Investigation into the Application and Performance of Constructed Wetlands for Wastewater Treatment in South Africa

A Wood

Report to the Water Research Commission
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No general consensus exists on the overall advantages of the FWS versus SF Constructed Wetland systems, since each application is very much site specific and largely dependent upon land availability, and construction costs and treatment objectives.

Advantages of the FWS are generally lower installation cost and potentially simpler hydraulics.

Advantages of the SF Wetlands are minimisation of vector and odour problems, and possibly greater assimilation potential per unit area of land in terms of organic and nutrients, particularly where winter temperatures are low (Reed 1993). However, the provision of a suitably permeable media tends to be the most expensive component of the SF systems, and the factor responsible for the majority of treatment problems when permeability is not adequately catered for (Crites 1992).

Table 3 illustrates process criteria for Free Water Surface (FWS) and Subsurface Flow (SF) Constructed Wetlands (adapted from Reed (1992) and Knight (1992))

Table 3 Process Criteria for Constructed Wetlands

Surface flow Subsurface flow

Factor	Typical FWS	Typical SF
Detention time, d	5 - 14 10 days	2 - 7 5 days
Max BOD loading rate, kg/ha.d	80	75
Water or Media Depth, m	0.1 - 0.5	0.10 - 1.0 0.6m
Hydraulic loading rate, mm/d	7 - 60	2 - 30
Aspect Ratio ℓ to w	2:1 to 10:1	0.25:1 to 5:1
Mosquito Control	Required	Not required
Harvest Frequency, yr	3 - 5	3 - 5

N.B. It should be recognised that areal requirements relate to the variations in wastewaters that the systems are generally designed to receive. The FSW systems are usually receiving pretreated or secondary wastewaters while the SF systems often receive primary wastewaters. The SF systems are also often a component of an integrated system where the discharge from the SF system passes to a FWS for polishing.

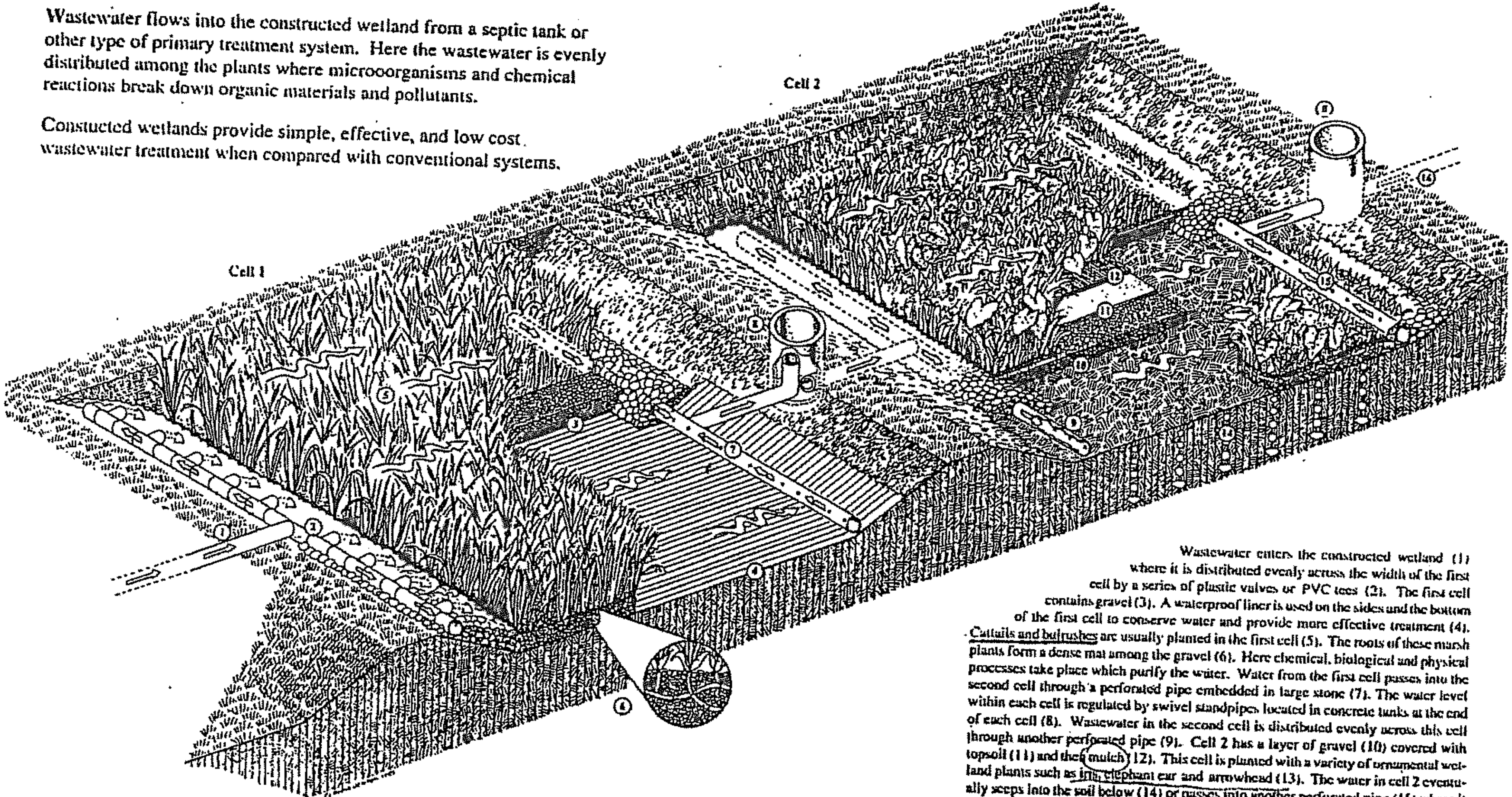
The earlier European design basis for soil media SF systems recommended an areal equivalent of 2 m^2/person equivalent (p.e.) (Kickuth 1984), but this was subsequently raised to 5m^2 to account for permeability limitations found with higher loading rates to soil based systems, and the tendency to short-circuit by surface rather than subsurface flow (Cooper 1990).

