CONSTRUCTED WETLANDS FOR WASTEWATER MANAGEMENT

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Abstract

The challenge for the 21st century will be the efficient use of natural resources to minimise wastage. The water in irrigation/drainage ditches of arid villages is often polluted but nevertheless is still used for drinking purposes. Constructed wetlands/reed bed treatment systems have been successfully developed for low cost and simple treatment technology. This paper explains what a constructed wetland is and its performance highlighting how long and wide it is used in Botswana and elsewhere in the world. Design example is shown for the climatic conditions of an arid zone. Most of the villages do not have electricity supply and hence the system has to work with gravity flow. Because of limited funding community participation is necessary to establish the system. The construction should wherever possible be appropriate making maximum use of local materials and labour resources. Hence constructed wetlands are ideally suitable for rapid implementation in the rural areas of developing countries. Few case studies are described. Finally the paper aims at encouraging its adoption and concludes with experimental observations and recommendations.

Key words: Constructed wetlands - low cost and simplicity - reed bed systems - effluent standards-design example

1 INTRODUCTION

.... And Noah said to his wife when he sat down to dine, " I don't care where the water goes if it doesn't get into the wine." *G.K.Chesterson, (Wine and Water)*

There is a prevailing public attitude of general unconcern over what happens to storm or drainage wastewater as long as it is out of sight! Constructed wetlands (CWLs) are designed and man-made complex of saturated substrates, emergent and submerging vegetation, animal life and water that simulates natural wetlands for human use and benefits. Most of the CWLs in Southern African regions are in operation successfully for domestic wastewater treatment in small community applications. CWLs are also being applied at several mining and industrial sites, storm water and urban catchment management, riverine rehabilitation and protection, ground water recharge and development of urban nature reserves and ecological sites. The majority of existing CWLs in South Africa appear to have been designed based upon reports on overseas systems or simple rule of thumb assumptions. In many cases, approach resulted in systems failing to meet design goal. The author carried out a detailed study into the potential for application of CWLs in arid/semi-arid developing countries. To avoid system failures the following primary objectives have to be reviewed.

- Identify the range of pollutants present in the canal and drainage water.
- Identify whether CWL technology adopted in Europe can be directly used to overcome such pollutant problems.
- Assess whether or not CWLs could usefully be employed as pre-treatment for canal and drainage ditch water prior to being further treated for potable use.
- Thorough understanding of the mechanisms and process of wastewater treatment through a constructed wetland system (CWL).
- Assimilation of data on the performance of existing CWLs to assist in the development of design and operational guidelines suitable to Southern African climate and sewage characteristics.

1.1 Application of Constructed Wetlands

Most of the CWLs have been built to provide advanced or tertiary treatment of Municipal wastewater. Treatment of animal wastes, agricultural runoff and industrial effluents are good potential for this technology.

Table 1. International Application of Constructed Wetlands (Kadlec[1] 1992)

	Applications	Scope
1	Municipal wastewater treatment	Advanced secondary, post tertiary, single family to 200,000 persons, Hotels, Hospitals and Reservation camps.
2	Mine drainage	Coal, base and precious metals.
3	Urban storm water	In conjunction with detention ponds
4	Rivers, lakes and reservoirs	In-line and recycle
5	Live stock wastewater	Ranches, dairies, piggeries etc
6	Industrial	
	▪ Food processing	Potato, sugar, sea-food, abattoir, brewery
	▪ Petroleum	Product water, refinery effluent
	▪ Chemical	Pulp and paper, textiles
	▪ Landfill leachate	Municipal landfills, remediation
	▪ Sludge drying	Municipal and industrial

2 TECHNOLOGICAL APPROACH OF CWLS

The methodology of constructed wetlands was first introduced by Dr. K. Seidel in the 1950s (Kaonga[2] 1998). Constructed wetlands should aim to control and optimise the removal or transform wastewater pollutants and also to create an aesthetic environment for the development of wildlife and social objectives. There are two basic types of CWLs.

