CONSTRUCTED WETLANDS IN ON-SITE WASTEWATER SYSTEMS

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Abstract

Constructed wetland technology is being applied to a range of water quality improvement situations in many parts of the world. Applications include the treatment of stormwater, polishing of effluent from large centralised sewage treatment works, and more recently the treatment of relatively concentrated effluents like landfill leachate and piggery washdown water. The technology has been applied to on-site domestic wastewater management in Europe and North America for several decades and is becoming increasingly popular in parts of Australia. The most widely used wetland design for on-site wastewater management has been the horizontal sub-surface flow (reed bed) configuration, however other variants have recently emerged. This paper reviews current experience with constructed wetland technology in the on-site domestic context. An outline of the main treatment processes operating in wetlands throws light on the various reed bed configurations currently in use and under development, leading to an understanding of their strengths and weaknesses with respect to the treatment of various pollutants. While constructed wetlands take up more space than more energy intensive treatment technologies they have the advantage of being relatively low-tech, easy to maintain, robust under peak loadings and aesthetically pleasing. The inclusion of wetlands in on-site systems leads to reduced disposal area requirements (under AS/NZS 1547:2000) because of the removal of BOD, suspended solids, pathogens and nitrogen from effluents. For this reason wetlands are particularly well suited to situations with disposal area limitations.

Keywords

Constructed wetlands, nutrients, on-site wastewater management, reed beds, water quality

1 Introduction

Domestic on-site wastewater management systems have traditionally consisted of three basic elements: the source (typically a household or cluster of houses), a collection device (typically a septic tank or grease trap) and a disposal field (usually an absorption trench). In such systems water quality improvement can occur in the collection device and (under favourable conditions) below the absorption trench. In recent years, with increasing levels of rural residential and unsewered peri-urban development on small blocks there has been a growing interest in additional strategies such as source control, reuse (as opposed to disposal) and secondary treatment. While source control and reuse are respectively the first and second best options from the resource management perspective, it is apparent that it will take some time for these approaches to make a major impression in the Australian on-site arena. On the other hand the practice of placing a dedicated secondary treatment device between the collection and disposal stages of the wastewater management train is becoming widespread. In Australia the most common approach to secondary treatment has been the aerated wastewater treatment system (AWTS), while in North America sand filters have been popular. The use of sub-surface flow constructed wetlands or reed beds for small to medium scale wastewater treatment has developed in Europe over the past three decades. Interest in this "natural", low maintenance approach to wastewater treatment has grown in Australia in recent years and, as familiarity with the technology grows, it is becoming more widely accepted.

This paper is based on experience with reed beds on the NSW North Coast over the past five years. It aims to describe the main features of reed beds as secondary treatment devices in domestic on-site systems, to identify their strengths and weaknesses, and to point the way towards future developments.

2 Subsurface Flow Constructed Wetlands (Reed Beds)

2.1 Function and applicability

In the natural environment wetlands provide a number of ecosystem services including hydrologic buffering and wildlife habitat. Wetlands also have a water quality control function in the environment, and for this reason they have been called the "kidneys of the catchment". After passing through a wetland water typically emerges with a reduced pollutant load. While much of our natural wetland heritage has been drained or filled in for human use, recent decades have seen a movement towards wetland restoration and even towards the creation of artificial or constructed wetlands. By virtue of their intended function as water quality improvers these constructed wetlands could be likened to "kidney transplants" into the ecological organism.

A form of constructed wetland which closely mimics natural wetlands in structure and function is the free water surface (FWS) wetland which typically consists of a shallow (<1m deep) inundated area populated by wetland plants, usually emergent macrophytes such as reeds and rushes. These FWS wetlands have been shown to be effective at removing biochemical oxygen demand (BOD), total suspended solids (TSS), pathogen indicators and nutrients from polluted water, and have become a standard tool in the repertoire of wastewater and stormwater managers. Pollutant removal occurs via a number of physical (eg settling and filtration), biological (eg plant nutrient uptake and predation) and chemical (eg nitrification and phosphorus precipitation) processes (Reed *et al.*,1995). Many of these chemical processes are a result of microbially mediated reactions occurring in the biofilm surrounding the submerged portion of the macrophyte stem (IWA, 2000).