In further developing the SF concept in Europe, systems have tended to move towards gravel beds to maintain hydraulic control, with >100 systems applied in the UK. A Constructed

Constructed wetlands like this one are being built throughout the nation to handle wastewater from mostly small rural communities and homes where traditional treatment systems are a problem.

Wastewater flows into the constructed wetland from a septic tank or other type of primary treatment system. Here the wastewater is evenly distributed among the plants where microoorganisms and chemical reactions break down organic materials and pollutants.

Constucted wetlands provide simple, effective, and low cost wastewater treatment when compared with conventional systems.



Wastewater enters the constructed wetland (1) where it is distributed evenly across the width of the first cell by a series of plastic valves or PVC tees (2). The first cell contains gravel (3). A waterproof liner is used on the sides and the bottom of the first cell to conserve water and provide more effective treatment (4). Cattails and bulrushes are usually planted in the first cell (5). The roots of these marsh plants form a dense mat among the gravel (6). Here chemical, biological and physical processes take place which purify the water. Water from the first cell passes into the second cell through a perforated pipe embedded in large stone (7). The water level within each cell is regulated by swivel standpipes located in concrete tanks at the end of each cell (8). Wastewater in the second cell is distributed evenly across this cell through another perforated pipe (9). Cell 2 has a layer of gravel (10) covered with topsoil (11) and then mulch (12). This cell is planted with a variety of ornamental wetland plants such as iris, elephant ear and arrowhead (13). The water in cell 2 eventually seeps into the soil below (14) or passes into another perforated pipe (15) where it is released into a drainfield similar to those used with conventional septic tanks (16).

CUTAWAY PERSPECTIVE OF A CONSTRUCTED WETLANDS SYSTEM

FIG No.
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6.5 Kruger National Park

The Kruger National Park has readily adopted the Wetland technology for the treatment of the wastewaters generated by the camps throughout the park. The larger camps, such as the Lethaba, Skukuza and Olifants, which accommodate up to 3 000 persons are provided with conventional Oxidation Pond systems, whilst the smaller camps of Crocodile Bridge and Shingwedzi are serviced by septic tanks. The Wetlands units are constructed as horizontal flow SF units operating with two cells in series. The sizing is based on accommodating the peak flow of the maximum number of visitors, or $5\ m^2$/person. The beds are nominally 1.0m deep of a sand media and planted generally with *Frogmouths Sp.*

6.6 Pilansburg Game Reserve

The Wetland system at the Bakgatla Gate site of the Pilansberg National Park was constructed to treat septic tank effluent for a peak population of 300 persons, in a SF horizontal flow gravel bed planted with *Frogmouths Sp.* The Wetland was a single unit 60 m wide by 20 m long to accommodate available space and optimise the hydraulic distribution of the wastewater across the inlet zone. The media is a sand base with inlet and outlet areas of graded gravel.