Free water Surface Flow (FWS): In this system water flows over the bed of wetland as a shallow water pond and is filtered through dense stand of aquatic plants. FWS are popular in the United States of America, particularly for large wastewater flows and polishing nutrients.

Subsurface Flow (SF): In these system water flows in a horizontal or vertical flow path through a shallow permeable media in which the plants are grown. Treated effluent is collected in an under drain for discharge. SFs are widely used in Europe, Australia and South Africa.(Wood 1991). Figure 1 shows Mpophomeni CWL. This is a vertical flow type 1.5 m deep soil and 2500 m^2 surface area constructed to polish bio-filter effluent to a phosphate level <1 mg/l at a maximum hydraulic loading of 200 mm/d. The influent into this system is introduced from a central distribution channel to the surface of soil bed planted with *frogmouth Spp,* where it is designed to filter vertically through the media into gravel drainage. The final effluent is discharged on to marshland above the sensitive Midmar Dam.

2.1 WORKING PRINCIPLES

Wastewater consists of soluble and insoluble materials. Treatment processes are sedimentation and filtration by the soil, absorption (uptake by plants, thereby reducing conductivity) and by biodegradation by bacteria because of reduction of, biological oxygen demand, BOD. As wastewater percolates through soil it gets clear by the removal of turbidity. Bacteria of the type anaerobic, facultative and aerobic fed from the wastewater for their energy releasing by-products that either escape as gas or dissolve in water and taken up by plants in the system. The filtering media traps the insolubles and bacteria start acting upon them. Simpler compounds are produced which include nitrates, phosphates, carbon dioxide, hydrogen sulphide and so on. This process is called bio-degradation. The plants thrive on CO_2, NO_3 and PO_3. In this process of taking up nutrients the plants also take up other dissolved substances including pathogens. Plants release oxygen into the wastewater through their root hairs during biomass growth. The aerobic and facultative bacteria eventually initialise the released O_2. Ultimately wastewater is purified to a great extent.

2.2 DESIGN GUIDELINES

2.21 Site Selection

- Elevation of land in relation to the wastewater treatment works or septic tank to decide for gravity flow or pumping.
- Topography to minimise cost.
- Type of soil that influence excavation.
- Groundwater pollution potential i.e. distances from boreholes and wells.
- Prevailing winds. Wetlands should preferably be down wind of the residential areas. If correctly loaded and well operated and keeping mosquito breeding in check CWL need not be greater than 300 m away from the nearest rehabilitation for treating volumes greater than 250 m^3/d. and as close as 25 m for individual houses or volumes < 1 m^3/d.

2.22 Layout

CWL on flat ground may have any practical shape. Overflows from cell to cell must have large connecting pipes, overflow weirs or riprap for distribution and aeration. On steeper ground wetlands could be long and narrow along the contours and special overflows had to be designed. Sub dividing the surface area into individual units allows greater hydraulic control, flexibility in maintenance and treatment feasibility. Parallel or series flows or both can do this way of sub dividing. Compartments allow good control, repair and maintenance.

2.23 Organic Loading

Control of odour, insects and hydraulic problems are the considerations for organic loading. The carbon required to enhance nitrogen removal through denitrification, which is the primary objective, may also determine the rate of loading. The Environment Protection Agency[3] (EPA) of USA design guidelines, 1988 suggests the upper loading of wetlands be of the order of 110 kg BOD/ha/d. The Tennessee Valley Authority[3] recommends a design limit of 0.24 $kg/m^2/d$ of BOD at inlet, which can be increased, to 0.45 $kg/m^2/d$ of BOD in large systems on steep slopes.

2.24 Hydraulic Loading

In case of SF system rate of loading is important to decide the length to breadth ratio of horizontal flow system or overall surface area of vertical flow systems.

