REPORT TO THE WATER RESEARCH COMMISSION

ARTIFICIAL WETLAND USE FOR WASTEWATER TREATMENT

THEORY, PRACTICE AND ECONOMIC REVIEW

by

A WOOD
P PYBUS

Stewart Scott Inc.
Consulting Engineers and Town Planners

and

Division for Water Technology
CSIR

WRC REPORT NO. 232/1/93
ISBN 1 86845 022 8

PRETORIA
DECEMBER 1992

ARTIFICIAL WETLAND USE FOR WASTEWATER TREATMENT

THEORY, PRACTICE AND ECONOMIC REVIEW

Prepared for the
Water Research Commission

by

Stewart Scott Inc.
Consulting Engineers and Town Planners

and

CSIR
Division for Water Technology

Project Leader	Project Team	Editorial Committee
Dr A Wood	Dr L C Hensman	Mr C Chapman
	Miss M Rowley	Mr A L Batchelor
	Mr P J Pybus	Dr K Rogers
		Mr W Alexander
		Mr W Scott
		Prof G C Bate
		Prof D Lord
		Mr H Maaren
		Mr D Huyser

ARTIFICIAL WETLAND USE FOR WASTEWATER TREATMENT

THEORY, PRACTICE AND ECONOMIC REVIEW

TABLE OF CONTENTS

TABLES : PART I

TABLES : PART II

PART II : ECONOMIC REVIEW

FIGURES : PART I

DIAGRAMS : PART II

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Water Research Commission for their support for this project and the many people from the Division of Water Technology of the CSIR, SDWA and Water Research Commission for their efforts and contributions to the project.

Special mention must be made to Messrs J Scheepers and M Hills and Ms M Rowley, who assisted Dr Wood with the practical research into Artificial Wetland Wastewater Treatment at the CSIR experimental site at Daspoort, Pretoria, and the development of the theory and practice aspects of this report.

Thanks are also due to members of the EEC Expert Group and the IAWPRC Specialist Working Group on Macrophytes in Water Pollution Control who provided valuable information and contacts.

Finally, thanks should be made to the members of the CSIR Wetland Research steering committee and the WRC project steering committee for their support and enthusiasm.

Mr C Chapman	Dr A Wood
Mr D Kerdachi	Mr P J Pybus
Mr H Smit	Mr W E Scott
Dr DJ Bosman	Dr L C Hensman
Ms L M Sephton	Mr B Corbett
Mr W Alexander	Dr D F Toerein

ARTIFICIAL WETLAND
USE FOR
WASTEWATER TREATMENT
THEORY, PRACTICE AND ECONOMIC REVIEW

The potential of artificial or constructed wetlands as a reliable and fundamental process for the secondary treatment of wastewater and for nutrient removal has received considerable attention during the past ten years in the USA, Europe and Australia. Interest has been shown recently in the use of wetlands in South Africa with several systems being constructed for a range of effluents with variable degrees of success.

It is generally accepted by researchers that wetland systems have considerable potential and may offer a number of advantages compared to conventional wastewater treatment options:

- low operating cost
- low energy requirements
- low maintenance requirements
- can be established close to the site of wastewater production
- can be established by relatively untrained personnel
- robust process able to withstand a wide range of operating conditions
- environmentally acceptable offering considerable wildlife conservation opportunity
- can readily be integrated into existing forms of effluent treatment

The discharge of wastewaters into constructed wetlands may be considered a viable alternative treatment option, particularly suited to small and medium sized communities in sparsely populated and developing areas.

Internationally adequate, cost effective design guidelines for the different applications and types of constructed wetlands do not exist for users, engineers and regulators. In 1988 the Water Research Commission contacted Sviridov De Waal Inc, in association with the Division of Water Technology of the CSIR, to develop engineering guidelines based on research being undertaken by the DWT and international experience for the application of constructed wetlands for the treatment of domestic wastewater.

The study also included an economic appraisal to compare the following systems:

1.1 Treating raw and pretreated raw sewage:

(a) Conventional extended aeration activated sludge.

(b) Oxidation ponds incorporating anaerobic, facultative and maturation lagoons.

(c) Constructed wetlands treating raw sewage.

(d) Constructed wetlands with anaerobic pretreatment ponds.

1.2 Constructed wetlands for the removal of nutrients from secondary treated activiated sludge plant and biofilter effluents.

1.3 Constructed wetlands for suspended solids removal and 'polishing' of oxidation pond effluent.

SYSTEM DESIGN BASICS

A constructed wetland consists of a shallow, often lined excavation, (depending upon acceptance of seepage to the ground system) containing a bed of porous soil, gravel or ash, in which emergent aquatic vegetation is planted (commonly *Phragmites Australis*). The depth of the bed is generally 0,3 - 1,0 m deep and is constructed with a peripheral embankment at least 0,5 m high above the bed to contain storm conditions and accumulation of vegetation and influent solids.

The earlier beds were usually constructed at an incline of 2-8% where a soil media was used to ensure adequate hydraulic gradient to encourage passage of the effluent through the bed. Gravel and ash beds may, however, be constructed essentially level as long as the length to width ratio is adequate, in relation to the influent flow. The selection of the permeable media represents the dominant factor in ensuring the desired hydraulic path, surface or subsurface, and consequently the treatment efficiency and reliability. It also forms the dominant cost factor for the wetland, particularly if a gravel or ash is required and has to be imported to the site. However, it has been identified that it is rarely possible to compensate for poor permeability by incorporating an incline, one that an incline can encourage surface ponding and short circuitry, diminishing treatment efficiency.

TREATMENT MECHANISMS

Although the aquatic plants are the most obvious biological component of the wetland ecosystem, the actual purification is accomplished through a combination of biological, physical and chemical interactions between the plants, the media and the microbiological community. The primary role of the plants is to provide surfaces for bacterial growth, the filtration of solids, the translocation of oxygen to the rhizosphere and improvement of the soil's permeability.

In addition to biological processes, wetland systems are capable of removing significant amounts of pollutants by physico-chemical mechanisms. Ion exchange and precipitation processes within soil and ash media will result in a substantial reduction in certain ions. For example, co-precipitation of phosphate with iron, aluminium and calcium can dramatically reduce phosphate levels. Heavy metal may be precipitated with sulphide in zones where sulphate reduction occurs, and the formation of organo-metallic compounds may also represent an active mechanism for pollutant removal.

INTERNATIONAL EXPERIENCE

The reed bed method of wastewater treatment is well established in Europe and the United States. Systems are now being installed in South America, Asia, the Far East and Australia. Many units have been constructed on the 'root-zone' principles developed in West Germany whereby the wastewater passes horizontally through the media in which the plants are established. Other systems incorporate surface flow, comparable to natural wetlands, or vertical flow (upflow and downflow) through the media, or combinations of individual wetland units to optimise the removal of pollutants (modularisation of systems).

Practical application rates for the treatment of municipal wastewaters range from 40 to 200 m3 $ha^{-1}d^{-1}$ for hydraulic loading and 30 to 400 kg. $BOD_5ha^{-1}d^{-1}$ for organic load.

A considerable variation in design and operational criteria, a lack of understanding of the process and factors influencing the behaviour of the system and the impact of climatic conditions is apparent resulting in widely disparent performance data relative to confirmed design criteria.

SOUTH AFRICAN EXPERIENCE

Research to date with pilot scale units has demonstrated that constructed wetlands can meet the General Standard in terms of COD and suspended solids at overall loading rates of 2 000 $m^3ha^{-1}d^{-1}$ when polishing oxidation pond effluents and secondary effluents, and 500 to 1 000 $m^3ha^{-1}d^{-1}$ for raw, septic or settled domestic sewage.

A loading rate for simultaneous nitrogen removal of 300 to 500 $m^3ha^{-1}d^{-1}$ is considered adequate, being lower than required for COD removal in order to ensure an adequate availability of oxygen. Phosphate removal is intimately associated with the physio-chemical characteristics to the media. Clay or iron-rich soil types and waste ash can achieve significant removal of phosphate to below 1 mgl^{-1} phosphate at loadings as high as 2 000 $m^3ha^{-1}d^{-1}$ secondary effluent, though gravel and sand are relatively inefficient as phosphate absorbant media (Hensman 1988).

ECONOMICS

The estimated present day costs for the alternatives for treating raw sewage as well as those for improving secondary effluents of poor quality are tabulated hereunder.

Alternative Systems Treating Raw Sewage

	Activated Sludge (Rand)	Oxidation Ponds (Rand)	Wetland with Anaerobic Ponds (Rand)
Net Total Civils	672 000	618 000	1 121 000
Net Total Mechanicals	173 000	35 000	35 000
Net Total Electricals	41 000		
Allow for Contingencies	89 000	65 000	116 000
Allow for Price Adjustment	133 000	98 000	173 000
Engineering Fees, etc.	219 000	149 000	157 000
	1 327 000	965 000	1 602 000

The present worth of each scheme has been calculated for the projected cash flow over a period of 30 years. It has been assumed that the systems will operate at full load over this whole period. A complete range of discount rates has been used to take into account different economic conditions.

Summary of Present Worths (R x 1000)

Discount Rate	0,0%	2,0%	4,0%	6,0%	8,0%	10,0%
a) Activated Sludge	7 724	6 069	4 945	4 160	3 595	3 177
b) Oxidation Ponds	4 605	3 662	3 023	2 576	2 254	2 014
c) Wetlands with Anaerobic Ponds	6 210	5 000	4 172	3 590	3 168	2 852
Wetlands with Nutrient Removal	5 257	4 129	3 361	2 824	2 437	2 151
Wetlands for Effluent Polishing	4 948	3 884	3 161	2 656	2 291	2 021

The discount rate does not effect the relative worth of the four schemes that are compared.

The oxidation pond system has the lowest present worth. This is not surprising as the quality of the effluent from an oxidation/maturation pond system will not comply with the General Standard as set out in Government Gazette Notice No 991 of 18 May 1984. The presence of algae will raise the concentration of suspended solids and with it the chemical oxygen demand and oxygen absorbed values to between 2 to 3 times the permitted standard. E.coli counts of less than 1 000/100 m*l* are the best that can be expected. The cost of additional wetlands to improve the effluent to an acceptable standard will bring the present worth of this system to values very similar to that for Alternative (c) being the constructed wetland preceded by anaerobic ponds.

Wetland System Treating Secondary Effluent

	Wetlands for Nutrient Removal (Rand)	Wetlands for Effluent Polishing (Rand)
Net Total Civils	614 000	603 000
Allow for Contingencies	61 000	60 000
Allow for Price Adjustment	92 000	90 000
Engineering Fees, etc	95 000	94 000
	862 000	847 000

Too little is known as to the adsorptive capacity of phosphate deficient media, the period and phosphate load that can be reached prior to saturation and loss of adsorptive capacity. For economic comparative purposes we have assumed this will be ten years. We have also assumed the use of clinker which has a high adsorptive capacity and is very porous. The use of clays which have good adsorptive properties would for hydraulic reasons increase the size of the beds enormously although not necessarily the cost provided local clays could be suitably used.

The effluent polishing system is to improve the quality of secondary effluents from biofilter plants or from an oxidation pond system. It has been designed as an 'add-on' to an existing oxidation pond system and not in combination with such a system as differing results could be expected.

