RESEARCH TO ASSESS THE POTENTIAL OF ARTIFICIAL WETLANDS FOR WASTEWATER TREATMENT IN SOUTHERN AFRICA

by

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ABSTRACT

The utilization of Artificial Wetlands for Wastewater Treatment and Control may prove to be a cost effective and reliable option under South African conditions.

At present, however, there are few design criteria available that can be used to predict reliably the performance of natural wetlands or to determine the size of artificial wetlands. Internationally research into the mechanics of the technologies has only progressed to full scale implementation within the last decade, and long term operational and management data remains lacking.

This paper discusses the research being undertaken at the Division of Water Technology of the CSIR directed at assessing the potential for such systems under Southern African conditions for the treatment of primary and secondary effluents.

KEYWORDS

Artificial wetlands, wastewater treatment, pilot scale studies, substrata permeability, macrophyte species.

INTRODUCTION

In recent years considerable interest has been shown in the capacity of Natural and Constructed Wetlands to treat both domestic and industrial wastewaters. Much of this interest has stemmed from work undertaken in Germany in the 1970's and more recently in Europe, the United States, Australia and now South Africa (Kickuth 1984, Finlayson 1984, Gersberg 1986, Brix 1987, Wood 1988, Furness 1988).

Applications of the systems have included the treatment of raw and primary treated sewage, the upgrading of oxidation pond and secondary effluents, aswell as the treatment of abbattoir and paper mill effluents, acid mine drainage, heavy metal wastes, thermal and petrochemical discharges, amongst others (Brix 1987, Cooper 1988 Hammer 1988, Watson 1988, Wood 1988).

It is generally accepted by researchers that Wetland Systems have considerable potential and may have a number of advantages compared to conventional wastewater treatment options, including:

- low operating, energy and maintenance requirements;
- they can be established at the site of wastewater production;
- being a 'low technology' system they can be established by relatively untrained personnel;
- they are a robust process able to withstand a wide range of operating conditions; and
- they are environmentally acceptable offering considerable wildlife conservation potential (Brix 1987, Wood 1988).

The system is essentially a shallow, (0,3-1,5 m) excavation containing a bed of porous soil, gravel or ash, in which emergent aquatic vegetation is planted. Constructed with a slight incline (1 - 3%) between the inlet and outlet, effluent flows horizontally through the rhizosphere of the wetland plants, penetrating the substrata, but prevented from surface flow. Conversely, the effluent is introduced to the surface of the bed to flow vertically through the rhizosphere to a drainage channel at the base of the bed.

The Division of Water Technology (DWT) initiated an Artificial Wetland research programme in late 1985 to develop engineering guidelines for the application of such systems in Southern Africa.

EXPERIMENTAL INVESTIGATIONS

Substrata Permeability

The substrata in which the macrophytes are established provides a stable surface for microbial attachment, a solid substrate for plant growth, and functions directly in the purification of the wastewater by way of physical and chemical processes. It also determines the permissible loadings rates to ensure subsurface penetration, and to prevent surface short-circuiting in both horizontal and vertical flow systems. (Cooper 1988, Brix 1987, Steiner 1988, Watson 1988).

Laboratory investigations with a number of representative substrata types have demonstrated a characteristically wide range in hydraulic permeability. Substrata receiving secondary effluent (humus tank) showed permeability constants ranging from 10^{-6} to 10^{-3} m/s. Stabilization pond effluent reduced permeability constants to range from 10^{-7} to 10^{-5} m/s, though passage through a simple ash prefilter system could recover permeability by removing much of the suspended solid pollutant load. Where raw or septic sewage was applied, permeability tended to be less than 10^{-6} m/s, except for coarse sands, waste ash and gravel systems.

Macrophyte Species

All aquatic plants appear to possess water treatment characteristics since they offer a surface to which microorganisms can adhere, and absorb nutrients (Greiner 1982). However, since the principal function of the plants is to supply Oxygen to the heterotrophic organisms in the rhizosphere, and to increase or stabilize the hydraulic conductivity of the substrata, it is essential that species physiologically adapted to these requirements should be utilized.