6.7 Pietersburg Truck Stop

A truck rest stop, cafeteria and petrol station in Pietersburg has a 2 stage horizontal flow SF, gravel channel Wetland constructed to accommodate the septic tank effluent discharge flow of 50 m^3/d. Each cell being 5 m wide, 50 m long by 0.75 m deep, and planted with *Typha Sp.*

6.8 Klipdrift

A construction camp and service depot for the railways at Klipdrift had a single stage horizontal flow SF gravel and ash Wetland constructed to treat septic tank effluent at a flow of 40 m^3/d. The cell was nominally 7.5 m wide, 30 m long by 0.75 m deep, and planted with *Frogmouths Sp.*

6.9 Middelburg

A rest stop, cafeteria and petrol station in Middelburg had a single stage horizontal flow SF gravel Wetland constructed to polish the effluent from a Rotating Biological Contractor system prior to chlorination and discharge. The design flow was a peak flow of 80 m3/d. The cell was nominally 10 m wide by 20 m long by 0.45 m deep, and planted with *Typha Sp.*

3) Maintain Wetland inlet and outlet zones and system surrounds clear of excessive grass and weed encroachment.

4) Flush inlet distribution pipelines regularly ie at least monthly, to remove accumulate solids blocking outlets points. This can easily undertaken by shutting off all other Wetland inflows to cause all wastewater to flush through the one pipeline being cleared at a time.

5) Monitor inflow distribution across the bed width to ensure that the inlet pipe system is appropriately levelled and that a nominally even flow is provided across the whole bed inlet zone.

6) Clear gravel and associated vegetation from around the influent pipe distribution nozzles and allow wastewater to flow freely onto the inlet zone.

7) Replace *Arundo donax* (Spanish Grass) in beds 4 & 5 with *Frogmouths* reed as possible.

8) Replace inlet flow metres as possible.

9) Drain beds down on a monthly basis to assist in the redistribution of solids matter accumulating within the bed, and particularly from the inlet zone, and to introduce aeration to the lower bed levels.

10) Clear inlet zone of excessive surface solids and surface slimes accumulation during drainage exercises.

11) Operation of the Wetlands with the outlet drain position set at a mid-point level to enhance aeration of the wastewater as it transfers through the upper levels of the Wetland, as hydraulic load permits.

7.5 KRUGER NATIONAL PARK

7.5.1 System Configuration

The Kruger National Park has adopted the Wetland technology for the treatment of the wastewaters generated by the camps throughout the Park. The larger camps, such as Lethaba, Olifants, and Skukuza were initially provided with conventional Oxidation Pond systems, whilst the smaller camps of Crocodile Bridge and Shingwedzi were identified as suitable for Constructed Wetlands at a time when the Wetland technology in South Africa was just being introduced in the late 1980's. During 1992-93 the Park installed Wetland systems at each of their camps either to polish pond effluent or to treat the septic tank effluent directly. There are presently 17 systems in operation

The Wetland units generally follow a common format, being designed to accommodate the maximum possible number of visitors that are to be accommodated at the camp at any one time, and then providing an additional contingency of ± 25% to account for limitations in the knowledge of the technology and the desire to be conservative rather than risk further problems. Additional contingency is built into the hydraulic capacity of the beds in that the media depth has been set at 1 000 mm, rather than the generally accepted depth of 600 mm for Rootzone systems, but less than the Mpophomeni bed depth of 1 500 mm which was used as an example of the technology at the time of the initial interest in the approach.

The Wetland systems also generally consist of two beds of river sand operated in series to ensure adequate organic load capacity and disposal of effluent via evaporation and infiltration from the bed rather than unnecessary discharge to the local rivers, which would inherently attract wildlife to the discharge which is also undesirable.

7.5.2 Wastewater Treatment Performance

Table 22 illustrates the performance of 3 Kruger Park constructed wetland systems receiving septic tank effluent. The Crocodile Wetland indicates a better PO_4-P removal efficiency than the other systems which is believed to be a result of the greater PO_4-P adsorption potential of the sand media in this system, and partially the significantly denser vegetation development in the Crocodile system which has been in operation for > 7 years.