CONCLUSIONS

There is still a great deal to be learnt and understood concerning the very complex reactions taking place within an artificial wetland system. Design criteria are at this stage very tentative and the required effluent quality objectives may not be met at the design loading rates. Experience overseas in this regard has been most erratic. The costs of the wetland systems are relatively high as the result of the assumption that suitable porous media would have to be imported and obtained from commercial sources. Should local circumstances be favourable great savings can be made in minimising excavation and making best possible use of the local resources in order to achieve the required design. Such an approach may take up more land than more expensive designs would require, which aspect has not been considered in the appraisals above as it has been assumed that this would be a relatively low factor in a rural situation.

Despite the imponderables, artificial wetland systems nevertheless have a place in sewage treatment technology. They are not suitable for treating raw sewage but can be used successfully to treat raw sewage which has either passed through an anaerobic pond system or some form of primary treatment ie: with septic tanks. The construction should whenever possible be appropriate making maximum use of local materials and resources.

Factors not taken into account in the design of these pond and wetland systems are the water losses to the main soil body which will occur. These losses may be very significant where the ponds are constructed over semi-permeable materials of very low natural moisture content. Initial filling of the systems may take many months or even years in saturating the local soil body. In European practice use has been made of geomembranes to line the pond systems. These would become prohibitively expensive and could not be justified unless the effluent has a high economic value.

Artificial wetlands are complex biological physical systems that are as yet little understood. In consequence design criteria are tentative only. The successful application of one set of criteria on a particular site does not mean that the same set will be applicable elsewhere. Nor should they be regarded as an alternative low cost sanitation system as they presuppose a water borne sewerage scheme with a concomitant water supply.

RECOMMENDATIONS

Scientific Research needs in wetland treatment

The literature search and experimental studies undertaken to date have resulted in the development of preliminary guidelines for constructed wetlands for wastewater treatment in South Africa. It is clear, however, that many of the concepts need to be further evaluated in large scale practice in South Africa.

The following are some of the important **scientific** factors that have not yet been fully quantified.

1. Effect of plant type on degree of treatment achieved (e.g. reeds, rushes, sedges).
2. Effect of systems management, including plant harvesting on degree of treatment.
3. Effect of media type on pollutant uptake and degree of treatment.
4. Definition of removal kinetics as a function of plant type, operational regime, detention time, and seasonal conditions.
5. Effect of wetland configuration on degree of treatment.
6. Definition of steady-state constituent removal capacity.

From an **engineering** point of view there are also questions of:

1. effective design criteria relative to pollutant removal kinetics and steady state capacity;
2. the relative advantages/disadvantages of constructed wetland;
3. the ability to comply with discharge consent requirements;
4. availability of confirmed design and operational criteria;
5. the cost-effectiveness;
6. the transfer and acceptability of the technology to users and regulators.

This document provides a background to the scientific and conceptual engineering basis for the implementation of Artificial Wetlands for Wastewater Treatment. It is not meant as a design manual, and should not be considered as such.

PART I : THEORY AND PRACTICE REVIEW

Dr A Wood

ARTIFICIAL WETLANDS FOR WASTEWATER TREATMENT

1. A PERSPECTIVE

1.1 Introduction

The application of sewage and wastewaters to land and natural wetlands is a long established and traditional method of effluent treatment, in many cases, representing the only means of disposing of a community's wastes (Lawson 1985).

In the U.K. reports of wastewater treatment in wetlands date back to 1877, where 6 m^3 of sewage was being applied daily to 1 m^2 of land resulting, not unexpectedly, in the production of an offensive smelling swamp. By providing suitable underdrainage, it was possible to achieve efficient treatment at a reduced loading of 50 $l m^{-2} d^{-1}$, the soil beds being rotated, as with conventional agriculture, to rest a bed prior to ploughing and replanting (Cooper 1987).

In North America, natural systems have also been used extensively in rural areas to receive domestic effluents, for example Brillion Marsh in Wisconsin has been receiving domestic sewage since 1923. Recent practice has been to apply treated effluent to natural wetlands to effect an improvement in quality to comply with environmental control legislation as well as enhancement of the natural wetland ecosystems (Tchobanoglous 1980).

Artificial or constructed wetlands designed for wastewater treatment are usually created either as a totally independent system or as an engineered modification of natural systems to enhance the natural purification processes.

Engineered wetlands can either mimic natural wetlands, in the sense that wastewater flows over the surface of the bed and is filtered through dense stands of artificially established aquatic plants or they can be designed to promote subsurface flow of effluent through the media in which the plants are established. This latter concept has been accepted and developed throughout Europe and Australia, whilst the surface flow marshes are popular in the United States (Wood 1988).

Several hundred systems for both domestic and industrial effluents, including wastes from dairy, brewery, paper mill, sugar plants and mines are either built or in the firm planning stage in Europe and the USA alone (Ronsch 1985, Wood 1988).

A coordinated set of design principles is needed for the widespread acceptance of the technology. Foremost among these are the engineering of the facilities, the hydrodynamics of the wetland, and the biological and physiochemical interactions governing wastewater treatment efficiency.

This review presents a perspective of the mechanisms of wastewater treatment through an artificial wetland to assist in the understanding and design of wetland systems.

2. ARTIFICIAL WETLAND WASTEWATER TREATMENT

2.1 Review

The concept of using aquatic plants to treat wastewater (rural, agricultural, industrial and municipal) has received increasing attention. This has stemmed from work carried out by the US Space Agency (NASA) and in West Germany on industrial and urban effluents (Seidel 1976, Seidel 1978, Kickuth 1980, Kickuth 1984). Research into artificial wetland wastewater treatment has extended throughout Europe in association with an EEC Expert Group on Wetland Systems, and internationally in association with an IAWPRC Specialist Group on Macrophytes in Water Pollution Control.

The first phase of research conducted by NASA involved the use of Water Hyacinth (*Eichhornia crassipes)* and Duckweed *(Lemna, Spirodela* and *Wolffia sp*). In over eleven years of operation at the NASA site upgrading sewage lagoons, cost saving estimated at several million dollars has been realised *(Wolvertan, 1987).*

Although the Water Hyacinth/Duckweed combination has proved effective, sensitivity of the Water Hyacinth to cold climates has led to the adoption of cold-tolerant species for wastewater treatment in more northern regions, such as Pennywort (*Hydrocotlyle umbellata*) *(Wolvertan, 1987).* In South Africa the Water Hyacinth has been responsible for serious river and impoundment congestion and is a declared pest species.

In order to extend the range and application of aquatic plant systems, a hybrid system was developed which combined immersed, cold-tolerant and salt-tolerant plants with microbial filter technology. The first hybrid system consisted of an anaerobic sludge collecting and digesting chamber followed by an upflow rock filter in which reed (*Phragmites communis*) or rush (*Juncus effusus*) were grown with considerable success.

The hybrid system has changed over the past several years by adding aerobic and facultative lagoons to collect and digest sludge. The reeds and rushes have also been replaced in many cases by more aesthetically desirable plants when constructed close to urban areas or associated with individual households. Species such as Canna lily, Arrowhead, Arrow-arum, Elephant ears, Pickerrelweed, Water Iris and even Roses have performed equally well in treating effluent, whilst producing beautiful yellow, red, orange, white and blue blooms *(Wolvertan 1987).*

The Reedy Creek wetland treatment system developed at Walt Disney World Flordia since 1969 is the largest full scale forested wetland effluent discharge system that has been extensively studied. The 35 ha swamp receives up to 14 760 m^3/d secondary effluent and consistently produces an acceptable tertiary treatment (*Wolvertan 1987*).

At the same time as the NASA investigations, research was being undertaken in Europe with horizontal flow soil beds planted with emergent plants (the Root Zone Process), gravel trenches (the Krefeld process), and surface flow hydroponic channels planted with reeds (the Lelystad process).

The gravel of the Krefeld and Lelystad processes is considered to provide effective permeability as well as a suitable habitat for a large population of microorganisms comparable to an extended biological trickling filter, which can stabilize organic material and sediment out suspended solids. The use of soils in the Root Zone Process is considered to enhance the ability to remove suspended solids, pathogenic bacteria and viruses by filtration and sorption, with the added ability to absorb nutrients such as PO_4, NH_4, Fe and K and heavy metals onto charged particles and humic substances.

The Ijsselmeerpolders Development Authority in Holland started to use marsh vegetation to treat sewage in 1967. The first pond was 1 ha in area and was planted with *Scirpus lacustris* (bulrush), to treat effluent emanating from a camping site during the summer months. Purification results were considered excellent, investment and annual costs were low, and the process was less sensitive to peak loads than conventional methods. A much larger (15 ha) tertiary treatment system has since been created to cope with a population equivalent (p.e.) load of 70 000 (*de Jong 1967, Greiner 1984*).

The Root Zone Process was implemented for the first time in Othfresen, Lower Saxony, Germany in 1974. The system was designed to treat domestic sewage of a p.e. of 5 000. Subsequently, this was followed by a system to treat a textile effluent with an organic load equivalent to 60 000 p.e at Bielefeld (*Ronsch 1985*).

Practical application has demonstrated that artificial wetland systems can form a highly efficient and adaptable wastewater treatment option with potential to treat domestic effluents to secondary and tertiary standards; upgrade conventional oxidation-stabilization pond and secondary treatment systems to meet special high standards; and a range of industrial effluents including those from abattoirs, pulp and sugar mills, acid mine drainage, leachates, animal wastes and urban and stormwater runoff (Wood 1989).

It is generally accepted by researchers in the field that macrophyte based systems have certain advantages compared to conventional treatment systems (Brix 1987):

- low operating cost;
- low energy requirements;
- low maintenance requirements;
- can be established close to the site of wastewater production;
- can be established by relatively untrained personnel;
- robust process able to withstand a wide range of operating conditions;
- environmentally acceptable offering considerable wildlife conservation opportunity
- can readily be integrated into existing forms of effluent treatment.

The wetland systems achieve treatment through bacterial metabolism and physical sedimentation as do conventional wastewater treatment systems. The fundamental difference between conventional and wetland systems is that in conventional systems, wastewater is treated rapidly in highly managed energy intensive environments (ie reactors) whereas in wetland systems treatment occurs at a comparatively slow rate in essentially unmanaged ecological environments.

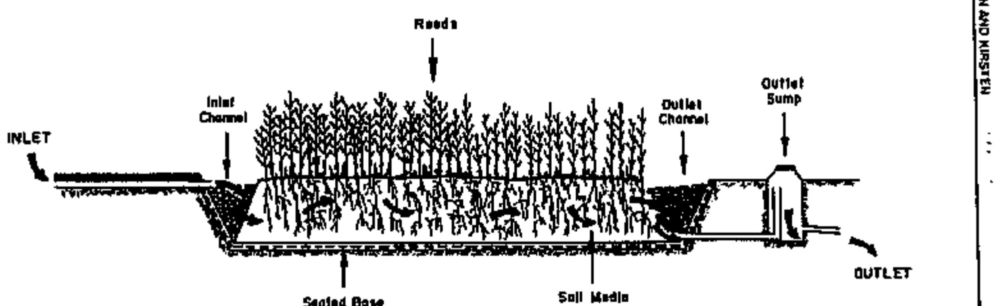
2.2 System Design

2.2.1 Root Zone Method

The Root Zone Method (RZM) was developed during the early 1970's in Germany by Professor Reinhold Kickuth of the University of Landes Hessen, to make the maximum effective use of the natural ability of a wetland to purify wastewater applied to it.