Many of the local or indigenous reed species are suitable candidate for wetland systems. At batch loading rates of 2.8 cm/d (28 l/m²/d) septic sewage to small scale units over an effective 12 month period species of *Phragmites*, *Scirpus*, *Typha*, *Arundo*, *Cyperus* and *Pennisetum* were each able to produce an effluent low in COD, SS, PO_4-P, NH_4-N and NO_3-N as they could when receiving Stabilization Pond Effluent at 84 l/m²/d (Table 1).

The growth rate of *Typha* and *Arundo* was observed to be more rapid than *Scirpus* and *Cyperus* with *Pennisetum* and *Phragmites* least of the macrophytes. Removing the plants at the end of the 12 month period indicated that the *Pennisetum* rhizosphere was principally located in the top 10 cm layer, *Arundo* in the top 20 cm, *Typha* in the top 35 cm, whilst the *Scirpus*, *Cyperus* and *Phragmites* had approached the bottom of the 50 cm substrata layer.

The ability of the plants to produce an extensive root structure is essential for the transference of Oxygen to the heterotrophic microorganisms in the rhizosphere throughout the substrata depth, and therefore determines the active bed depth of wetland systems.

The above-ground development determines the capacity to transfer Oxygen to the subsurface zone throughout the year. In this respect, despite the apparent prolific short term development of the *Typha*, *Arundo*, *Scirpus* and *Cyperus*, these species were subject to almost total die-back and senescence during the Autumn, remaining dormant until Spring. In contrast, *Phragmites* maintained its central stem upright above ground whilst the leaves are lost. These standing dead stems and shoots provide most of the Oxygen flux to the rhizosphere throughout the Winter period (Yamasaki 1987).

Small Scale Wetland Units

12 small-scale reactors, each of 4 m² surface area were established to operate in a vertical flow regime. For these studies two macrophyte species were planted, *Phragmites* and *Scirpus*; to treat three effluents; stabilization pond effluent (SPE), and ash filtered stabilization pond effluent (AFSPE) at a design surface loading rate of 24 cm/d, and septic tank effluent (STE) at a design surface

loading rate of 8.4 cm/d; through two substrata types, soil and ash. The SPE was drawn from the third of a series of three facultative ponds at a total detention time of approximately 15 days. The AFSPE passes through a coarse ash prefilter with a nominal detention time of 4 hours prior to the pilot wetlands, and the STE is drawn from a tank of 24 hour nominal detention time receiving raw sewage.

The wastewaters received by the wetland systems were relatively low in organic pollutant load, consequently, the pollutant removal achieved through these units was highly significant, in respect of organic and inorganic components, suspended solids and pathogens (Table 2).

The presence of macrophytes generally resulted in superior pollutant removal of COD and Nitrogen, though some inconsistencies in loading of individual units does influence precise quantification from these small scale units.

The contribution of the macrophytes to improved permeability of the soil had not manifested after two years of operation, with all the soil units able to maintain adequate permeability with the hydraulic head adjusted to between 200-300 mm from top water level. Some short-circuiting was observed which reduced overall treatment efficiency by decreasing total detention times, and contact between the wastewater and the substrata, essential for optimal pollutant adsorption.

Pilot Scale Studies

Three systems were established each of 25 m^2 surface area x 750 mm deep. One bed was filled with gravel (19 mm), whilst a second was filled with waste bottom ash (from Pretoria West Power Station), and a third with local 'top soil' covered with a 50 mm layer of waste bottom ash.

The gravel system was started in early 1986, being planted with the local *Arundo*, and received septic sewage at a continuous loading rate equivalent to 10 cm/d (100 $l/m^2/d$). After a year, the *Arundo* was removed and replaced by *Scirpus* occupying the influent zone (1 m) and *Phragmites* in the remainder of the bed. After six months receiving septic sewage, the influent was changed to raw sewage supplemented with **Molasses** to simulate high COD loadings associated with rural communities.

