CVF-CW is generally sized at ~0.5 m^2 per person. Alternatively, an unaerated rock filter may be used (Chapter 5).

3.5 PHYSICAL DESIGN

Both SSHF-CW and VF-CW are lined with an impermeable plastic liner (at least 0.5 mm thick), unless the soil has an in-situ coefficient of permeability of $\leq 10^{-7}$ m/s, in order to maintain the bed water level and avoid any groundwater pollution.

3.5.1 SSHF-CW

The bed is generally at a longitudinal slope of 1 in 100 (from inlet to outlet) and the outlet is often adjustable to provide the required wastewater depth in the bed (Figure 3.2). The length-to-breadth ratio is in the range 2−10 to 1, with a preference for higher values as this makes the influent distribution easier and more uniform across the width. García *et al*. (2004) found that a depth of 0.27 m in a SSHF-CW planted with *Phragmites* yielded better process efficiency than a depth of 0.5 m; they also confirmed the importance of the areal hydraulic loading rate (i.e., Q_i/A; cf. equation 3.6), but found the length-to-breadth ratio and the bed medium size to be less important (at least within their experimental ranges of 1−2.5 to 1 and 3.5−10-mm gravel, respectively).

The wastewater depth in SSHF-CW is a compromise: if shallow beds are used, the surface area has to be large enough to ensure the required hydraulic throughput and retention time can be achieved; if it is too deep, and the head requirement may be excessive and pumping becomes necessary.

3.5.2 VF-CW, including CVF-CW

Uniform distribution over the wetland surface is crucial. This is closely achieved by dosing the bed at approximately hourly intervals through a network of perforated half-pipes (e.g., gutters) on the bed surface; the objectives are to flood the surface so that oxygen is trapped in the bed voids for use by the bacteria on the bed medium surfaces, and to allow the wastewater to trickle down through the bed before the next dose arrives (hence the critical nature of the HLR). The gravity-operating dosing chamber shown in Figure 4.10 may be used; alternatively the wastewater can be pumped intermittently from a wet well after the primary treatment stage.

The design challenge for VF-CW is to ensure that the influent wastewater does not drain through the bed medium so fast that the bed is unable to flood, but it must pass through the bed at a sufficient rate that the bed has drained by the start of the next doing cycle. Design is complicated by the fact that the bed drainage time changes with time as solids accumulate in the bed.

3.5.3 Planting

Spring and early summer is the optimal time for planting; planting later does not allow for sufficient time for the plants to establish good root growth and they are therefore likely to be either killed or have their growth retarded by frosts. A planting density of four plants per m^2 provides good cover at reasonable cost; commercially grown seedlings offer the simplest and most effective method of establishment. The bed should be flooded after planting to prevent rabbits damaging the immature plants. Provided that regular weeding is undertaken in the first year, and low water levels in the bed are avoided, a dense stand of reeds will develop which requires little attention. However, there may be evidence of plant yellowing and poor growth towards the downstream end of the bed in the first two seasons.

3.6 OPERATION AND MAINTENANCE

O&M for both SSHF-CW and CVF-CW is very simple. During the first year of operation the beds need to be weeded to remove invading plants; thereafter this is not normally necessary. The whole works (preliminary and primary treatment units and the

CW) should be checked regularly, preferably at least twice per month for SSHF-CW, and several times a week for VF-CW (including CVF-CW), particularly to ensure that wastewater distribution over the surface is adequate. The water level should be checked at each visit to ensure it is just below the bed surface. In spring the water level may be raised to flood the bed and discourage the growth of invasive weeds which may outcompete the wetland plants if they are allowed to become established. Inlet structures, especially siphonic inlets, should be water-jetted once every 2−3 months.

In late autumn or early winter the reeds in CVF-CW are cut down to a height of ~250 mm. This is not generally done with SSHF-CW, but it may be necessary if 'lodging' occurs − i.e., when a thick layer of wind-flattened reed stems forms a dense thatch over part of the bed surface which prevents plant regrowth in the spring.

3.7 CVF-CW TREATING RAW WASTEWATER

Compact vertical-flow CW systems treating raw wastewater (RWVF-CW) have gradually been developed in France over the past 20 years to treat the wastewater from villages of up to ~1500 people (most serve ~200−700 people) (Groupe Macrophytes et Traitement des Eaux, 2005; Molle *et al*., 2005; Paing and Voisin, 2005). There were over 400 plants in operation by the end of 2004, with more than 100 commissioned in that year alone. They comprise two stages:

(a) three RWVF-CW in parallel, which discharge into:
(b) two secondary VF-CW in parallel.