The system is a shallow, lined (or sealed) excavation containing a bed of soil and usually planted with *Phragmites* reed to provide oxygen, sites for microbial attachment and enhance hydraulic permeability.

The wastewater is introduced across the width of the inlet zone and is designed to flow horizontally subsurface through the length of the bed. An adjustable weir in the outlet chamber permits control of hydraulic head and maintenance of water level 2-3 cm below the top of the soil.



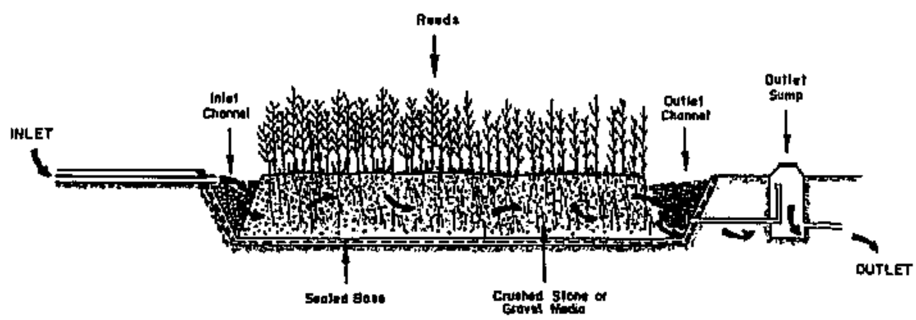
SCHEMATIC REPRESENTATION OF ROOT-ZONE TREATMENT SYSTEM

FIGURE 1

Kickuth has recommended that the slope of the bed should normally be in the range of 2% to 6% *(KicKuth 1984)*. Steeper slopes (7% - 9%) should only be used where combined drainage systems result in short periods of excessively high flow rates of diluted sewage. However, in order to prevent surface flow and permit full establishment of the macrophytes it has been suggested that no gradient be created other than that operated by the control of the effluent weir height (WRC 1988), particularly if the media has an inherent high permeability ie gravel or ash (Wood 1987).

2.2.2 Max Planck Institute Process

The Max Planck Institute Process (MPIP) or Krefeld process was developed by Professor Kathy Seidel and others (Seidel 1976, 1978). It relies on the growth of wetland plants to achieve satisfactory treatment in a 'constructed' marsh, in trenches which may be 2 - 4 m wide, up to 100 m length and between 0,5 - 1 m deep and filled with stone, gravel or sand.



SCHEMATIC REPRESENTATION OF KREFELD TYPE TREATMENT SYSTEM

FIGURE 2

These systems therefore have a close similarity to conventional biological trickling filters designed for removal of carbonaceous and nitrogenous compounds. However, without the presence of suitable metal binding compounds, such as iron, calcium and aluminium, phosphate removal is principally restricted to microbial and plant assimilation and adsorption, and is therefore limited.

The Krefeld system has been successfully used to treat sludges as well as domestic sewage. The system dewaters the sludge by evapotranspiration (1,5 - 2 m/y) and improved drainage (resulting from the development of roots and rhizomes in the sand and gravel), and treats the sludge and sewage by biochemical oxidation, fermentation, filtration and adsorption to remove residual organic substances and solids (Ronsch 1985).

2.2.3 Lelystad Process

The Ijsselmeerpolders Development Authority developed the Lelystad process from the MPIP utilising both subsurface flow through, and surface flow over, the bed.

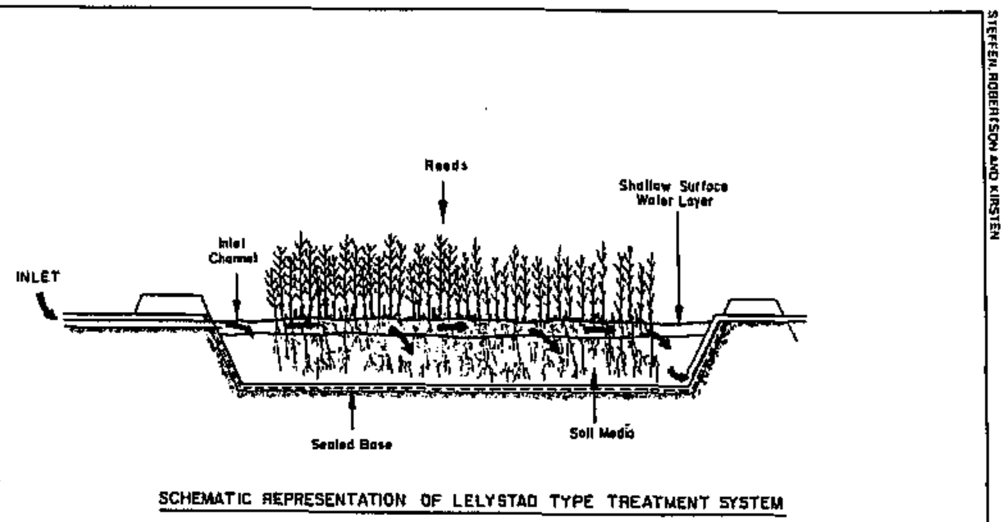


FIGURE 3

The Lelystad system simulates the natural wetland to a greater degree than the previous two systems. It is often associated with ponds or dams built in parallel to give an extended hydraulic retention time.

As the system develops the macrophyte root area develops hydroponically above the media, such that in time a dense mass of root structure is established through which the 'surface' flowing effluent is filtered. In this hydroponic zone or space the roots proliferate rapidly since there are no pressure constraints of soil or gravel. Microorganisms readily attach to the submerged stem and roots, utilizing the released oxygen in biological degradation of the organics.

Such systems, and integrations of ponds, marshes and RZM are popular in the USA for the treatment of domestic sewage, stabilization pond effluents and acid mine drainage. Potential problems with flies and mosquitoes, unpleasant odours, short-circuiting and freezing in winter may develop with a surface flow system if conditions permit.

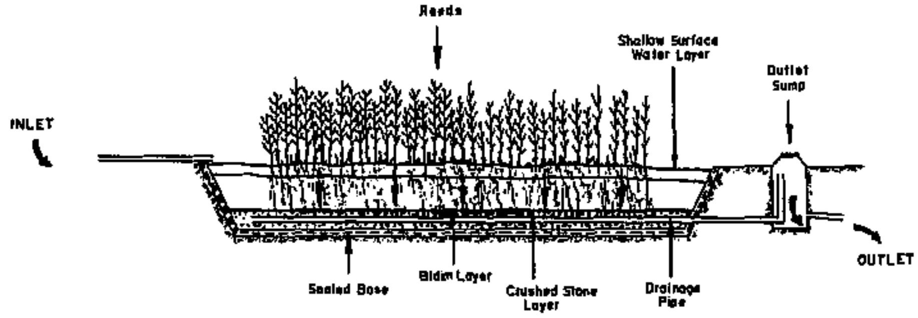
2.2.4 Vertical flow wetlands

Utilization of the Lelystad process for dewatering sludges, and the operation of conventional sludge drying beds relies on the vertical flow of effluent decanting through the permeable media.

Alexander (1985) extended this principle to the design of a vertical flow wetland to treat secondary sewage principally for phosphate removal. The secondary sewage is discharged across a bed, flooded to ensure even distribution, and then it flows vertically down through a phosphorous deficient weathered soil. A horizontal drainage path is provided at the bottom of the wetland. The provision of a short vertical flow path overcomes the difficulties of controlling horizontal flow through a bed of extended length ie 50 - 300 m long, as opposed to 0,5 -1,5 m flow path in the vertical system.

A more uniform loading is given to the wetland i.e. no longer concentrated effluents at one end, and a more constant water level can be maintained across the bed conducive to macrophyte development, since gradients from inlet to outlet are not required.

The provision of the drainage layer adds to the cost of construction, although it permits greater operational control than a horizontal flow system, since surface and subsurface short circuiting should not be as great.



SCHEMATIC REPRESENTATION OF REEDBED TREATMENT SYSTEM

SCHEMATIC REPRESENTATION OF VERTICAL FLOW TREATMENT SYSTEM

STEFFEN, ROBERTSON AND KIRSTEN

FIGURE 4

A recent development in Australia (*Rogers 1990*) reverses the flow in an upward direction vertically through a gravel bed system, comparable to an upflow gravel filter. This arrangement is claimed to optimise the supply of nutrients to the plants, promoting nutrient uptake and removal for the wastewaters. The performance achieved on the pilot scale with this arrangement indicated that these wetlands could treat the load of 1 person equivalent of primary settled effluent per 0,8 m^2.

2.3 Factors Contributing to the Efficiency of Wastewater Treatment

Figure 5 depicts a conceptualised chemical storage and flow model for a wetland system. (D Venhuizen: Personal communication with the author.)

2.3.1 Plant Species

The direct role of the macrophytes in wastewater treatment is the provision of surfaces for bacterial growth, the filtration of solids, the translocation of oxygen to the root zone and the improvement of soil permeability.

In terms of direct nutrient removal potential Ashton (1979) estimated the mean standing crop and productivity of different aquatic plants according to Table 1. The carbon is principally gained from atmospheric CO_2 or bacterial respiration and reflects only a minor contribution to carbonaceous pollutant (COD) removal.

Die-back and senescence of the plants at the end of the growing season can result in a substantial percentage of the assimilated nutrients being returned to the wetland sink. Gersberg (1983) estimated artificial wetland nutrient assimilation could only account for approximately 150 to 200 mg N and 30 to 40 mg $Pm^{-2}.d^{-1}$, significantly below incoming nutrient wastewater loadings.

Although the plants are the most obvious biological components of the wetland ecosystem, the actual treatment of wastewater is accomplished through a integrated combination of biological, physical and chemical interactions between the plants, the media and the inherent microbial community.