The other two beds, were planted with *Phragmites* in June 1988, receiving raw sewage at a rate of 10 cm/d. The effluent from the ash bed passing to the soil and ash bed. The first bed was designed to act as a primary treatment stage principally for solids and carbonaceous removal, with the second bed designed for removal of Phosphate and Nitrogen

Wetland Performance

The *Arundo* demonstrated prolific growth in the gravel bed, to occupy surface space within six months after planting, with individual stems in excess of 2 m in height. However, although the suspended solids and COD levels were being reduced by an average of 80% and 65% respectively (annual basis), these did not reliably meet the effluent discharge standards of 20 and 75 mg/l (ss and COD), whilst only 18% Ammonia and 7% Phosphate removal was achieved. (Table 3a) In removing the *Arundo* from the bed, their root structure, which had only penetrated a maximum of 25 cm; was found to be predominantly black, indicating that reducing conditions had prevailed even in the immediate vicinity of the rhizosphere.

Replanting the bed with *Scirpus* and *Phragmites* required a slightly greater period for revegitation to be completed as aphids attacked the young *Phragmites*, necessitating insecticidal treatment.

The *Scirpus* were not visibly affected by the aphids, but were susceptible to high winds and rain which occasionally laid them flat, from where they did not readily recover, reducing potential Oxygen translocation to the rhizophere.

Loading raw sewage resulted in a build up of organic matter across the inlet zone where it was degraded both aerobically and anaerobically. This did not result in significant fly or odour nuisance, or disruption of infiltration into the gravel substrata.

Effluent Suspended Solid levels remained less than 20 mg/1, whilst COD and Ammonia removal improved, though Phosphate removal remained erratic and unreliable (Table 3b).

Supplementation with Molasses significantly increased the organic loading rate per unit area to an average of 34.5 g/m^2/d, which resulted in increased effluent COD and Ammonia levels (Table 3c).

Some of the COD in the effluent may be accounted for as low biodegradable components, since it was tainted with residual colour from the Molasses. Even so COD removal of the order of 80-90 % must be considered as highly promising, with the macrophyte community still to become fully matured.

The ash and soil systems slowly developed a viable *Phragmites* community during the Winter and Spring of 1988, with almost full surface occupancy, stems 2 m in height and horizontal rhizomes generating renewed growth by December. During the younger stages of growth, where the community was relatively dispersed, aphid attacks did occur and required management.

The ash system proved highly efficient in the removal of COD, Suspended Solids, and Phosphate for a period of approximately six months, whereupon the Phosphate began to break through into the effluent. The Phosphate removal was related to the adsorptive capacity of ions and salts within the ash substrata, principally Aluminium, Iron, Silica and Manganese. Initially therefore, Phosphate removal was accomplished efficiently whilst ample binding components were available, though with time, leaching out of some of these components, reduced Phosphate removal potential.

Passage of ash bed effluent through the soil bed further improved treatment efficiency, with Phosphate reduced to less than 0.5 mg/1, and overall Nitrogen removal efficiency in excess of 50%.(Table 4) As the systems become fully established it is expected that the Nitrogen removal will increase proportionately to increased Oxygen supply to the rhizosphere, and depth of the aerobic zone.

Combined Artificial Wetland High Rate Algal Pond

The system consists essentially of two units, each 22 m long by 11 m wide and of 400 mm nominal depth. The Artificial Wetland having been converted from an obsolete drying bed, has slopes from the longitudinal sides towards the middle and a slope from end to end. Septic sewage was initially introduced at the far end of the bed at a rate of 13.5 cm/d. The effluent from the wetland passed into the algal pond where the depth was varied to afford the effective detention time according to climatic conditions of 1-3 days.

The wetland bed of coarse gravel media, was also initially planted with *Arundo* and *Typha*, which resulted in substantial pollutant removal through the combined activities of the macrophytes, micoorganisms and substrata (Table 5).

The inability to achieve total organics removal and nitrification was a reflection of the high surface loading rate, short circuiting and incapacity of the macrophytes to~~oo~~ meet the Oxygen demand. Subsequently, the *Arundo* was removed and replaced by *Typha*, *Phragmites* and *Scirpus*, and the influent introduced stepwise along the two sides.