- Free water surface flow system < 200 mm/d
- Hybrid system (FWS & SF) 50 to 200 mm/d
- Surface flow system 20 to 30 mm /d (WRC[4] report)

For SF wetlands Boon[5] (1985) suggests that the superficial velocity be kept under 8.6 m/d to prevent disturbance of the root-rhizome structure of plants and to allow sufficient contact time for treatment. Full bed area has to be utilised and short-circuiting of flow is to be minimised. The contact with plants must be optimised. This can be achieved by high value of length to width ratio. Knight[6] (1992) found that for FWS wetlands the removal efficiency of BOD and total nitrates (TN) increases with L:B as 4.1 : 6.1.

2.25 Detention Time

This is the time which the wastewater is retained in the system and is determined by the void volume of the filter to water depth. Exact estimation is very difficult because of the various parameters involved in the process. Knight (1992) suggests 6 to 7 days. Longer periods of detention time are required for significant removal of Nitrates and phosphates but may result in stagnant anaerobic conditions.

Table 2 Process criteria for Constructed Wetlands

Factor	Typical FWS	Typical SF
Detention time in days	5 to 14	6 to 7
Maximum BOD loading rate kg/ha. d	80	75
Water or media depth in m	0.1 to 0.5	0.1 to 1.0
Hydraulic loading rate in mm/d	7 to 60	2 to 30
Aspect ratio Length : Breadth	2 : 1 to 10 : 1	0.25:1 to 5:1
Harvest frequency in years	3 to 5	3 to 5
Mosquito control	Required	Not required

2.26 Pre-treatment

Some form of pre-treatment at least to the primary level is required for SF wetlands. Systems without pre-treatment are reported to have frequent clogging at influent side and excessive surface deposits and problems with insects and odours. Primary treatment using septic tank is suitable for small to moderate sized systems. Chinese systems follow the use of Upflow Anaerobic Sludge Blanket (UASB) reactor as pre-treatment units (Hu[7] 1994). Fig.2 shows some optional flow schemes for pre-treatment. Imhoff tank with sludge drying bed is required for large treatment systems. Very large communities may require a more complicated sedimentation tank with sludge drying beds.

2.3 Design Models of Constructed Wetlands

There are lot of disparities in the philosophy and performance of CWL. This is mainly due to the simplicity of assumed design procedure in detention time and BOD removal. The mathematical model for BOD removal is

$C_e = C_i e^{-(kt)}$ ----- Boon, 1985, where C_e and C_I are effluent and influent BOD in mg/l, k = temperature dependent rate constant, t = detention time in days.

A general value of k is taken as 5.2 for a low risk situation where the effluent quality is not much critical (Cooper 1988). European guidelines (WRC[4] 1999), recommends K_{BOD} = 0.1 in case of CWL surface area of 5 m^2/person for settled domestic sewage of septic tank effluent. The Water Pollution Control Federation[8], WPCF, 1990 indicates the temperature coefficient be based upon a modified Van't Holf-Arthenius equation, $K_T = K_{20}(1.06)^{T-20}$ for each day, where K_T = rate constant at temperature T, K_{20} = rate constant at 20°C and T = operating temperature in C°. Several authors support this description of biological degradation rate constants. In the Surface flow CWL concept, to ensure the flow to be maintained the European guidelines recommends hydraulic slope be provided according to D'Arccy's law as $\frac{dh}{ds} = \frac{Q_S}{A_C \cdot K_T}$ where dh/ds = bed slope inlet to outlet, Q_S = average flow in m^3/s, A_C = cross sectional area of bed in m^2. Length to width ratio of wetland should provide non-silting and non-scouring velocity of flow. Boon[5], (1985) recommends a maximum velocity of 6.4 m/d for soil bed system.

2.4 Design Example

Determine the dimensions of a constructed wetland for a community of 100 houses in a rural village of northern province of Botswana assuming each house has a septic tank.

Assumptions: Average number of people per house is 4; average per capita flow is 250 lpd, which includes their live stock also. Septic tank has an average temperature of 25°C but cools down to 20° as it reaches the site.