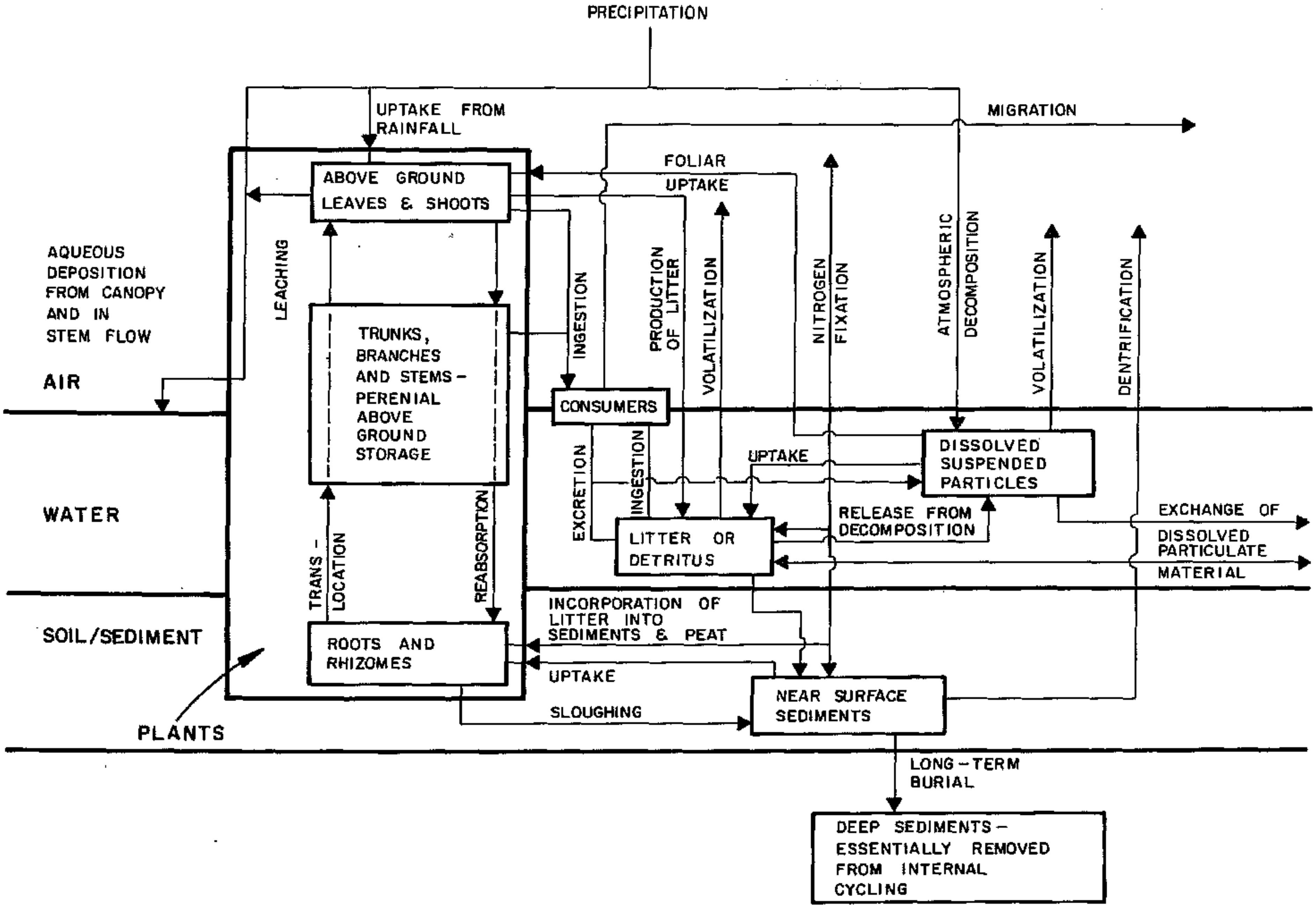


FIGURE 5

CHEMICAL STORAGES AND FLOWS IN A WETLAND

Table 1: Estimates of mean standing crop and production of different forms of aquatic plants (Ashton 1979)

Community	Dominant Species	Mean Standing Crop (kg.dwt.m^{-2})	Mean Annual Crop (t.dwt.ha^{-1}.a^{-1})
Emergent	*Cyperus papyrus*	5,0	100
	Phragmites communis	2,9	90
	Typha latifolia	1,5	85
Free-floating	*Eicchornia crassipes*	1,5	80
	Salvinia molesta	0,5	60
	Pistia stratiotes	0,5	30
Submerged	*Potamogeton pectinatus*	1,9	25
	Ceratophyllum demersum	0,7	9
	Chara globularis	0,14	3

Table 2: Uptake of N and P by three common wetland species in kg/(ha.a) (from Rogers, 1985)

Species	N uptake capacity	P uptake capacity
Cyperius papyrus	1220	60
Phragmites communis	2313	162
Typha latifolia	1164	179

Nutrient removal in wetland systems is therefore predominantly accomplished by the microorganisms and physicochemical mechanisms within the media to, which the macrophytes are providing oxygen.

The oxygen flux to the rhizosphere of rooted aquatic plants is a species-related phenomenon. Evolution has allowed different macrophytes to occupy various ecological niches, depending on their ability to occupy waterlogged and oxygen stressed environments. The common reed, *Phragmites australis,* has been accepted worldwide as a candidate species for wetland wastewater treatment facilities. This is principally due to its production of deep roots and rhizomes (1,5 m or more) which create a great volume of active aerated root zone per surface area of reed bed. Other suitable species are *Scirpus* and *Typha*, where the lower root penetration of *Typha* has encouraged simultaneous nitrification and denitrification (Wood 1988) and provision of conditions conducive for sulphate removal from acid mine drainage.

The other major function of the plants is to increase and stabilize the hydraulic conductivity of the soil media. Maesener (1982) has shown that percolation through soils is improved by the presence of roots and rhizomes of *Phragmites*. As the roots and rhizomes penetrate through the soil they loosen it, increasing porosity by forming pores of tubular shape. Upon decay the roots and rhizomes will leave horizontally interconnected channels behind, which are frequently filled with loosely packed organic material primarily derived from the decaying roots and rhizomes themselves. According to Kickuth (1980) these macropores will stabilize the hydraulic conductivity in the rhizosphere at a level equivalent to coarse sand within 2 to 5 years regardless of the initial porosity of the soil.

Water losses to the atmosphere from a wetland occur from water and soil (evaporation), and from the emergent portions of the plants (transpiration). The combination of the two processes is termed evapotranspiration. There are many reports of studies of these wetland vaporization losses, including the reviews of Linacre (1976), Ingram (1983), Kadlec (1988) although quantitative estimation of evaporative loss for a particular location is dependent upon local climatic and topographical conditions, ecosystem development.

Transpiration rates from dense reed beds often exceed those measured above free water because of large leaf areas and rapid photosynthesis. Nevertheless, in sparser beds, the shelter and higher humidity caused by the reeds may reduce overall evapotranspiration compared with open water (Bernatowicz 1976, Kadlec 1988).

Kadlec (1988) also summarises that wetland evapotransporation, over at least the growing season, is well represented by about 0,8 times class A pan evaporation from an adjacent open site. The seasonal variation in evapotransporation is also considered to show the effects of both radiation patterns and vegitation growth patterns. During the course of the year, the wetland reflectance changes, the ability to transpire is gained and lost and a little layer fluctuates in a mulching function.

2.3.2 Media

The media in which the macrophytes are established provides a stable surface area 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. The media affect retention time, contact opportunities for organisms with the wastewater and the availability of oxygen, all of which relate directly to treatment capabilities (Reed 1988, Brix 1987, Good 1987, Steiner 1988).

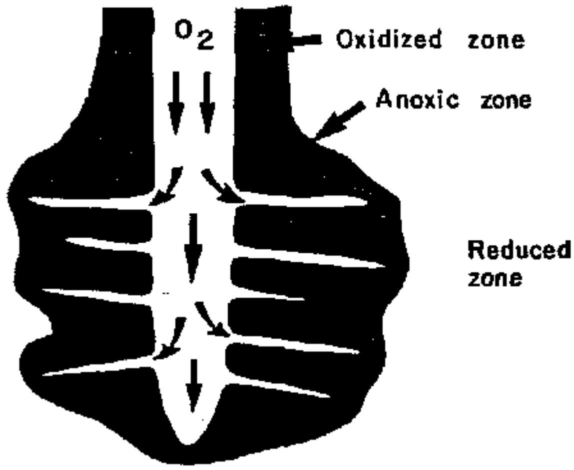
To provide maximum porosity of the bed in which the reeds are to be grown it is necessary to select a soil or media which has a composition from which a stable structure can evolve so that wastewater can flow freely around the living rhizomes and roots and also through the 'tubes' created by dead and decaying rhizomes. Studies in the UK (Cooper 1987) indicate that soils classed as sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay and the lighter part of clay may be suitable if gravel, river sand, or waste ash is not available and nutrient removal is required at reduced hydraulic loading.

In soil systems, the structuring may be strengthened by adding chalk, hydrated lime or gypsum to achieve a calcium content of 2 to 2,5% by mass (Kickuth 1984). Initially, the hydraulic conductivity of the replaced soil should be about 10^{-3} to 10^{-5} m/s. Kickuth claims that conductivity will increase as the bed matures, and roots and rhizomes develop, so that within 2 to 4 years (depending on the growth rate of the reeds) the value should reach 10^{-3} m/s, although, experiences in Europe in systems where soil hydraulics were not adequately considered have shown that in the first years of performance the systems actually have a low hydraulic conductivity (2-3 x 10^{-6} m/s) and function basically as surface flow systems, resulting in channelling with poor vegetation growth in some areas due to lack of water, and poor treatment performance (Brix 1987, Cooper 1987, Boon 1986, Davies 1988, Steiner 1988).

2.3.3 Microorganisms in the Root Zone

Figure 6 depicts the aeration conditions occuring with the root zone.

Microorganisms, which may be either attached to the macrophyte root and stem structures and the media particles or free-living in the water, form the basic physiological mechanisms by which pollutants are removed from the wastewaters passing through the artificial wetland. There positioning and development is regulated by the oxygen demand within the vicinity of the roots, as well as the photosynthetic and free-diffusion characteristics of the plant to provide oxygen to the microorganics.



Simplified representation of the redox-conditions around roots of wetland plants. Oxygen is transported from the atmosphere to the roots via the aerynchyma. A part of the oxygen diffuses into the substrate creating an oxidised zone (+ oxygen) and an anoxic zone (- oxygen, + nitrate) around the roots in the otherwise reduced substrate (+ oxygen, - nitrate) (Brix 1987)

FIGURE 6

The aerobic zone within the rhizosphere extends no further than a few millimeters from the site of oxygen release, and processes for the oxidation of carbonaceous and nitrogenous materials occur in this zone. As ammonia is nitrified to nitrate by nitrification processes the nitrate acts as terminal electron acceptor for denitrification through facultative aerobes in adjacent anoxic zones. In the absence of oxygen and nitrate, and as the redox potential decreases, anaerobic degradation processes occur using energy from SO_4^{2-}, Mn^{4+}, Fe^{3+} and CO_2.

The presence of such diverse ecological environments leads to the development of a wide spectrum of microorganisms capable of degrading the variety of organic and inorganic compounds in wastewaters. In addition, the types of bacteria change both vertically and horizontally with increasing distance from the inlet (Rheinheimer 1974, Boon 1985). The number of protein and sugar decomposing organisms is high at the inflow and close to the rhizomes (aerobic conditions). The number of these organisms decreases steadily downstream, while the number of cellulose and lignin decomposers increases (Rogers 1985).

2.3.4 Temperature

Variations in the temperature of wastewaters appear to have little effect on effluent quality even when the temperature changes from just above freezing in winter to 25° C in summer. This is reportedly because the total number of active bacteria in the soil and rhizosphere increase in winter months, which allows increased concentrations of substrate away from the inlet end of the bed, with the effect that the concentrations of bacteria increase in the middle and outlet zones of a bed as a result of reduced activity of individual bacteria (Cooper 1986, Watson 1988).

There are also a number of factors which will help to maintain a relatively high temperature in the rhizosphere during winter:

- the plant cover and the litter on the surface has an insulating effect;
- production of heat from microbial activity increases the temperature in the rhizosphere;
- the influent of wastewater generally has a higher temperature than the surroundings.

These factors should prevent the infiltration areas and the rhizosphere from freezing during winter (Brix 1987).