A second type of constructed wetland is the subsurface flow (SSF) wetland or reed bed, a submerged bed containing a porous medium of gravel, sand or soil about 0.5 m deep supporting aquatic macrophytes. Water flows horizontally (hence the name horizontal flow or HF wetland) through the pore spaces between the media and plant roots which provide a large surface area for colonisation by the pollutant removing biological communities. While treatment occurs as a result of the same combination of processes occurring in FWS wetlands, the increased amount of reactive surface area per unit volume in SSF wetlands means that they produce higher rates of pollutant removal per unit of wetland area. On the other hand they are more expensive to construct because of the added cost of the media. Reed *et al.* (1995) suggest that the oxygen exuding plant roots provide aerobic micro-sites in the largely anaerobic environment of the reed bed thus creating conditions for a variety of water purifying chemical reactions. These authors also report that, while some large SSF wetlands have been built (up to 13 ML/d), they are usually not an economical proposition above design flows of 0.25 ML/d or roughly 1200 equivalent persons (EP). Reed beds are popular in Europe and it is estimated that 95% of the 10,000 or so constructed wetlands built there are of the SSF type. Platzer (2000) estimates that roughly 90% of these are in on-site domestic wastewater treatment systems with a capacity between 4 and 10 EP. Larger systems are used to provide secondary wastewater treatment for villages of up to 1,000 EP (Vymazal, 1997).

Studies in Australia (Bavor *et al.*, 1989; Davison *et al.* 2000) and overseas (Reed *et al.*, 1995) have shown that reed beds are very effective at removing BOD and total suspended solids TSS with load removal efficiencies of over 90% being common after only three or four days residence. With residence times of a week, total nitrogen (TN) load removal efficiencies of over 50% are commonly achieved (Davison *et al*., 2000). Experience also shows that faecal coliform concentrations can be reduced by two to three logs (99% to 99.9% removal) after a week's residence. Reed beds will commonly remove phosphorus from wastewater for a limited period prior to saturation of adsorption and precipitation sites on the substrate. Studies on the NSW North Coast show that the emergent macrophytes used in reed beds have high crop factors (>2) and hence can considerably reduce the hydraulic loading to the disposal area in dry weather (Headley *et al*., 2001). Conversely an uncovered reed bed will take in incident rainfall during wet weather thus increasing hydraulic load and reducing residence time during wet periods. While most theoretical models for reed bed treatment predict a decline in performance with falling temperature, experience shows that treatment continues, even in sub-zero atmospheric conditions. In a study of two reed beds in the subtropics Headley and Davison (1999) found no significant difference in performance between winter, spring and summer monitoring periods.

In the context of an on-site wastewater management system disposing of effluent through irrigation, reed beds offer the following advantages:

- filtering action, thus reducing the risk of downstream clogging by suspended solids;
- odour reduction by virtue of the removal of BOD;
- some disinfection (but usually not sufficient to achieve the 30 cfu/100 mL faecal coliform concentration necessary to allow above ground irrigation);
- phosphorus removal for a limited time (depending on P loading and media material);
- nitrogen removal; and
- minimal risk of mosquito breeding and direct human contact because water flows below the media surface.

For on-site systems disposing via trenches the removal of BOD and TSS provided by SSF wetlands ensures a reduction in the degree of biomat clogging at the trench-soil interface. Accordingly AS/NZS 1547:2000 permits a 50% to 67% reduction in absorption trench area for new on-site systems with an appropriately sized reed bed installed between septic tank and trench. Converse and Tyler (1994) report that clogged absorption trenches actually recovered when a BOD removing treatment element (in this case AWTS), was installed between the septic tank and trench. Headley and Davison (1999) indicate that reed beds handle peak loadings well, with effluent water returning to pre-peak quality within days of the flow returning to design levels.