The influent BOD level of sewage is assumed as 140 mg/l and that we expect the effluent BOD as 10 mg/l. The depth of wet land is assumed as 0.6 m and the porosity of bed material is 0.4

Rate flow = 100 x 4 x 250 = 10^5 lpd = 100 m^3 / day.
Rate constant K_T = 1.104 x $1.06^{(25-20)}$ = 0.825 /day

$$\text{Area of surface} = \frac{100X(\ln 140 - \ln 10)}{0.825X0.6X0.4} = 1340m^2$$

Alternate method to determine the area of surface: Campbell[9] suggests the following rate of BOD removal per year for effluents of warmer climate.

10°C	-	2.5 kg/m^2/year
15°C	-	3.3 kg/m^2/year
20°C	-	4.4 kg/m^2/year

According to the value of 4.4 kg/m²/year BOD removal the area required is calculated as follows

Total BOD removed per year: $\frac{(140-10)x100}{1000}x365 = 4745kg/year$

Hence area required = 4745/4.4 = 1100 m^2

Provide 14 m x 90 m with 1.2 m average depth of liquid.

Determination bed slope:

Discharge Q_S = 100 / 24 x 60 x 60 = 0.00116 m^3/s

$$\frac{dh}{ds} = \frac{0.00116}{14x1.2x0.825} = 0.0000835 \text{ i.e. 1 in 12000 slope.}$$

3 COST ANALYSIS

The capital cost of wetlands can be broken down into the following components. (Creig & Ogden[9] 1999)

- Excavation
- Liner (Petroleum products like Polyvinyl chloride(PVC), polyethylene(PE), polypropylene(PPE) and soil with compacted clay (bentonite)
- Gravel.
- Plants (cattails, reeds, bushes etc.)
- Distribution and control structures
- Fencing and other items.

Factors like detention time, treatment achieved, depth of media, type of pre-treatment, number of cells, availability of gravel and terrain affect the cost of wetlands.

4 ADVANTAGES AND CONSTRAINTS OF CWLS

Advantages:

1. Minimum operating power and maintenance requirements
2. Environmentally acceptable
3. Wildlife conservation potential
4. Potential receiver for the effluents from integrated existing farms.

It is estimated at 90% of the wetlands within the San Francisco Bay region have been drained or filled to make way for agricultural, residential and industrial uses.

Constraints:

1. Land area required is 4 to 5 times that required for conventional treatment
2. Lack of well defined design and guidelines
3. Difficulties in monitoring optional flow of water through extensive shallow open surface and through the media sub-surface.
4. Availability and cost of suitable permeable sand or gravel for subsurface.
5. The difficulty of removing nutrients, particularly phosphate.
6. Geographical and topographical limitations and availability of plant species.
7. Limited market for the removed or harvest plant material.

5 CWLS IN BOTSWANA

The concept of recycling wastewater is not new in Botswana. CWL technology was adopted by the Rural Industries Innovation Centre[2] (RIIC) to treat sewage water for irrigation purposes. Some of the CWLs in operation in Botswana are listed below.

- Thuso Rehabilitation Centre in Maun, 1994
- Kanye Prisons, 1997
- Mokolodi Nature Reserve
- Association of wildlife Clubs
- Ramatea Vocational Training School
- Tonota College of Education

Results from analysis of treated water from the CWLs from these places have been very good showing high efficiency. Figures 2,3 and 4. There is marked reduction of faecal coliforms and *streptococci* bacteria. Both BOD and COD are much reduced. The removal efficiency of these parameters fall within 72% and 99% with respect to BOD and between 61% to 99% with respect to COD. The elimination of nutrients like total nitrogen and phosphate is almost 100%. Faecal coliforms removal mechanism is by adsorption, ingestion, temperature, flocculation and sedimentation. Removal this FC is normally in the range of 99%. Substances like nitrate, phosphates, chlorides copper, magnesium,, iron, nickel etc. in the effluent water are very low and hence environmentally friendly.