3. MECHANISMS OF POLLUTANT REMOVAL

3.1 COD/BOD Removal

The COD/BOD associated with settleable solids in wastewater is removed by sedimentation. The colloidal and soluble COD/BOD remaining in solution is removed as a result of the metabolic activity of micro-organisms that are suspended in the water column, attached to the sediments and to the roots and stems of the aquatic plants. Conceptually, wetland systems are slow-rate, horizontal flow trickling filters with built-in secondary clarification in which plants supplement rocks or other media as bacterial support structure as well as transmitting oxygen into the wastewater system.

The rate of biodegradation of various organic substances depends on temperature, oxygen concentration (gradients and profiles), pH, nutrient availability, substrate concentration and the presence of potential toxins (Goldshalk 1978, Wuhrman 1972).

The character of any organic compound will also affect its biodegradation rate (Rheinheimer 1974) so that within the readily biodegradable fraction, rates of degradation vary widely. The most readily biodegradable substances such as protein, sugar and starch are metabolized very rapidly while fat, wax, cellulose, lignins, phenols and cyanides decompose more slowly, and sometimes incompletely. As a result, the time taken for wastewater to flow through a wetland determines which organic compounds are present at their outflow. While the readily biodegradable portions of wastewaters are decomposed rapidly, less readily biodegradable fractions may be incorporated into the organic sediment to be anaerobically degraded over an extended period extending the overall retention time available for pollutant removal by microorganism degradation (Wuhrmann 1972, Rogers 1985).

The removal of BOD_5, TOC and COD on both natural and artificial wetlands and on overland flow systems can most easily be described as a first order function of the form:

$$C_t = C_o e^{-kt} \qquad (1)$$

where

C_t = concentration remaining at the time t, (mg/l)

C_o = concentration at time t = 0 (mg/l)

k = specific removal rate constant for given constituent at 20 °C, (d^{-1})

t = detention time in wetland, (d)

Such a relationship may also apply to the removal of pathogenic microorganisms, certain trace organics, and heavy metals (Tchobonoglous 1980).

If it is assumed that 95 per cent of the BOD_5 in primary wastewater is removed in 10 days, the value of k (which is temperature dependent) is on the order of 0,3 d^{-1}, according to North American conditions. This requires re-evaluation under long term Southern African conditions, but may be assumed, in general, to be lower as a consequence of a more condusive climatic environment.

The effect of temperature can be modelled with sufficient accuracy using the following expression.

$$k_t = k_{20}\Theta^{(T-20)} \qquad (2)$$

where

k_t = removal rate constant at temperature T (d^{-1})
k_{20} = removal rate constant at 20 °C (d^{-1})
Θ = temperature coefficient, 1,05 to 1,08
T = temperature, (°C) of the water in the wetland

The significance of the above equation for cold regions is that the area of most wetlands must be increased by a factor of two or more during the winter to achieve the same level of treatment. As it is assumed that the bacteria attached to the plant stems and humus are responsible for treatment, the fact that the wetland plants may be dormant or die in the winter is of little concern with respect to BOD removal unless the physical plant support structure is lost.

3.2 Solids Removal

Wetland systems have long hydraulic residence times. Consequently, virtually all settleable and floatable solids of wastewater origins are removed. Colloidal solids are removed, at least either by bacterial growth (which results in the settling of some colloidal solids and the microbial decay of others) or collisions (inertial and brownian) which result in adsorption to other solids (plants, pond bottom and suspended solids) (Stowell).

The annual build-up of solids within the system has been observed to be very low, reflecting efficient mineralization and degradation mechanisms. The inlet areas, however, may require additional attention where high loadings per unit area are evident. In horizontal systems, solids removal occurs predominantly in the initial 12 to 20% of the wetland area. The remaining area may be important to remove autochthonous solids which are produced by the system including those precipitated as salts (Gearheart 1983, Herskowitz 1986).

The root structure of plants such as *Phragmites* also provide infiltration pathways through the upper layers of the bed thereby ensuring that the surface of the filter bed does not clog up (Alexander 1985).

3.3 Nitrogen

There are two pathways by which wetlands can be used for nitrogen removal from wastewater (1) nitrogen can be stored (assimilated or adsorbed) in the system, or (2) it can be removed from the system through denitrification and ammonia volatilization. Leaching and runoff can also remove nitrogen from a wetland but these are not desirable pathways for wastewater treatment.

Storage of nitrogen in a wetland is a temporary measure in terms of wastewater treatment. Regardless of whether nitrogen is assimilated into biomass or absorbed onto the soil, the maximum capacity of the system will be reached sooner or later. When nitrogen is assimilated into biomass it is frequently returned to the sediments through biomass senescence and die off.

Harvesting plants to remove nitrogen is inefficient. Herskowitz (1988) reported harvested material to account for less than 10% of nitrogen removed whilst Gersberg (1985) reported harvesting to account for 12% to 16% Assuming favourable conditions, the maximum nitrogen removal rate of this mechanism is approx. 6 kg $ha^{-1}d^{-1}$. To achieve this, approximately 2,25 t (dry weight) of plant biomass would have to be harvested per hectare per day, representing a significant solid waste handling and disposal problem (Stowell 1981).

A neutral pH is usually maintained in artificial wetlands. Ammonia volatilization is therefore not likely to be a significant pathway for nitrogen removal under normal circumstances. If the pH is raised to 8 or more as a result of CO_2 uptake by submerged plants during photosynthesis, volatilization of ammonia may occur. The nitrogen removal potential of this mechanism is seasonal and inconsistent and can best be estimated for a particular locale by determining the nitrogen loss from local stabilization pond systems. Volatilization of NH_3 can result in nitrogen removal rates as high as 22 kg $ha^{-1}d^{-1}$, concomitant treatment benefit of removing nitrogen by NH_3 volatilization that metalphosphate precipitates are also formed at elevated pH's (Stowell 1981).

Biological nitrification and denitrification are the key processes for long term nitrogen removal from a wetland. These are two sequential processes which co-exist in many ecosystem where heterogeneous aerobic, anoxic and anaerobic microsites exist.

Under conditions where dissolved organic carbon is not limiting, (required for denitrification) the factor most limiting nitrogen removal is the supply of oxygen which is necessary to sustain nitrification. In this regard, the ability of an aquatic plant to translocate O_2 from the shoot to the root, and thereby establish an oxidized rhizosphere is an important factor.

The nitrification potential is also limited by water temperature and BOD fluxes, which cause alternative demands to be made on that oxygen. A simplistic (and thus somewhat inaccurate) description of this interaction is that any oxygen flux in excess of the BOD flux will be used to nitrify ammonia if the water is sufficiently warm (nitrification virtually ceases at water temperatures below 10° C).

A guideline for summer nitrogen removal is 9-11 kg $ha^{-1}d^{-1}$. (Gerheart 1983, Reed 1986) although figures as high as 44 and 54 kg/$ha^{-1}d^{-1}$ have been reported (Zirschy 1986, Stowell 1981). Winter nitrogen removals (or releases) will be site-specific and a function of climate and plant species.

In a new wetland, optimum nitrification and ammonia reduction reactions will not occur until optimum oxygen transfer is occurring. This will be when the vegetation has 'matured' (ie growing densely above the surface and forming a dense root/rhizome system within the substrate). The vegetation usually takes about two to four years to reach this stage depending on the initial plant density. A new system cannot be expected to meet stringent ammonia or nitrogen limits until the vegetation has 'matured' unless alternative methods are employed to enhance the nitrification reaction. The addition of oxygen to the wastewater either by mechanical means or by changing the configuration of the system, is such an alternative.

3.4 Phosphorous Removal

Phosphorus removal in a wetland is achieved through plant uptake and the biological and physico-chemical storage of phosphorus in the sediments. These latter mechanisms are the more significant in most wetland systems and must be properly considered in designing the wetland.

3.4.1 Plant Uptake

The initial removal of dissolved inorganic phosphorus from water under natural loading levels is due largely to microbial and aquatic uptake and the geochemical adsorption by aluminium and iron minerals in the soil. The microbial pool is small and quickly becomes saturated even where luxury phosphate can be accomplished under aerobic conditions by species such as *Acinetobacter*.

Aquatic plants supplied with sewage effluent tend to show increased growth, and usually have increased tissue P concentrations. As a result, they have the potential to remove significant quantities of P from wastewater under low loaded conditions. Uptake values vary considerably between plant species, and the actual amount taken up in any wetland will depend on a number of factors. These include standing crop of the plants, age of the plants and nutrient status of the water. For the principal wetland system plants, P removal may be expected to be of the order of 60 -180 $kg.ha^{-1}.a^{-1}$ as plant assimilation (Rogers 1985).

Algal communities associated with the surface waters may also remove considerable quantities of P from wastewater though the growth is erratic and removal of algae from the water phase represents a significant problem.

P absorbed in rooted emergent vegetation and algae is released back into the water body and sediments after tissue death. Richardson (1985) suggests between 35 - 75% of the plant phosphorus is rapidly released on plant senescence. Thus, vegetation only serves as a short term sink for phosphorus unless the biomass is harvested.

3.4.2 Chemical Binding Reactions

The mechanism involved in P sorption is thought to involve the exchange of a phosphate ion with an OH^- of an edge MOH, where M = Fe or Al, and is essentially irreversible at iso-pH, constant ionic strength and in the absence of competing ions. The saturation of the sorption complex is positively linked to the desorption of P which is finite dependent on soil chemistry.

Sorption theory requires that the P concentration in solution largely determines the amount of P sorbed, with surface 'activity' changing accordingly. Precipitation theory, however, requires that the P concentration be controlled by the solubility product of the least soluble P compound, the surface activity remaining constant. With the sorption model, the P concentration maintained in solution is greater at high sorbent saturations than at low sorbent saturations, and this is directly relevant to wastewater disposal (Iskander 1981).

In utilizing soil based wetland systems for effluent treatment it has been observed that soils have the capacity to regain, and in some cases enhance, their adsorptive capacities after apparently having reached saturation and subsequently been allowed to rest. (Ellis 1969.)

This characteristic has important bearing on the system design and operation for phosphate removal from wastewaters. The explanation behind the phenomenon is related to the slow dissolution of aluminium and iron compounds to create new sites for adsorption of phosphate with time.

Average soils can be expected to contain from 2 - 4% iron and from 5 - 7,5% aluminium. Thus if all iron and aluminium were dissolved and converted to iron and aluminium phosphates, nearly 1 000 tons of P could be precipitated per hectare m^3 (1 hectare area x 1 m deep). However, under normal conditions, ie near neutral pH, and moderate temperatures, iron and aluminium are both slow to dissolve, and only a fraction of the possible capacity of the soil to precipitate P will be realized in the short term.

3.4.3 Pathogen removal

There is little information available on the long term fate of biological indicators of pollution such as total coliform bacteria in wetlands. Although it is recognized that 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 media and the attached biofilm, physical removal factors include sedimentation, aggregation and inactivation by U.V. radiation. 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 1988, Rogers 1985).