2.2 Structural features

Figure 1 illustrates the main features of a typical reed bed. Depth of media can vary from 0.3 to 0.6 m with 0.5 m being common. The skin or shell of the reed bed should be impermeable, durable and be able to resist penetration by macrophyte roots. Materials that have been used on the NSW North Coast include reinforced concrete, ferro-cement, stainless steel, polyethylene cattle troughs, fibreglass troughs, sealed concrete blocks laid on concrete slab, and flexible liner membranes. This author's current preference is for a 0.75 mm polypropylene liner in an excavated hole. When using a plastic liner it can be advisable to place either sand or geo-fabric as a cushion between the liner and soil to avoid penetration by sharp objects embedded in the soil.

The choice of wetland substrate will depend on the type and quality of influent and the desired quality of effluent. As a rule, media consisting of larger particles will have higher hydraulic conductivities and be less prone to clogging. Smaller particles will offer greater reactive surface area per unit volume but will be more prone to clogging. Because clogging is most likely to occur in the entrance zone of the wetland it is desirable to surround the inlet device (in the case of Figure 1, a 100 mm horizontal pipe) with stones of about 100 mm diameter.

The inlet device should extend the full width of the wetland and can be above or below the surface. A below-surface inlet device distributes influent more evenly throughout the depth profile thus enhancing hydraulic efficiency. A negative aspect of this arrangement is reduced access to the inlet device should maintenance be required. Some designers prefer to create an open water area at inlet and/or outlet using a baffle to exclude gravel, thus minimising the risk of macrophyte root invasion of these areas. When treated effluent is being disposed into a soil with low phosphorus sorption capacity it can be advantageous to use a wetland substrate such as crushed brick which has a strong affinity for that nutrient. Adcock *et al.* (2000) report that loam soils are sometimes used as reed bed media in Europe because of their high P uptake. However, Reed *et al.* (1995) sound a note of caution in relation to the use of soils as media because their lower hydraulic conductivity makes them highly susceptible to clogging. All commonly used media, including sands gravels and soils have an initial porosity of approximately 40%. This decreases with time as pore spaces become occupied by macrophyte roots and effluent borne solids.