6 CONCLUSIONS

- The technology is appropriate but has to be modified to suit local conditions.
- In many villages of African countries the biggest problem is that there are no proper reticulated drainage systems like septic tanks for pre-treatment of sewage and these are need to be installed before CWLs are constructed.
- Wetlands are the lifeblood of wild life. They provide essential habitat for many threatened and endangered animals and bird species.
- Most enzymes, which are required for microbial growth, have optimal activity between 20°C to 30°C and hence CWLs are ideally suitable for arid and temperate climates.
- Hydrological complexity makes design and data interpretation difficult for wetland treatment system. Rainfall causes two opposing effects.
    1. dilution of wastewater reducing concentration
    2. increased velocities, reducing detention time within wetland

  Evaporation increases concentration reducing the reaction time of treatment.

Finally although all of the processes are not well understood, CWLs are capable of moderating, removing or transforming a variety of water pollutants while also providing wildlife and recreational benefits (Hammer[10] 1989).

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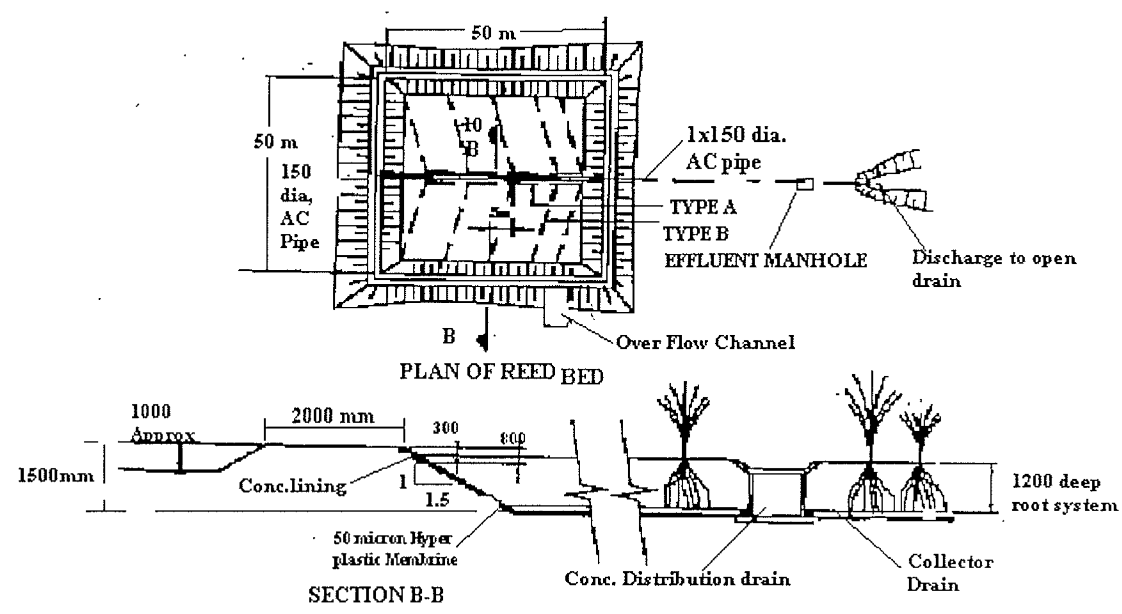