COD and SS removal has generally been as good as would be expected from basically sand filtration beds, but the presence of surface short-circuiting at Mobeni and Tshokwane, and containment of the effluent in the discharge sumps allowing algal and bacterial development, results in elevated effluent pollutant qualities.

NH_3-N removal is limited by the ability of the nitrifying bacteria to compete for the available oxygen in the system. Although > 70% removal in NH_3 -N is indicated for the Crocodile bridge system this is achieved at an HRT in excess of 5 days (assuming minimal short-circuiting potential). Each of the other sites where an effluent is being discharged from the primary Wetland demonstrate significantly poorer NH_3-N removal efficiency, generally < 25%. This poor performance is primarily related to poor vegetation development on the bed surface and the propensity to short-circuit.

Each of the Wetland, has a second Wetland cell to receive the overflow. Usually the discharges from the primary beds is adsorbed within the secondary beds and no final discharge occurs. Although this suggests the Wetlands designed are over-sized it is necessary to see this in respect of the greater desire to protect the receiving environment and not to produce a discharge steam which may attract wildlife to the sites with consequent impact upon the integrity of the site.

7.5.3 Crocodile Bridge Wetland System

The Crocodile Bridge Wetland system one of the two original Wetland units has received septic tank effluent for almost 7 years with little direct management other than occasional removal of excess above ground plant. The system consists of two beds of river sand operated in series of which only the first Wetland has to date been planted with *Frogmouths*. The second Wetland is to contain and polish discharges from the first Wetland prior to discharge to the Crocodile river.

Table 22. Performance of 3 Kruger Park Constructed Wetland System Receiving Septic Tank Effluent

	Crocodile Bridge	Crocodile Bridge	Mopani	Mopani	Shingwedzi	Shingwedzi
	In	Out	In	Out	In	Out
pH	7.55	7.25	7.3	7.65	6.9	7.15
TDS	787	748	929	1187	518	570
Ec	108	102	127	158	72	79
T.Alk	390	215	510	175	250	325
COD	166	23	142	35	135	30
OA	23	11	18	12	18	10
NH_3-N	44	10.5	25	29.25	36	33
PO_4-P	6.4	1.3	5.6	6.2	7.2	5.4
Ca	37	35	25	36	29	39
Mg	22	33	55	66	15	17
Na	105	105	121	204	46	66
Cl	90	99	105	138	31	34
SS	4	3	28	4	15	3.5

7.5.4 Hydraulic Characteristics

Based upon a projected HRT of the order of 72-96 hours, automatic samplers were only set to sample the discharged effluent over the first 48 hours to indicate any early break through and to provide an indication of the treatment performance, whilst visual observation by the plant supervisor over following days was undertaken to indicate the release of the dye and the extent of the discharge pattern.

The period over which dye emerged from the bed clearly illustrated that the Wetlands are not operating in a distinct plug flow mode, but that there is internal mixing, diffusion and retention in the path between input and output. The tracer studies also illustrate that if

The experience of Ladybrand has clearly illustrated the difficulties in optimising vertical flow through a coarse media to optimise retention within the wetland and to minimise short-circuiting. In such cases, a sand media would be preferable for vertical flow systems.

Despite less than optimal flow conditions and limited plant contributions to pollutant removal, the South African systems do demonstrate significant potential for wastewater treatment. Surface flow systems receiving secondary sewage can achieve removals of COD and SS up to 20 g/m²/d, NH_3 and NO_3 removal up to 1.5 and 6.0 g/m²/d respectively, but limited pathogen removal of 99%, and low phosphate removal. Subsurface flow soil systems are severely limited by permeability, but where flow is maintainable for secondary wastewaters, COD, SS, NO_3 and PO_4 removal can be in excess of 85%, and pathogen removal of 10^5 fold, but NH_3 removal is low, <30%, due to poor oxygen transfer to the rootzone. Subsurface flow gravel beds can achieve high COD removal rates at loadings up to 100 g COD/m²/d with settled sewage, acting as anaerobic filters. Secondary units are then required to polish residual organic, nutrients and pathogens.

9 GUIDELINES FOR THE IMPLEMENTATION OF CONSTRUCTED WETLANDS

9.1 Primary Wastewater Treatment

- For the treatment of primary wastewaters such as septic tank and anaerobic pond effluents, agricultural and industrial wastewaters with an organic character (>500 mg/ℓ COD), it is recommended that a gravel bed SF system be implemented to provide primary organic reduction in conditions that will limit odour generation.