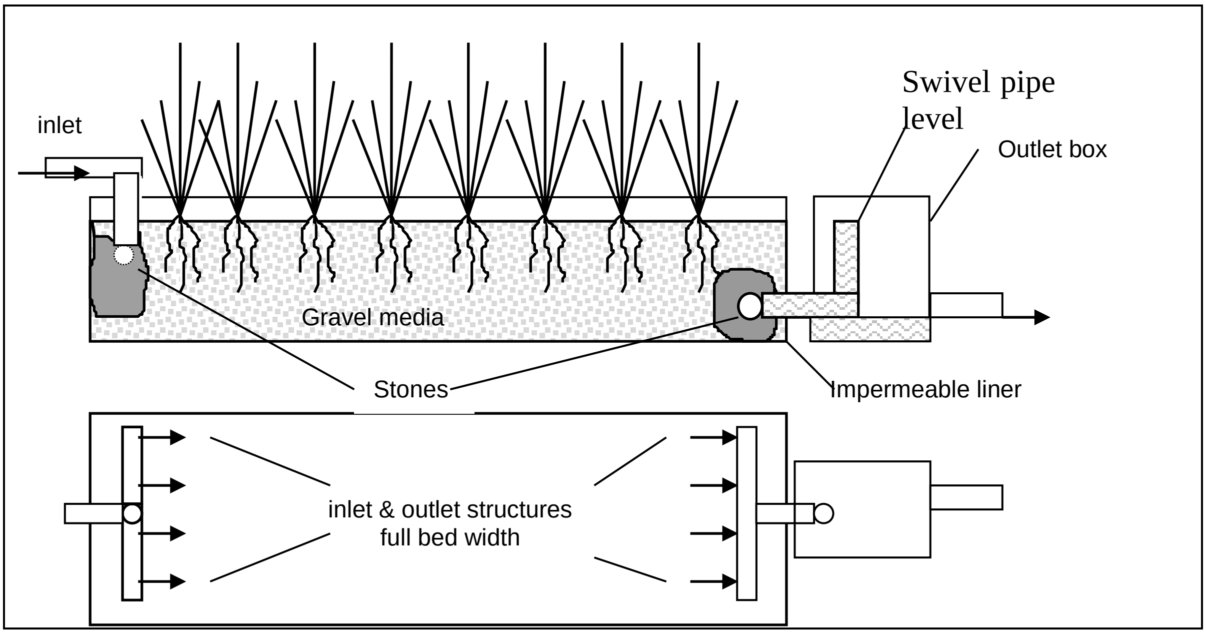

Figure 1: Elevation and Plan Views of Typical Horizontal Subsurface Flow Wetland

Because substrate clogging by refractory solids is the main factor limiting the useful life of reed beds, an appropriately sized and regularly maintained primary treatment device is necessary to minimise solids buildup and extend wetland life. Volatile solids breakdown can be assisted by periodic lowering of the water level. Davison *et al.* (2000) report an instance of one reed bed that has been colonised by earthworms (*Eiseniella tetraedra*) which appear to be translocating solids from the lower, inundated layers to the surface zone where aerobic conditions enhance breakdown.

Most reed beds built on the NSW North Coast have been planted with *Phragmites australis* (common reed). Other commonly used macrophytes are *Schoenaplectus validus* (giant club rush) and *Typha orientalis* (bull rush). Tube stock may be purchased from nurseries that specialise in wetland plants. These plants can also be propagated vegetatively by dividing root clumps obtained from exiting wetlands.

2.3 Design, Sizing and Management of Reed Beds

In order to minimise short-circuiting and the formation of dead zones (ie maximise hydraulic efficiency) reed beds are normally created with a rectangular plan and an inlet device which distributes the influent evenly across the entrance zone. Platzer (2000) recommends a flat bed and a relatively short hydraulic path. Longer reed beds (>20 m.) will require a sloping bed to maintain an even depth during design flow conditions. Problems can arise with longer beds under reduced or zero hydraulic load conditions when the inlet end drains, leaving macrophytes without water. It is common practice to install a swivel pipe or similar device as part of the reed bed outlet structure to facilitate water level control (Figure 1). In this way the wetland can be flooded to help with control of terrestrial weeds during establishment. Also, lowering the water level can create aerobic conditions in the upper layers thereby assisting breakdown of volatile suspended solids in the media interstices and extending wetland life. It is common practice, when hydraulic loads are sufficient, to design systems with two or more wetlands in parallel. This way one wetland can be taken offline for maintenance or to allow water level drawdown for substrate declogging.

There are a number of approaches to sizing reed beds ranging in complexity from the application of simple rules of thumb up to the use of models such as those developed by Reed *et al*. (1995) who present a design procedure based on hydraulic loadings and desired level of treatment. In the case of domestic wastewater, where it is common, at the design stage of a project, to assume typical influent concentrations and to aim for a certain level of purity (eg secondary standard of 20 mg L^{-1} BOD and 30 mg L^{-1} TSS), it is often sufficient to size a wetland (ie determine the required surface area) on the basis of a particular nominal hydraulic residence time (HRTn). This can be done quite simply by applying the relationship:

$$\text{Area } (m^2) = \{\text{HRTn (d) x hydraulic loading } (m^3/d)\} \,/\, \{\text{depth(m) x porosity}\} \quad (1)$$