Fig. 1 MPOPHOMENI CONTRUCTED WETLAND

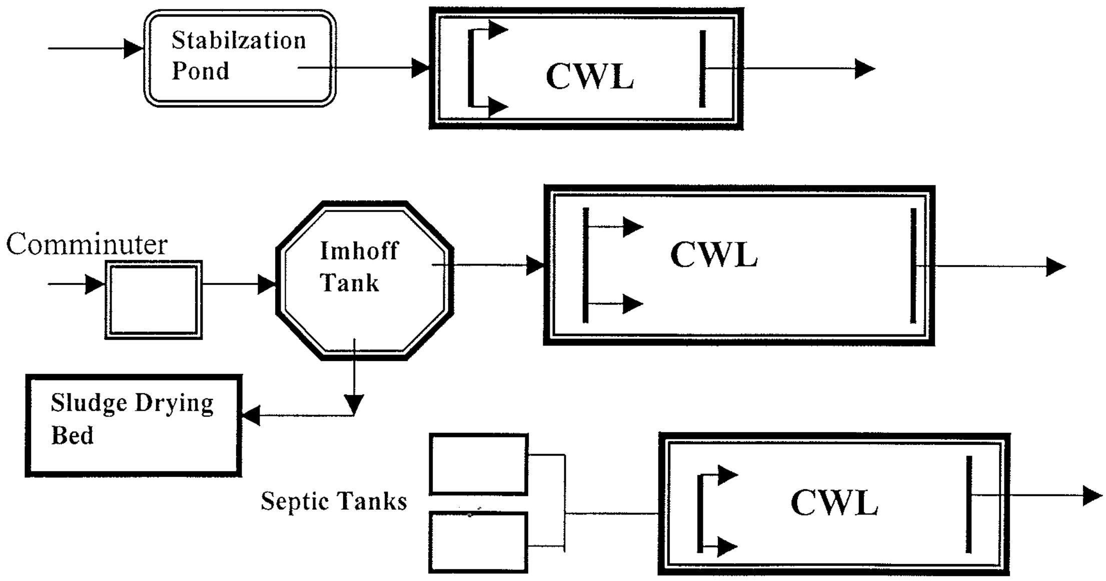

Fig. 2 Optional Flow schemes for Pre-treatment with CWL

The CWLs are cost effective methods for wastewater treatment and have been continuously used in several countries. A few of them are stated in the following table 3. All of them are reported to be functioning very well.

Table 3. Examples of some of the existing CWLs.

Arcata city, California, **USA.**	1990	Horizontal type, free surface flow - first 5 years it was on experimental basis on 6m x 66 m. Now has an area of 3.8 hectares.
Abu Attawa, **Egypt**	1998	Horizontal - Free surface flow - gravel bed, 100m x 2m, domestic and industrial WW and effluent used for agriculture. Excellent performance reported.
Villages in **Columbia**	1997	Coffee producing villages in steep hills. Horizontal flow - Sub-surface flow - rock filled filter - Typha plants - very good function.
Dar Es Salaam, **Tanzania**	1998	Pilot scale - two facultative ponds in series and a maturation pond. Horizontal, sub-surface flow.
Restaurant and a resort at Nairobi, **Kenya**	1993	Horizontal, sub-surface flow system 1200 persons, 2400 sq.m, 2beds and 3 ponds. Planted with Typha plants.
Hospital at Dhulikhel, Khatamandu, **Nepal.**	1997	Two stage hybrid system for 50 persons. No electric power - 160m^2area of horizontal bed surface flow and 120 m^2 area of subsurface flow -planted with *phragmites karka.*
Treatment of Polluted river water at Amalandia, Sao Paulo, **Brazil**	1998	Vertical flow, subsurface system - only known CWL where treated effluent is used for potable purpose - no electric power - effluent is chlorinated - designed for 6490 persons - 200 litres /d/p.
South Africa About 70 CWLs are in operation in SA. A few of them are listed. 1.Mpophomeni Fig 1 2.Karbochem 3. Ladybrand 4.Moketsi		2500 m^3/d - vertical, subsurface flow -tertiary - Refer fig.1 6000 m^3/d - meandering channel - tertiary 4300 m^3/d - 2 vertical subsurface flow gravel bed - tertiary 200 m^3/d - 3 dual horizontal surface flow beds - secondary

Fig. 2 COD Removal

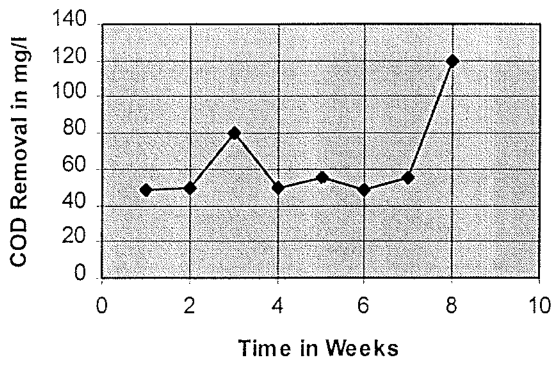

Fig. 3 Nitrates & Phosphates Removal