9.2 Maximum Loading

- Primarily based upon the detailed investigations of the South African CSIR, loading to the primary bed can be as high as 100 gCOD/m²/d and 1 000 ℓ/m²/d with an expectation of > 60% reduction in COD and SS. In practice, it is recommended that at least two primary beds each loaded at a maximum of 50 gCOD/m²/d be constructed to provide flow and load contingency.

9.3 Bed Depth and Media

- To optimise anaerobic processes in the bed depth and allow extended degradation of residual solids and organic whilst minimising odour generation potential and possible toxic effects on the plant community, the primary bed may be 700-1 000 mm deep containing washed gravel of 20-40 mm diameter and void fraction of > 50%.

9.4 Inlet Distribution

- Wastewater should as far as possible be introduced across the full bed width. To further optimise and control hydraulic integrity the length : width ratio should be as great as practical site topography and permeability (K_f) potential of the media, as determined by D'Arcy's Law, will allow at the given hydraulic loading. A minimum length to width ratio of 1:1 is recommended for washed gravel, and maximum of 3:1. The inlet zone should be of coarse media to accommodate the elevated unit organic and solids loadings and to allow clearance, as and when required.

9.5 Terracing

- Where practical a terraced arrangement and/or series of cells will allow greater hydraulic control and assist in minimising short-circuiting potential and optimises redistribution of flow. Open water and baffled areas within the flow path can assist in maintaining hydraulic integrity through the Wetland system.
- An irregular site may be adapted to provide a desired configuration by the incorporation of baffling or meandering channels in both the FWS and SF option.

9.6 Parallel Cells

- The provision of parallel discreet Wetland units allows flexibility in operation and the capacity to alternate feeding regimes to encourage simultaneous nitrification-denitrification and overall wastewater treatment potential.

9.7 Vertical Flow

- Vertical flow beds should contain graded media to restrict channelling of the wastewater directly to the underdrain. A surface layer of coarse river sand overlying pea gravel is recommended above the drainage layer. The drainage layer should be arranged to collect the underflow from across the full bed area rather than localised areas.
- Integrated vertical flow units, at $> \pm 200$ ℓ/m^2/d, should be provided with parallel cells allowing for alternate feeding and draining regimes, operating single beds on a daily basis, and return after between 3 and 6 days.

9.8 Secondary Wastewater Treatment

- Secondary treatment, after a primary SF cell, may be accomplished with either a FWS Marsh, a Pond, a shallow, (250-400 mm), gravel SF, or a Biological Trickling Filter to optimise nitrification potential. The selection being depended upon treatment priorities, site location and relative economics of SF media as compared to FWS, open pond or Biological Filtration.

9.9 Secondary Organic Loading

- Secondary FWS and SF Wetland units can be loaded at 15-30 gCOD/m^2/d or 100-200 ℓ/m^2/d with an expectation of a further 60% reduction in COD and SS load and > 30-50% reduction in ammonia. A recommended design loading would be 15 gCOD/m^2/d.

  For nitrification-denitrification in a shallow SF or FWS system a loading of 2-5 g NH_3-N/m^2 may also be applied with the recommendation being to design for a lower loading, ie 2g NH_3-N/m^2/d.

  A biofilter loaded at 5m^3/m^2/d top surface area should achieve comparable nitrification but would have limited overall NO_3-N removal if identification is required, a Biofilter may be followed by subsequent polishing through an FWS or SF Wetland.

9.10 Tertiary Wastewater Treatment

- Where a pond or shallow SF unit is utilised the resultant effluent may require final polishing. A FWS Wetland of macrophytes or grass, or a low rate or recirculating sand filter loaded at 100-200 ℓ/m^2/d should suffice.

- For PO_4-P and pathogen removal it is preferable to provide a suitable iron rich media, either as a soil or a soil-sand-gravel mix for which hydraulic permeability can be maintained either by the selection of permeable media mix, the provision of terracing or intermittent loading to draw the water through the media matrix. Coarse waste ash or equivalent may be utilised but leaching of salts and dissolution of fines inhibiting hydraulic integrity must be accounted for.