If we assume that a nominal residence time of five days is required to achieve the above effluent quality, and specify a depth of 0.5 m with an initial porosity of 0.4 (pre clogging and root penetration), then a family of three, generating 500L (0.5 m^3) per day will require a reed bed with surface area:

$$A = 5 \times 0.5 / (0.5 \times 0.4) = 12.5 \text{ m}^2$$

A single reed bed 6.3m x 2m or two beds in parallel (each say 4.2m x 1.5m) would do the job. The figure of 12.5m^2 for three people, or just over 4 m^2 per person, agrees approximately with the rule of thumb mentioned by Vymazal (1997) who suggests that 5 m^2 per person is appropriate in the Czech Republic to achieve a secondary treatment standard. In Australian subtropical conditions a figure of 4 m^2 per person is sometimes applied as a rule of thumb for secondary treatment of combined black and greywater, and 2 m^2 per person for greywater only.

Reed beds require minimal maintenance. Harvesting of reeds, while not necessary, does promote fresh green growth and thus enhance a reed bed's aesthetic appeal while resulting in increased nutrient removal. This job is easily performed using a sharp knife or sickle and it takes only ten or fifteen minutes to harvest a family-sized bed. January (after the spring/summer growth flush) and May (prior to dormancy) are probably the optimum harvest times from the perspective of both nutrient removal and aesthetics. The cut material can be used as mulch.

3 Dealing with Nitrogen: other SSF wetland configurations

A number of councils in NSW now consider total nitrogen (TN) (as well as hydraulic and phosphorus) loading when determining disposal area size. In many situations TN loading will be the determining factor, and hence TN removal can become a major objective of effluent treatment. A number of recent studies on the NSW North Coast indicate that the TN load in wastewater will probably halve after seven days in a reed bed (Davsion *et al.*, 2000). The family in the example above would require an additional 5 m^2 of reed bed area to obtain the 17.5 m^2 necessary to achieve this seven-day residence time.

Numerous studies have indicated that the major TN removal pathway in HF wetlands is via nitrification / denitrification and that the aerobic nitrification process is the limiting step (Reed *et al.*, 1995). This fact has led to a growing interest in the vertical flow (VF) configuration.

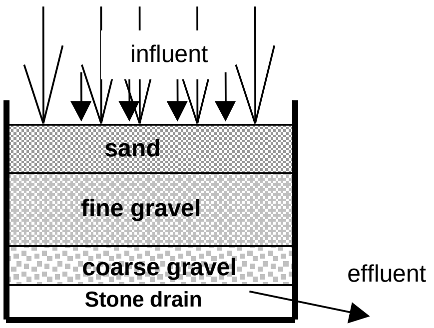

Figure 2: Typical Vertical Flow Wetland Structure

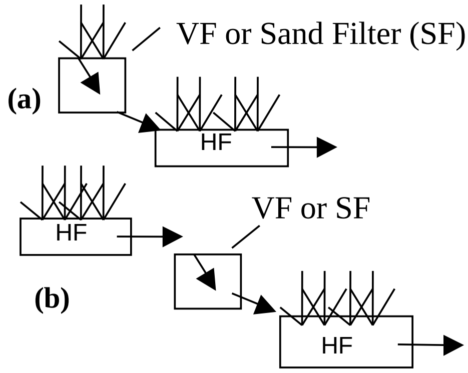

Figure 3: (a) VF (SF) – HF sequence
(b) HF-VF (SF) -HF sequence

A typical VF wetland consists of a 100-150 mm layer of sand (into which reeds are planted) above successive layers of increasingly coarse gravel grading into an underdrain that collects the treated effluent (Figure 2). The bed surface is flooded intermittently in such a way that the substrate is subjected to a wetting-drying cycle in which both nitrification and denitrification occur. Treatment occurs as water flows downwards over the biofilms attached to the substrate and plant roots.