Table 3: Pollutant Removal Efficiency Reported in the Literature for Wetland Systems Treating Wastewaters

		Reference	BOD	TSS	NH_4	NO_3	TP	TN
Grits	1988	Constructed Wetland	80	89	85	94	50	85
Watson	1988	Gravel Bed	94	98	56	-	36	38
de Jong	1978	Bulrush Pond	>98	-	-	-	93	95
Pound	1984	Lagoon & Wetland	99	97	90	-	94	-
Martin	1988	Detention Pond - Wetland Marsh	-	50-66	-	-	28-38	10-18
Mejorin	1988	Marsh	35	64	10	5	48	28
Brix	1987	Constructed Wetlands	60-80	-	-	-	20-40	25-50
Nuttall	1985	Canopy Covered Lagoon	44	65	69	-	-	29
Ariywathie	1987	Sand Beds	85-97	-	-	-	76-100	63-88
Pope	1981	Sand & Gravel Trenches	88	91	33	-	8	31
Roser	1987	Artificial Wetlands	88	86	-	-	25	56

4. IMPLEMENTATION OF WETLAND TREATMENT SYSTEMS
(Adapted from Tchobonoglous 1980)

To design wetland systems for the treatment of wastewater, information must be available on

1) treatment objectives,
2) usable system configurations,
3) the applicable design criteria,
4) the media plants and animals, available locally,
5) the operational requirement,
6) resource and energy consumption,
7) the cost of facilities for each type of wetland system, and
8) related legal and environmental impacts.

4.1 Treatment Objectives and Application

To date, the most common use of natural wetlands is for the advanced treatment of wastewater following conventional secondary treatment, where nitrogen and phosphate limits must be met and integration into environmentally and socially attractive ecosystems such as nature reserves and conservation areas.

An artificial wetland can be designed to treat the various forms of domestic wastewaters such as raw, settled or conventionally treated wastewaters as well as septic tank effluent, night soil or conservancy tank contents. Artificial wetlands can also be designed to treat pond system effluents (aerobic, anaerobic, facultative stabilization, maturation and oxidation ponds), agricultural wastes and wastewaters, urban runoff, storm waters, biodegradable industrial effluents and mining effluents where physico-chemical activity within the wetland is important.

Essentially the wetland system can be designed to achieve the treatment potential of conventional biological trickling filter and activated sludge systems, the precise quality objective depending upon the application, discharge requirements, local conditions and economics.

4.2 System Configuration

The actual system design depends on the treatment objectives and location conditions such as:

- climate conditions;
- population size, ie too small to justify conventional purification;
- technical infrastructure;
- management;
- funds availability;
- land economics;
- whether organic loading fluctuations can be accommodated;
- whether potential toxin loadings can be accommodated;
- whether the hydraulic regime is adequate to maintain wetland conditions during periods of low flow demand.

Dependent upon these factors the system can be designed to incorporate more conventional treatment facilities, septic tanks, pond systems and energy intensive systems (activated sludge or biological trickling filters). The system can operate as a single unit or combination of individual units, operated in parallel, in series or intermittently. Similarly, the systems may operate in a plug-flow, step feed or recirculation mode.

4.3 Design Criteria

At present, there are a few, and somewhat variable design criteria available that can be used to predict reliably the performance of natural wetlands or to determine the size of artificial wetlands. Research into the mechanics of the technologies has only progressed to full scale application within the last decade, and long term operational and management data is lacking as to the precise requirements and practicalities of the system for specific locations and applications.

4.3.1 Natural Wetlands

The area of land required is large, somewhere in the range of 25 - 50 $m^3ha^{-1}d^{-1}$. Even so removal of nitrogen and phosphores are uncertain and may require even larger areas for significant removal.

Because the climatology, hydrology, hydrogeology, geology, and biology of each natural wetland is so specific it may be necessary to conduct pilot studies at each location to establish the proper loading rates, engineering and operational requirements to ensure adequate flow distribution and treatment efficiency through the wetland, whilst reducing the creation of overloaded, stagnant or short-circuiting zones which may results in management and aesthetic problems.

4.3.2 Artificial Wetlands

Tchobonoglous (1980) presented criteria for artificial wetland according to Table 3. The criteria presented are for the application of primary or secondary effluent. For a given wastewater the corresponding organic loading rates can be derived from the hydraulic loading rates. Where primary effluent is applied it was assumed that the removal of SS and BOD_5 are of principal concern. Where secondary effluent is applied it was assumed that nitrogen control is of prime concern, although some phosphorus would be removed for this particular data.

Watson (1988) in reviewing the performance expectations and loading rates for artificial wetlands found a range in loading rates of from about 83 - 6 250 $m^3ha^{-1}d^{-1}$. Surface flow systems typically being larger or loaded less than the subsurface flow systems with an arbitrary breakline in the vicinity of 370 $m^3ha^{-1}d^{-1}$.

Kickuth (1983) has calculated that the wetland system design can simply be created from a knowledge of the BOD_5 loading where the area of a bed (Ah) is derived from the equation:

$$A_h = KQ_d (\ln C_o - \ln C_t)$$

where

A_h = plan area of reed bed (m^2)

K = constant = 5,2

Q_d = the average flow rate of sewage (m^3/d)

C_o = the average BOD_5 of the influent (mg/l)

C_t = the average BOD_5 of the effluent (mg/l)

The value of K = 5,2 relates to the removal of BOD from sewage in a bed which is to be 0,6 m deep and operated at a minimum temperature of 8°C.

For wastewaters that are more difficult to biodegrade and for lower temperatures the value of K will be greater, up to 14 or 15. For domestic sewage this tends to produce an area of approximately 2,2 m^2/p.e. This seems to be optimistic, however, and many European systems are designed between 3 to 5 m^2/p.e. or are built in low-risk situations where the effluent quality is not critical (Cooper 1988, Tannersdorf 1986). In practice, the wetland sizing should be determined as a consideration of both the effluent organic and volumetric loads, rather than a person equivalent basis. It is recommended that a COD loading of approximately 270 kg COD $ha^{-1}d^{-1}$ should represent a conservative basis for evaluating the wetland basis of design.

4.4 Selection of Media, Plants and Animals

In natural wetlands, the greater diversity of plants and animals already present will affect the degree of treatment that can be achieved whilst contributing to the aesthetic and wildlife benefits of the system. In artificial wetlands, selection of plants to be used will depend on their ability to remove, or to contribute to the removal of, the contaminants of concern under the conditions in which they are to operate. In general, wetland plants that are available locally should be used. This will not only blend in with the environment to a greater degree, but will also be more acclimatised to the local climatic conditions and will be of economic advantage for the initial planting, and subsequent replanting if required.

The plant species also contribute to the natural diversity of the ecosystem and habitat for a variety of other plants, animal, insect, fish and bird species, essential in the role of nature conservation. In a wastewater treatment role species such as *Phragmites* and *Schoenoplectus/Scirpus* have been identified as providing the greater oxygenation and root proliferation and ability to develop in, and treat a variety of effluent types and conditions. Species such as *Typha* tend to have higher short term productivities, but limited root proliferation and overwintering capacity.

An adequate stand of plants can be expected to develop within six to twelve months after planting though it may take 3 - 4 years for the stand to become fully developed with an active rhizosphere capable of achieving full secondary discharge standard (Kickuth 1984). The correct selection of the media type, not only is the dominant factor in achieving the desired hydraulics path of the effluent through the reedbed (surface or subsurface), and consequently the treatment efficiency, but also the capital economics of the system since the correct media represents the dominant cost factor, particularly if a gravel is required and has to be imported to the site.

Local media types should be evaluated in terms of their hydraulic permeability and nutrient (esp. P, N, Fe, Mn and SO_4) adsorption capacities. For carbonaceous and nitrogenous removal a coarse soil or gravel may suffice. Soils with a high Al or Fe content are required for P removal, and organic media for Fe, Mn and SO_4 removal.

The consequences of not carefully considering the selection of the media are discussed in section 2.3.2, 3.4.1 and 5.5.1.

4.5 Operational Requirements

The operational requirements of wetland systems are related to the techniques that will be used to manage these systems and whether the system is to be operated in a surface or subsurface flow regime. Some of the management techniques that have been used include seasonal application, inflow and outflow regulation, flushing, upland application, underground application, harvesting of vegetation, and chemical treatment. The management techniques(s) that will be used will impact upon the design and operation of wetland systems, and their ultimate long term success in a wastewater treatment role as with the operation of any conventional treatment system.

4.6 Energy and Resource Consumption

To assess the consumption of energy in natural and artificial wetlands for a particular application, comparison must be made with alternative systems such as activated sludge processes, biological filters and pond systems.

The comparison should include:

Primary energy	-	electricity, fuel;
Secondary energy	-	construction, chemicals, parts and supplies.

It has been suggested that the consumption of energy in artificial wetland systems may be as low as 40% of that used for conventional activated sludge treatment. The corresponding value of natural wetland systems would be lower. Ultimately, it may be possible to reduce energy consumption to 10 - 15% of that of conventional treatment if screened domestic effluent is applied directly to wetland systems (Cooper 1988). The precise energy requirements will be site, location and operation specific.

4.7 Cost of Wetland Treatment Systems

To assess the cost of wetland treatment systems, the annual and unit cost for the systems should be compared, the cost of land and the labour requirements including management, supervisory and technical demand and training. It has been estimated that wetlands systems may be as low as 10% of conventional systems designed to meet comparable effluent standards.

In comparison with pond systems the wetland reliability and performance efficiency gives the wetland technology superior overall cost benefits. Actual costs for Southern African situations can only be estimated with the establishment and implementation of the technology. Facilities in the U.K are estimated to cost between £50 - 150 per person equivalent though most of these systems involve lining and concrete structures (Cooper 1988). In the USA systems are calculated to cost within the \$0,011 to \$0,057.$m^{-3}.d^{-1}$ range for conventional, mechanical-type plants (Watson 1988). The cost is expected to be reduced as system design and operation optimized and implementation becomes more standard. The Part II of this document represents a detailed economic review of the wetland technology in relation to a series of treatment scenarios and comparable alternative technologies.

4.8 Related Legal Environmental Impact

As provided for in the Water Act (No 54 of 1956) General and Special quality standards were promulgated in 1962 and revised for phosphate in 1985 and effluents have to comply with these before return to a water course. In terms of the Act it is in fact obligatory to return a purified effluent to a river for use by others entitled to that use. Other means of disposal may be authorized by the Minister of Environmental Affairs, but are the exception rather than the rule (Drews 1983).

The Department of Water Affairs have recently (1989) adopted the concept of Fitness For Use, whereby the General Standard may be superceeded by a specific Waste Load Allocation in relation to the capacity of the receiving water to assimilate and accommodate a pollutant load, setting a Receiving Water Quality Objective. It may be possible to receive a relaxation of the General Standard, or alternatively a tightening of the General Standard requirements for any particular effluent discharging. It should be also recognized that in arid or semi-arid climates, there is the potential for significant consumptive use of water by wetland vegetation. This will decrease ultimate downstream water discharges which may adversely affect the water rights of others. Also, the salinity of the water may increase due to leachate and transformations within the media, particularly if waste ash is to be used.