- Wetland systems are able to remove 10^3-10^5 pathogens/100 mℓ, at HRT's >7 days, but they are not expected to produce pathogen free discharges. This is due to the limited hydraulic time within the Wetland system, and the additional contribution from animal and birds frequenting the Wetland.
  If General Standard final effluent quality is required some form of disinfection should be provided.

9.11 Hydraulic Control

- Hydraulic integrity is the over-riding factor in ensuring optimal treatment performance. Outlet collection and transfer facilities between Wetland cells should allow for collection across the width of the bed and not encourage preferential flow to a single point.

- Hydraulic and Organic Loading rates indicated above should be used only as a guide and tailored to specific treatment objectives and individual site conditions.

- Recirculation of effluent between cells, the provision of aeration cascades, or more sophisticated aeration and recirculation facilities can improve overall treatment performance by providing additional hydraulic control and better distribution of the contaminant loads throughout the cells.

- Intermittently loading the cells enhances overall treatment efficiency, particularly nitrification and total nitrogen removal.

- For the maintenance and control of water level within the cells, the level of water draw-off should be flexible and adjustable.

  The basic requirements for effluent control are:

  a) When the system receives maximum flow, water mounding should not result in surface flow in the upstream section of the bed.

  b) When the system receives low flow, the outlet level should be controlled to maintain adequate water depth throughout the bed to prevent drying out of the plant root systems, particularly in highly permeable gravel horizontal subsurface flow systems.

  c) The depths of root contact in water should be as uniform as possible.

- Only where native ground conditions may make seepage excessive or threaten groundwater contamination is it necessary to seal the Wetland bed with a clay or synthetic liner.

9.12 Plants

- Local Wetland plant species, preferably *Frogmouths* should be used for the primary SF and FWS cells, although *Typha* and *Schoenoplectus* are acceptable, with dense grass such as blue, bermuda or kikuyu grass in shallow, (<100 mm) FWS/Meadow units.

- Planting density should be as numerous as economically viable to provide in relation to creating as rapid establishment of good plant cover as possible. Planting may be carried out with nursery cultivated seedlings or clumps of shoots obtained from a local natural or Constructed Wetland. Plant spacing should be ± 9/m^2 in small beds but may be reduced to ± 3/m^2, or even 1/m^2 in large Wetlands as an economy measure.

- In most cases harvesting of the vegetation is not required, but may be undertaken to encourage more complete cover of the bed surface and to discourage preferential channel formation. Where excess plant material is accumulating the bed may be burned annually without detrimentally affecting system integrity.

9.13 System Monitoring

- In order to ensure that the Wetlands are developing and subsequently operating efficiently it is advisable that regular inspections and water quality sampling an analysis be performed, and flow/water level monitoring included in the management of the systems. Monitoring of the system and plant development and basic health on a regular basis would also permit control measures to be taken timeously in the event of flow/water level and water stress problems or aphid infestations occurring.

10 CHALLENGES/FUTURE RESEARCH OPPORTUNITIES

Table 23. Challenges for Future Development of Constructed Wetlands for Wastewater Treatment and Pollution Control (adapted from Haberl 1994)

Application	Some Challenges/Research Opportunities
Treatment of Primary Settled and Secondary Treated Sewage	Provision of complete integrated Wetland systems, including nutrient removal, for all community sizes.
Tertiary Effluent Polishing	Long-term maintenance of functionality particularly in regard to phosphorus and nitrogen removal, and paltogen destruction
Domestic Water Treatment	Development of Constructed Wetland potential for providing clean drinking water in degraded catchments
Environmental Enhancement	Establishment of appropriate species diversity for integrated Wetland systems.
Urban/Rural Run-off Management	Identification of appropriate sites and strategies for Constructed Wetland systems and associated, design, operation and maintenance requests.
Toxicant Management	Development of understanding and modelling of the processes by which metals and organic can be immobilised and/or transformed
Land-fill and Mining Leachate Treatment	Development of understanding and modelling of the processes by which metals and organic can be immobilised and/or transformed
Industrial Effluents	Development of understanding and modelling of the processes by which metals and organic can be immobilised and/or transformed
Sludge Management	Long-term disposal of residues which may contain substantial levels of heavy metals and toxic material
Biomass Production	Identification and development of uses and viable markets for Wetland products
Groundwater Recharge	Development of understanding of the potential of Wetlands as Groundwater Recharge systems.
Pretreatment and Storage of Water for Reuse Schemes	Assess levels of treatment appropriate to different reuse options and local economics