It has been common practice to build VF wetlands in pairs with one unit drying and re-aerating while the other is being loaded. Such a regime requires a high level of operator involvement, thus making VF wetlands unsuitable for small systems. This deficiency appears to have been addressed in the development of the “second generation” (G2) VF wetlands in which the sand layer is deepened to 60cm to create a device which resembles a single pass sand filter planted with reeds. Wheedon (2001) reports that a single G2-VF wetland in the UK loaded at $2m^2$ per EP, receiving influent as generated (ie no resting period) achieved TN removal efficiencies exceeding 60%. Further TN removal in an 800 mm deep holding pond following the G2-VF wetland brought overall TN reduction in the system to over 80%. In a study of a HF wetland followed by pond in northern NSW, Headley and Davison (1999) reported similar reductions in TN. The additional disinfection generated by the pond is a further bonus.

Table 1 summarises the author's view of the attributes of HF and VF wetlands and compares them with other commonly used secondary treatment devices. Because of their complementary capabilities with respect to nitrification and denitrification VF and HF wetlands can be used in tandem as shown in Figure 3(a) to achieve higher TN removals than are possible in the individual elements. In Figure 3(b) this VF-HF combination is preceded by a small HF stage to remove solids and protect the sand layer in the VF stage from clogging.

Further improvements to wetland nitrogen removal performance can be achieved by increasing the technological complexity and energy consumption of the system. Figure 4 shows a configuration described by Reed *et al.* (1995) in which TN removal in a HF wetland is enhanced by recirculating a proportion (usually about 75%) of the effluent to an aerobic device (eg VF wetland, sand filter or trickling filter) above the front end of the HF wetland. The recirculated effluent, having been subjected to the nitrifying environment of the aerobic device is subsequently denitrified in the HF wetland with the help of labile carbon in the high BOD influent.

Table 1: Comparison Between Attributes of Secondary Treatment Devices
(Author's Views)

	AWTS	SINGLE PASS SAND FILTER	RECIRCULATING SAND FILTER	REED BED (HF WETLAND)	VF WETLAND
power required?	yes	no	yes	no	pump needed on flat ground
surface area	small	Small to moderate	relatively small	moderate 5 m^2 / EP	moderate 2-5 m^2/EP
maintenance	high	moderate	moderate	low	low
recurrent cost	hundreds $ p.a.	owner can do	owner can do	owner can do	owner can do
capital cost	high	moderate	high	moderate	moderate
nitrification	good	good	good	moderate	good
denitrification	poor	poor	good	good	moderate
aesthetics?	no	no	no	yes	OK
awareness?*	no	no	no	yes	yes

* Does the device invite the participation, and hence the awareness and commitment of the user?

Behrends *et al.* (2000) describe an arrangement in which polluted water is transferred between two VF wetlands every few hours (Figure 5). This "reciprocating wetland" configuration causes the biofilms on substrate and plant roots to continuously cycle through aerobic, anoxic and anaerobic conditions thereby creating a situation in which BOD, nitrogen and other recalcitrant compounds are removed from the water