Table 4: **Preliminary design parameters for planning artificial wetland wastewater treatment systems (Taken from Tchobonoglous 1980)**

Type of System	Flow regime[b]	Characteristic/design parameter					
		Detention time, d		Depth of flow, (m)		Loading rate (cm/d)[a]	
		Range	Typ[b]	Range	Typ[b]	Range	Typ[b]
Trench (with reeds or rushes	PF	6-15	10	0,3-0,5	0,4	3,25-8,0	4,0
Marsh (reeds, rushes others)	AF	8-20	10	0,15-0,6	0,25	0,8-8,0	2,5
Marsh-pond							
1. March	AF	4-12	6	0,15-0,6	0,25	0,8-15,5	4,0
2. Pond	AF	6-12	8	0,5-1,0	0,6	4,2-18,0	7,5
Lined trench	PF	4-20 h	6 h	-	-	5-15	12

[a] Based on the application of primary of secondary effluent

[b] PF = plug flow, AF = arbitrary flow, Typ = Typical value

Table 5: **Design data for constructed wetlands (from Wolverton 1987)**

Site	Areal Requirement $m^{2/pe}$	Loading Rate $m^2 kg\ BOD^{-1} d^{-1}$
Brookhaven	0,7 - 1,5	10 - 20
Kickuth	2,2	29
Mannersdorf	2,7	36
Moesgaard	2,8	37
Knudsby	5,6	74
Hardin	5,8	77 - 260
Lunderslow	7,5	99
Pembroke	16,5	222 - 346
Instrip	23,0	303

5. SITING AND WETLAND REQUIREMENTS (adapted from Drews 1986)

5.1 Planning

When planning the siting of a wetland system the following factors should be considered in relation to the wetland treatment theory covered in this document.

- cost of land;

- elevation of land in relation to the community/application (or wastewater treatment works) ie gravity flow versus pumping is to be considered;

- topography (whether steeply sloping or flat) and whether valleys or depressions could be made use of to reduce costs;

- all land between the wastewater purification plant and the nearest water course should be acquired and owned by the owners of the system. The gross area required should be calculated allowing for the nett wetland area calculated for the return of the waste to be treated plus allowances for embankments, roads, any preliminary treatment, area for screenings disposal as well as any buffer zone around the perimeter;

- type of soil (rocky, clayey or sandy soil), which influences the costs of excavation;

- groundwater pollution potential, ie the distance from water sources, boreholes and wells;

- prevailing winds. Wetlands should preferably be down wind of the residential area. If correctly loaded and well operated, and keeping mosquito breeding in check, secondary treatment wetlands need not be further than 300 m away from the nearest habitation, for large scale applications (> 500 persons) and 50 m (< 50 persons) for individual requirements;

- odours and fly breeding are not always easily controlled in primary treatment wetlands and large scale systems should thus be placed well away from the nearest habitation;

- for wetlands integrated into pond treatment systems receiving night-soil transport costs must also be considered and these ponds should therefore not be too distant;

5.2 Layout

Figure 7 depicts the conceptualised layout of a marsh-pond-meadow wetland system in Pembroke USA (adapted from Tennessee Valley Authority, personal communication), whilst Figure 8 depicts the layout of the Mpophomeni system in Natal (adapted from Healey 1988).

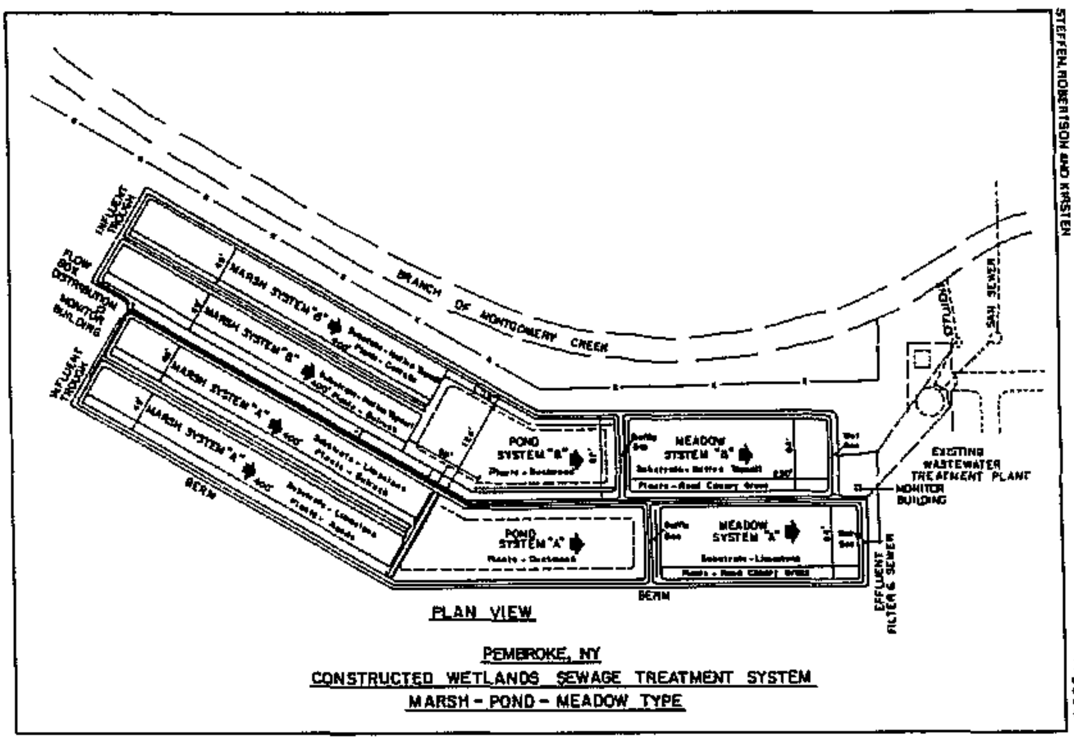
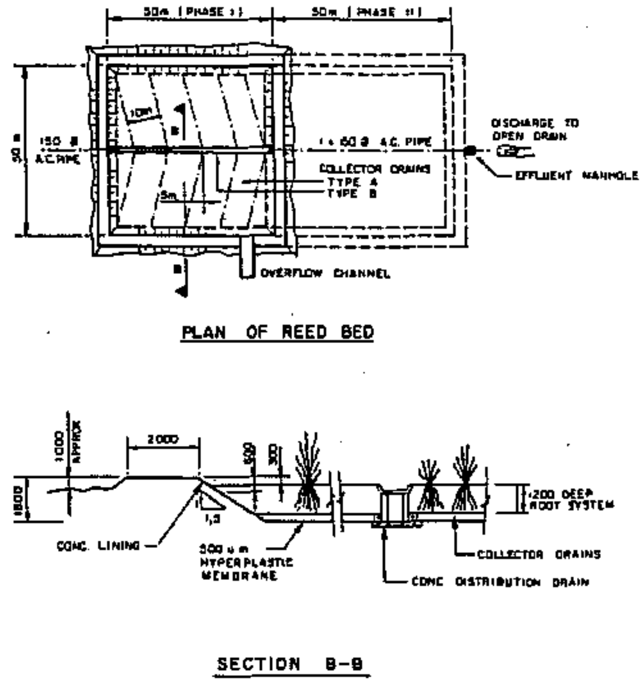


FIGURE 7

The layout of a wetland system depends largely on the topography. The perimeter of each wetland bed should be uniform and coves, islands and peninsulas should be avoided, unless the wetland is to form part of an ecological project, or in the case of low rate treatment where layout is not necessarily essential, i.e. leachate, acid mine drainage.

Wetlands on flat ground may have any practicable shape and water would usually be contained at the same level for all components in a system. Overflows from wetland to wetland could consist of connecting pipes, overflow weirs, or rip rap arrangements which could function to aerate the effluent passing from one wetland to another, if so required.

STEFFEN, ROBERTSON AND KIRSTEN



MPOPHOMENI REED BED
PLAN AND CROSS SECTION

FIGURE 8

On steeper ground, the wetlands could be constructed along the contours with reduced width. Greater control would be required to ensure even flow through the wetland units volume and restrict short circuiting.

The least amount of earthmoving for the construction of wetland is usually required on gently sloping land. However, it should be noted that this type of site is not necessarily the most suitable for the construction of a wastewater purification works of conventional design which may later replace the wetland system as a treatment facility.

5.3 Preparation of a Site

Existing soil should be removed below the level of incoming sewage so that sewage will gravitate through the reed bed. The actual excavation depth will ultimately depend on the site contours, gradient, layout, and permeability of replaced media.

When the effluent is required for re-use, or if pollution of underground water resources would occur from seepage, a sealant of clay (with hydraulic conductivity of less than

10^{-8} m/s), bentonite, synthetic membrane or asphalt is required to retain water in the wetland. After sealing the site, the media in which the reeds will be planted has to be replaced. The media should be carefully placed to a depth of about 0,6 to 0,8 m, avoiding the use of heavy vehicles which might compact the media and reduce its hydraulic conductivity.

5.4 Pretreatment and Flow Measurements

5.4.1 Screens and Grit Channels

Paper, cotton goods and other intractable matter can be expected to be conveyed in the sewage. Preliminary treatment for the removal of this material are screens or grids is strongly recommended. The screenings can then be disposed of in a controlled manner. The alternative of allowing these to enter a wetland or pond in an uncontrolled state will lead rapidly to offensive and unhygienic conditions. Space should be allowed for the construction of trenches for the safe burial of the screenings. Co-disposal with municipal refuse may also be possible.

Screenings would, on average, amount to 0,05 m^3 per 1000 m^3.

Sewage from rural areas may yield a high grit load because of sand used for cleaning utensils. A range of from 0,02 to 0,17 m^3 of grit per 1000 m^3 of raw sewage can be expected.

Wherever night-soil or conservancy tank effluent is discharged into a ponds system, prior to a wetland, a proper bar-screen system must be provided. Any other type of coarse screen eg, square mesh metal grids, are ineffective, because they are difficult to clean.

5.4.2 Flow Meters and other Measuring Devices

A flow measuring device should be constructed at the inlet of the larger wetlands. This device may take the form of a horizontal invert flume and approach channel for unsettled sewage or a weir or V-notch for secondary effluents. It may not be necessary to install a permanent meter, especially if the site is remote. Intense monitoring with a properly calibrated meter even over a short period, will yield more valuable information than a long record from an incorrectly calibrated instrument.

5.4.3 Pretreatment

Pretreatment of wastewater before it enters the system is advantageous, but it does not necessarily mean that the reedbed can be reduced in size according to COD removal in the pretreatment since it may on occassion be necessary to accept the higher infleunt load, be it in a soluble form. Raw sewage should not be loaded directly onto a reedbed where odour and blockage problems may result.

Pretreatment may involve any combination of the following screening, septic tanks, localised digesters, anaerobic lagoons, Facultative and Aerated Ponds, or conventional secondary treatment processes. In the case of agricultural industrial and mine effluents specific attention should be paid to pretreatment requirements such as toxin removal, pH correction (to an extent if required) and quality balancing (recycle), and ease of startup.