As the macrophyte community developed and greater control was afforded to the system, overall wastewater treatment efficiency has improved, though at present the loading rate still restricts efficient N and P removal (Table 6).

GENERAL DISCUSSION

The COD of wastewater associated with setteable solids is removed to a large extent by sedimentation and filtration as it passes through the substrata. This is then retained and degraded slowly by microorganisms that are either suspended in the water column, attached to the substrata particles, or attached to the roots and stems of the plants. Conceptually, the system acts as a slow rate trickling filter, with built-in clarification, in which the plants supply the Oxygen to the microbial community (Tchobanoglous 1980, Alexander 1986).

Since the biodegradation is essentially a microbial one, it is affected by those parameters that affect the metabolic rate of aerobic microorganisms in general, including temperature, Oxygen concentration (gradients and profiles) pH, substrate availability and relative biodegradability, and presence of potential parasites or toxins.

The supply of Oxygen is determined by the ability of the macrophytes to translocate photosynthetically derived and atmospherically diffused Oxygen from the above ground structure to the rhizosphere.

Although possible fluxes have been calculated at between 5-45 $g/m^2/d$ (Kickuth 1984, Lawson 1985), this is dependent upon the development of the macrophyte community (which is calculated to take 3-5 years), and overall environmental constraints placed upon it. The capacity of the experimental systems to achieve COD removal observed, was therefore also a reflection of anoxic (denitrification) and anaerobic processes within the vertical and horizontal profile. Similarly, binding of dissolved organics to salts and ions within the soil and ash matrix (particularly at the high pH generated in the ash system), assists in detaining COD pollutants for subsequent longer term degradation.

The initial removal of Phosphorus and Nitrogen from water is due largely to microbial and aquatic uptake and the geochemical adsorption by minerals in the soil, though the microbial pool is small and quickly becomes saturated.

Substrata Phosphate adsorption involves the exchange of Phosphate ion with an OH- of an edge MOH, where M = Ca, Si, Fe or Al. Factors that affect Phosphate removal are therefore soil base saturation, pH, texture, organic content, Al, Fe, Si and Ca concentrations, and the background Phosphate content.

Nitrogen can also be removed from the system through nitrification/denitrification and Ammonia volatilization. In artificial wetlands, the pH is usually maintained around neutrality, therefore, Ammonia volatilization is not likely to be a significant pathway for Nitrogen removal under normal circumstances. Although, in the ash systems pH levels were consistently elevated above pH 8 as a result of the solubilization of mineral salts (also indicated by significant increases in alkalinity).

In surface loaded systems i.e. vertical flow or surface flow, the presence of an active algal community can also elevate the pH in excess of pH 8 to encourage volatilization, though this will only be seasonal and inconsistent.

Biological and/or chemical nitrification/denitrification are the key processes of Nitrogen removal. The factor most limiting Nitrogen removal is the supply of Oxygen necessary to sustain nitrification; the alternative demands on that Oxygen; and water temperature. In simple terms, only that Oxygen not required to meet the carbonaceous oxygen demand is available for nitrification, if the water is sufficiently warm. (nitrification virtually ceases at water temperature below 10 °C.)

In respect of pathogen removal Artificial wetlands offer a unique combination of physical, chemical and biological factors which contribute to inactivation and removal of both pathogenic viruses and bacteria. In addition to filtration through the substrate and the attached biofilm, physical removal factors include sedimentation, aggregation and inactivation by U.V. radiation. (Rogers 1985). Chemical factors include oxidation, exposure to biocides which may be excreted by plants, and adsorption to organic matter and the biofilm. Biological removal mechanisms include antibiosis, ingestion by nematodes or ciliates, attack by lytic bacteria (or viruses), and natural die-off (Gersberg 1987).