Each of these five units is sized at 0.4 m^2 per person, giving a total of 2 m^2 per person, for separate sewerage systems; for combined systems each unit is sized at 0.5 m^2 per person − i.e., a total of 2.5 m^2 per person. (However, this sizing is likely to be too small to give the level of nitrification needed to achieve a 95-percentile effluent quality of $\leq$5 mg N/l in the UK.)

Only one of the first-stage RWVF-CW is used at any one time: it receives screened wastewater in batches from a self-priming siphon tank at an effective hydraulic loading rate of 0.37 m^3/m^2 day for 3−4 days and is then rested for 6−8 days, during which time the other two units are used sequentially (these design figures are based on 120 g COD (i.e., ~60 g BOD) per person per day, 60 g SS per person per day, 10−12 g TKN per person per day and a wastewater flow of 150 litres per person per day). The second-stage units are alternately loaded, with each being operated for 6−8 days. An operator (usually an employee of the village who also looks after village green spaces and the local cemetery) visits the plant for two hours twice a week to change the units and to do any required simple maintenance.

In some schemes there are three secondary units so that each series of primary and secondary units is operated for one week and then rested for two weeks. In this case the operator visits the plant only once a week.

Clogging of the primary unit may be a problem initially, and also at the end of winter or early spring, before the plants are established or start regrowing. However, the 1-week rest period normally ensures that this is not a major problem.

3.8 CW DESIGN EXAMPLES

A CW system is to be designed for a village with a population of 250. Design parameter values are:

Flow = 200 litres per person per day
BOD = 50 grams per person per day
Ammonia = 8 g N per person per day
Design temperature (winter) = 7°C
Summer temperature = 15°C

3.8.1 Solutions

3.8.1.1 Secondary subsurface horizontal-flow CW

The flow is 50 m^3/day and the BOD and ammonia concentrations are 250 mg/l and 40 mg N/l, respectively. Assume that primary treatment in a septic tank achieves 40 percent BOD removal (i.e., the tank effluent BOD = (0.6 × 250) = 150 mg/l), but increases the ammonia concentration (due to partial ammonification of the organic N in the raw wastewater) to 50 mg/l.

The secondary SSHF-CW is designed according to equation 3.6 to produce a mean effluent BOD of 20 mg/l:

$$A = \frac{Q_\mathrm{i}\,(\ln L_\mathrm{i} - \ln L_\mathrm{e})}{k_\mathrm{A}} = \frac{50\,(\ln 150 - \ln 20)}{0.06} = 1680\ \mathrm{m}^2$$

i.e., 6.7 m^2 per person.

The effluent ammonia concentration in winter is given by equations 3.5, 3.7 and 3.8:

$$k_{\mathrm{N}(T)} = 0.126(1.008)^{T-20} = 0.126(1.008)^{7-20} = 0.114\ \mathrm{d}^{-1}$$

$$C_\mathrm{e} = C_\mathrm{i}\,\mathrm{e}^{-k_\mathrm{N}(\varepsilon AD/Q)} = 50\,\mathrm{e}^{-[0.114\,(0.4 \times 1680 \times 0.6/50)]} = 20\ \mathrm{mg\ N/l}$$

i.e., an ammonia removal of 60 percent. In summer:

$$k_{\mathrm{N}(T)} = 0.126(1.008)^{15-20} = 0.121\ \mathrm{d}^{-1}$$

$$C_\mathrm{e} = 50\,\mathrm{e}^{-[0.121\,(0.4 \times 1680 \times 0.6/50)]} = 19\ \mathrm{mg\ N/l}$$

i.e., an ammonia removal of 62 percent.

Evapotranspiration. Widdas (2005) quotes an evapotranspiration rate of up to 25 mm/day in Europe. Taking a value of 15 mm/day as a typical maximum in a UK summer, the effluent flow is given by equation 3.4 as:

$$Q_\mathrm{e} = Q_\mathrm{i} - 0.001eA = 50 - (0.001 \times 15 \times 1680) = 25\ \mathrm{m^3/d}$$

i.e., a wastewater loss due to evapotranspiration of 50 percent.

3.8.1.2 Compact vertical-flow CW

The area per person is 2 $\mathrm{m^2}$, so for 250 people the area is 500 $\mathrm{m^2}$. The mean effluent ammonia concentration is given by equation 3.10, assuming an OTR of 28 g $\mathrm{O_2/m^2}$ day, as:

$$C_\mathrm{e} = C_\mathrm{i} - \frac{(\mathrm{OTR})(A/Q) - (L_\mathrm{i} - L_\mathrm{e})}{4.3}$$

$$= 50 - \frac{(28)(500/50) - (150 - 20)}{4.3} = 15\ \mathrm{mg\ N/l}$$

i.e., an ammonia removal of 70 percent.