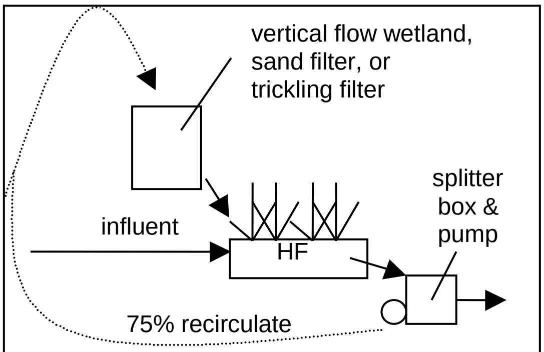

Figure 4: VF-HF Combination with Recirculation

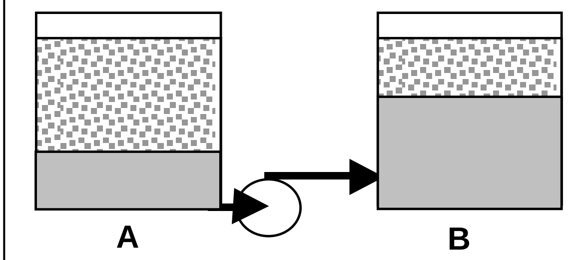

Figure 5: Reciprocating Wetlands During Transfer from A to B

4 Conclusion

The horizontal subsurface flow (HF) constructed wetland is a relatively well understood, low maintenance, easily built, relatively cheap, natural technology suited to on-site situations where there is a need for secondary treatment. Experience has shown that reed beds can bring domestic septic tank effluent to secondary treatment standards with residence times of four to five days. Longer detention is required to remove nitrogen. Phosphorus removal can be quite high in the early stages of use but falls away with time. Faecal coliform reductions of 2 to 3 logs can be obtained with detention times of up to a week. Because the useful life of HF wetlands is limited by substrate clogging it is advisable to ensure that the primary treatment device is effective and well maintained. Recent developments in vertical flow (VF) wetland technology offer increased opportunities for improved levels of nitrification. Complex systems in which HF and VF wetlands are combined, or in which effluent recirculation is introduced, are being developed to treat a range of effluents and can be applied economically to larger on-site domestic systems such as housing clusters, small villages, motels, schools and camping areas.

References

AS/NZS 1547 2000 *On-site Domestic Wastewater Management*, Standards Australia.

Adcock, P., Gill, L and Barlow, J. 1999 Reed beds take on industrial waste, *Water 21,* Sept.

Bavor, J., Roser, D.J., Fisher, P.J. and Smalls, I.C. 1989 Performance of solid-matrix wetland systems, viewed as fixed-film bioreactors, in D.A. Hammer (Ed.) *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural,* Lewis, 646-656.

Behrends, L., Houke, L., Bailey, E., Jansen, P. and Brown, D. 2000 Reciprocating constructed wetlands for treating industrial, municipal and agricultural wastewater, in *Proceedings of 7th International Conference on Wetland Systems for Water Pollution Control*, Orlando, Florida, Nov. 11-16, 1043-1050.

Converse, J.C. and Tyler, E.J. 1994 Renovating failing septic tank-soil absorption systems using aerated pretreated effluent, in *Proceedings of 7th International Symposium on Individual and Small Community Sewage Systems*, 11-13 Dec. Atlanta, Georgia.

Davison, L., Headley, T. and Edmonds, M. J. 2000 Performance of Small Subsurface Flow Wetlands in the Moist Subtropics, in *Proceedings of 7th International Conference on Wetland Systems for Water Pollution Control,* Orlando, 11-16 Nov., 911-918.

Headley, T. and Davison, L. 1999 On-site Treatment by Reed Bed and Pond: a Study of Two Systems, in *Proceedings of On-site '99 - Making On-site Systems Work*, Conference University of New England, Armidale, NSW, July, 165-173.

Headley, T., Huett, D. and Davison, L. 2001 Treatment of nitrified wastewater using reed beds, in *Proceedings of On-site '01 - Advancing On-site Systems,* University of New England, Armidale, NSW, 25-28 Sept.

International Water Association Specialist Group 2000 *Constructed Wetlands for Water Pollution Control*, Scientific and Technical Report No.8, IWA Publishing, London.

Platzer, C. 2000 Development of reed bed systems – a European perspective, in *Proceedings of 7th International Conference on Wetland Systems for Water Pollution Control,* 11-16 November 2000, Orlando, Florida, 23-28.

Reed, S.C., Crites, R.W. and Middlebrooks, E.J. 1995 *Natural Systems for Waste Management and Treatment*, McGraw Hill, New York.

Vymazal, J. 1997 Subsurface horizontal flow constructed wetlands for wastewater treatment - the Czech experience, *Wetlands Ecol. Mgmt* **4**, 199-206.

Weedon, C.M. 2001 Compact vertical flow reed beds: design rationale and early performance, *The use of macrophytes in water pollution control,* Newsletter No. 23, IWA, London.