Treatment area requirements in terms of m^2/person equivalent discharged applied internationally for the implementation of Artificial Wetlands for wastewater treatment range from 0.7 to 23 m^2/p.e; equating to between 10 and 346 m^2/kg BOD/d.In the United Kingdom between 2 to 5 m^2/p.e. is recommended to ensure an effluent with less than 20 mg/BOD/l on a 95 percentile basis. covering the frequent cold conditions. (Cooper 1987, Watson 1988)

Conclusions

Pilot scale studies being undertaken in South Africa indicate that Artificial Wetlands may represent a viable alternative to conventional treatment technologies, especially suited to rural areas and small to medium size communities. Wetland design is relatively simple, they require minimal operating skills or maintenance, and they can meet required discharge standards. However, precise operating and design criteria can only be realised through long-term experience of full-scale systems, complimenting further research at the experimental scale.

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Table 1. Nutrient levels in the Effluent and Removal Efficiencies for Macrophyte species Receiving Stabilization Pond Effluent or Settled Sewage at 8.4 cm/d and 2.8 cm/d respectively.

Pot	Species	Eff	COD		PO_4		NH_4N		NO_3N	
			mg/l	%Rem	mg/l	%Rem	mg/l	%Rem	mg/l	%Rem
1	T	SPE	16.3	54	0.77	51	0.54	61	1.3	70
2	S	SPE	17.1	51	0.77	54	0.36	74	0.7	84
3	C	SPE	17.1	51	0.71	51	0.35	74	0.3	93
4	K	SPE	13.36	62	1.06	32	0.38	72	0.25	94
5	S	SPE	23.1	34	0.4	74	0.35	74	0.5	89
6	P	SPE	16.19	54	0.84	46	0.33	76	0.77	82
7	A	SPE	23	35	0.3	81	0.45	67	0.37	92
8	T	SS_1	19.96	94	0.63	92	1.24	94	0.46	40
9	S	SS_1	21.07	93	0.99	88	0.73	97	0.35	54
10	C	SS_1	16.8	95	0.96	88	0.74	97	0.98	-27
11	K	SS_1	15.48	95	1.36	83	0.63	97	0.36	53
12	S	SS_1	16.16	95	1.48	82	0.89	96	0.43	44
13	P	SS_1	16.3	95	1.1	86	1.45	93	0.27	65
14	A	SS_1	24.9	92	0.47	94	1.25	94	0.45	41

Species

S	-	*Schoenoplectus lacustris*	P	-	*Phragmites australis*
K	-	*Pennisetum clandestinum*	C	-	*Cyperus platycaulis*
T	-	*Typha capensis*			

Influents

SPE	-	Stabilisation Pond Effluent
SS_1	-	Settled sewage.

Table 2: Small Scale Reactors - Average results Summer 1987 - 1988 and Winter 1988

			AFSPE	SPE	STE	1	2	3	4	5	6	7	8	9	10	11	12
Alkalinity	S		220	208	319	258	270	269	303	311	241	243	253	189	385	463	437
mg $CaCO_3$/l	W		298	293	365	261	304	306	319	317	329	566	521	383	573	503	555
pH	S		8.6	8.5	8	8.4	8.1	8.1	8.2	8.2	8.1	9.7	10.1	10	9.4	8.6	8.2
	W		7.3	7.3	6.9	7.4	7	7.2	7.1	6.9	7.2	7.4	7.8	7.4	7.3	7	7.1
Total Nitrogen mg/l	S		12.9	13.1	42.4	4	2.3	1.6	2.5	2.7	4.2	9.4	27.5	4.6	32.5	13.9	10.1
	W		21.5	20.3	57.7	8.5	9.7	5.9	6	5.2	8.3	15.3	34	14	24.1	8.7	27
NH_4-N	S		11.2	12	32.9	3.4	1.9	1.5	2.1	2.3	3.9	9	17	3.5	20.2	11.4	9.3
mg/l	W		11.7	11.7	30.2	7.9	6.7	5.6	4.6	3.6	8.2	15	26.4	5.8	18.7	5.9	23.4
NO_3+NO_2-N	S		3.2	3.4	0.9	0.9	0.9	1.2	1.7	0.7	1.2	0.7	0.4	2.1	0.4	0.4	0.5
mg/l	W		0.7	0.4	0.2	0.3	0.5	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.3	0.3	0.3
Total phosphorus mg/l	S		4.4	5	7.6	0.3	0.4	0.4	0.6	0.2	0.2	0.6	0.7	0.4	1.7	0.4	0.3
	W		5.4	5.7	8.5	0.4	2.2	0.6	1.1	2.7	0.6	0.9	2.7	1.3	1.5	0.1	2.9
PO_4-P	S		4.3	4.5	6.6	0.3	0.3	0.3	0.6	0.1	0.1	0.6	0.6	0.4	0.4	0.2	0.2
mg/l	W		4.9	5.5	6.9	0.2	1.9	0.3	1.1	2.1	0.4	0.6	2.2	1.3	1.2	0.1	1.7
COD	S		75	116	164	42	35	34	37	29	30	21	31	27	29	47	39
mg/l	W		40	76	192	25	23	19	22	28	24	15	14	14	12	16	29
SO_4	S		83	81	64	86	88	81	96	87	83	112	91	134	76	63	46
mg/l	W		109	107	75	67	92	86	99	97	84	71	53	99	72	74	48
Suspended	S	6	33	43	64	16	15	28	21	18	31	14	48	48	12	25	27
solids mg/l	W	112	17	17	43	12	16	27	25	34	13	2	2	6	2	3	27
Faecal coliform/100 ml	S	0	400	6100	>10^4	6	0	0	40	0	80	4800	1200	20	272	20	6100
	W	89	5800	20800	>10^4	124	64	3300	1100	47	2300	>10^4	>10^4	500	10	3	>10^4

Condition	Reactor
Soil Substrata	1 to 6, 11 and 12
Ash Substrata	7 to 10
Scirpus	2, 4, 7
Phragmites	3, 5, 6, 9, 10, 11, 12
AFSPE	1, 2, 3
SPE	4, 5, 6, 9
SS	7, 8, 10, 12

Reactor 11 receives the effluent from 10

Table 3.

	a		Plant Species	b			c with carbon supplement		
Determinant mg/l	*Arundo*			*Scirpus/Phragmites*			*Scirpus/Phragmites*		
	In	Out	% Removal	In	Out	% Removal	In	Out	% Removal
NH_4-N	42.8	35.1	18	36.4	22.7	38	54.1	47.6	12
NO_3-N	0.2	0.3	-	0.3	0.4	-	0.4	0.3	-
PO_4-P	8.2	7.6	7	8.6	7.9	9	8.8	8.5	4
COD	271	95	65	276	68	73	845	137	84
SS	162	34	90	88	16	84	143	19	87

Wetland performance of gravel bed planted with *Arundo*, and then *Scirpus/Phragmites* receiving effluent at 10 cm/d.

Table 4.

Determinant mg/l	BED 1			BED2		CUMMULATIVE REMOVAL %
	In	Out	% Removal	Out	% Removal	
NH_4-N	45.6	31.5	31	19.2	38	58
NO_3-N	0.3	0.4	-	0.5	-	-
PO_4-P	7.9	1.3	84	< 0.2	85	97
COD	364	40	89	16	60	95
SS	121	18	85	16	12	87

Wetland performance of ash bed prior to soil/ash bed planted with *Phragmites*, receiving effluent at 10 cm/d.

Table 5.

	Plant Species										
	Arundo/Typha					*Typha/Scirpus/Phragmites*					
	Wetland		% Removal	Algal Pond	% Removal	Wetland		% Removal	Algal Pond	% Removal	
Determinant mg/l	In	Out		Out		In	Out		Out		
NH_4-N	40	26	34	6	85 47	48.2	33.1	3.1	3.4	90	90
NO_3-N	0	2	-	13	+ -	0	1.9	-	19.1	-	+
PO_4-P	8	5	31	4	50 32	9.2	6.7	27	3.5	48	62
COD	223	91	59	46	79 49	293	81	72	48	41	93
SS	186	41	77	105	56 -	143	34	76	136	-	+

Wetland Treatment through a combined Artificial Wetland and High Rate Algal Pond receiving effluent at 13.5 cm/d.