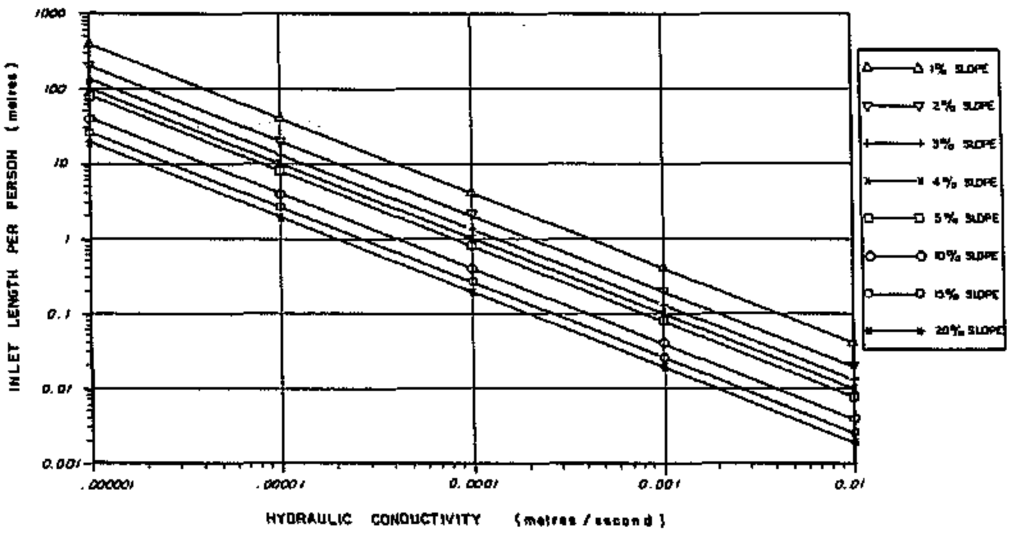
5.5 Wetland Appurtenances and other Physical Features

5.5.1 Slope

In practice systems have been constructed with grades of up to 8% although, experience in Europe has demonstrated that it is rarely possible to compensate for inadequate permeability by incorporating a slope into the design. Additionally a sloping surface causes further problems e.g. surface ponding of effluent, odour generation and erosion, uneven growth of reeds and most importantly poor effluent quality and difficulty in controlling competing weed growth by the preferred procedure of periodically flooding the bed (Cooper 1988).

Systems in Europe are being designed with the minimum slope needed to allow the water to pass through the bed (calculated from the D'Arcy's Law equation) and to use a level surface to permit complete flooding for weed control, with hydraulic gradient control via adjustment of the level at which the final effluent is drawn from the wetland profile.

Figure 9 depicts a graphical representation of the design inlet length per person in relation to hydraulic conductivity of the reed bed of various slope intensities.



REEDBED TREATMENT SYSTEM INLET LENGTH PER PERSON BASED ON DARCY'S LAW AND AN ASSUMED FLOW OF 200 l/PERSON DAY AND A BED DEPTH OF 0.6m (WRC 1990)

FIGURE 9

5.5.2 Bed Depth

The depth of the artificial wetland system is determined by the economics of media availability and construction rather than the expected long term depth penetration of the plant root system, which may be greater than 1,5 m.

The bed depths are typically 0,6 m, though depths of between 0,3 and 1,5 m have been used creating a shallow, horizontal filter arrangement.

It has been accepted in most of the UK and European systems that a depth of approximately 0,6 m is desirable. This is based on (i) the statement that beyond 0,6 m roots start to weaken and that (ii) thinner beds may suffer from freezing during extended winter periods. (Cooper 1988).

5.5.3 Feed Distribution

The incoming wastewater is distributed in the inlet zone into the main media throughout its depth. This is particularly important to reduce the potential for short circuiting ponding, stagnation in dead zones and surface flow during the initial establishment period, whilst reed rhizome structure is growing.

For the horizontal subsurface flow systems the feed should be introduced across the whole width of the influent area. In order to improve the distribution an inlet zone filled with 60 - 100 mm stones 1 to 2 m wide can be constructed.

Where horizontal flow systems are to be operated in series an efficient distribution system at the inlet of each cell must be constructed. Simple openings or weirs in the divider dikes are unlikely to achieve satisfactory flow regimes. In some of the more recently built systems in the UK and the USA, a simple pipe with a series of adjustable T-pieces has been used, to replace expensive castellated weirs.

Final effluent from subsurface flow systems can be collected into an outlet trench and flow out via a pipe. The discharge level of which should be capable of variation. During normal operation, the level of water would be maintained about 10 - 50 mm below the top of the bed to minimise potential for surface ponding and odour generation/release, and encourage mineralisation and composting of accumulating plant and bacterial humus.

In the case of vertical flow systems the influent can be introduced from central channels to the surface of the bed, herring-bone agricultural piping over the surface, spray systems or contoured channels crisscrossing the surface to approximate even distribution across the whole area. The alternative is to create a single inlet zone similar in form to that of the horizontal flow systems and allow a layer of liquor to remain on the surface (5 - 10 cm). This will effectively form a combination of the horizontal and vertical flow systems, since a proportion of the inlet area will be performing the majority of the treatment (particularly filtering action) as effluent percolates through the system.

The inlet distribution to the surface flow, meadow systems may involve simple discharge to a single inlet zone consisting of a coarse material to assist distribution and filtering prior to the main bed system,comparable to the inlet to RZM systems. These will usually have large length to width ratios to capitalise of inlet construction requirements, and flow distribution.

5.5.4 Baffles

Baffles may be required to control distribution of surface flow. Where an impermeable plastic butryl liner is utilized the baffle section can also be liner material seamed to the bottom liner, supported by plywood to facilitate installation of the media. Baffles may also be created from stone/gravel, hay bales, loop or planks to improve flow distribution and penetration.

5.5.5 Embankments and Verges

The embankments should provide for at least 500 mm above the media level to accommodate sludge and straw accumulation before the top layer of composed sludge (peat) needs to be removed.

The slopes of embankments would be dictated by normal engineering practice for small dams, depending on the construction material and compaction, embankment slopes should be at least 1:2 usually 1:3. Fringes may be designed to prevent ingress of vegetation with stone pitching, soil-cement or grassing.

5.5.6 Protection of Systems

Any system for waste treatment should be well protected against washaways by stormwater and the entry of natural run-off. Lead-off channels, which may be grassed, or concrete gutters may be used. These channels should be inspected after rains and be kept open.

Every system should be suitably fenced to keep animals and people out, yet in such a way that subsequent sludge clearing operations in later years are not hampered. Warning notices should be fixed at all entrances.

Rat and crab holes or cracks on the verges and embankments must be noted and closed immediately to stop leakages or breaking of the dam.

5.5.7 Sludge and Straw Accumulation

As the reed-bed develops, after the first three years, a layer of 'straw' and aerobically composting sludge is accumulated, derived from dead leaves and stems, which should not detrimentally influence the system since the hydraulic conductivity should be high (10^{-2} m/s) and process and microbial adsorption. This binding is not a permanent removal mechanism, but may buffer and thereby stabilize the system (Brix 1987).

Sludge and straw accumulation will be of the order of 15 mm/y over the bed area with up to 25 m/y at the inlet zone where organic loading is highest. If the accumulation over time results in performance deterioration it should be removed prior to spring regrowth.

The water table is held slightly below the wetland surface (2 - 5 cm) permitting aerobic composting of sludges and decomposing leaf litter.

5.6 Media

5.6.1 Media Selection

The media will determine the design and construction of the artificial wetland system in terms of permeability and pollutant adsorption (particularly phosphate and metals). For carbonaceous and nitrogenous removal a coarse media may be selected, for example crushed stone, gravel or waste ash. For adsorptive capacity a soil with adequate aluminium, iron or calcium content is required, of the more clayey type.

Published soil maps can be used as a guide to soil characteristics at a proposed site, and as a guide to the occurrence of other suitable natural soil or coarse materials in the locality. The Department of Agriculture should be able to assist in providing such areal maps, as can the Geological Survey Department.

Even the most detailed published soil map is unlikely to hold data for small areas of land associated with an exact proposed site. Each proposed site needs to be surveyed in detail and it is also advisable to check alternative sources with a field survey particularly in terms of permeability of the local media.

Eskom can advise as to the location of waste power station ash, as can the mining houses in terms of coarse and fine ashes.

5.6.2 Media Characterization

In the case of coarse materials such as gravel, sand or waste ash, the characterization can be as straightforward as particle size determination and quantification. Sands and gravel are likely to have limited adsorption and leachate capacity, though the waste ash can be analyzed for such requirements.

The key soil physical characteristics are:

1. particle - size distribution - proportions of sand, silt and clay;
2. structure - development of fissuring and visible macropores;
3. consistence - in soil mass and individual structure units (peds);
4. soil water regimes - assessing the nature, depth and duration of seasonal water logging where appropriate, and presence of impermeable layers in the soil profile.

The key soil chemical characteristics are:

1. organic matter content - usually only significant in the top soil;
2. free $CaCO_3$ - measured in the fine earth (<2 mm);
3. acidity - measured as pH;
4. phosphate absorption - related to Aluminium, iron and calcium organic matter and clay content;
5. iron and Manganese adsorption related to sulphate and organic contact, pH and oxygen regime.

It has been recommended that all necessary surveys should be carried out well before the date of proposed construction, to allow any necessary preparation work to be undertaken well before earthmoving commences on site. This will also allow the choice of alternatives if the material is found to be totally unsuitable.

Table 6: Permeability and Drainage Characteristics of Soils (after A Casagrande and R E Fadum)

Coefficient of Permeability *k* in cm per sec (log scale)

10^{2} — 10^{1} — 1.0 — 10^{-1} — 10^{-2} — 10^{-3} — 10^{-4} — 10^{-5} — 10^{-6} — 10^{-7} — 10^{-8} — 10^{-9}

Drainage	Good		Poor	Practically Impervious
Soil Types	Clean gravel	Clean sands, clean sand and gravel mixtures	Very fine sands, organic and inorganic silts, mixures of sand silt and clay, glacial till, stratified clay deposits, etc "Impervious" soils modified by effects of vegetation and weathering	"Impervious" soils, eg homogeneous clays below zone of weathering
Direct determination of *k*	Direct testing of soil in its original position - pumping tests. Reliable if properly conducted. Considerable experience required.			
	Constant-head permeameter. Little experience required.			
Indirect determination of *k*		Falling-head permeameter. Reliable. Little experience required.	Falling-head permeameter. Unreliable. Much experience required.	Falling-head permeameter. Fairly reliable. Considerable experience necessary.
	Computation from grain-size distribution. Applicable only to clean cohesionless sands and gravels.			Computation based on results of consolidation tests. Reliable. Considerable experience required.

6. MANAGEMENT STRATEGIES OF THE SYSTEMS

6.1 Management of the Systems

For the treatment of domestic or industrial effluents in natural or artificial wetlands some form of management and control is required. This should, wherever possible be so designed as to complement and enhance the natural wetland function and allow natural processes to accomplish the desired result. Rogers (1985) identifies three main management spheres.

i) Control of hydrology
ii) Control of vegetation
iii) Control of wastewater quality.

6.1.1 Control of Hydrology

i) Controlled flushing, to restrict detrimental impact on receiving waters of nutrient release directly or subsequent to chemical treatment.

ii) Outflow regulation, to control depth, velocity and retention time in the system.

iii) Modifications within the wetland, to reduce short circuiting and improve overall flow distribution, via shallow channels, levees and ponds within the system.

iv) Input regulation, to improve distribution of influent throughout the wetland and reduce localized loading conditions and flow regimes.

6.1.2 Control of Vegetation

The plant species established in a wetland system influence treatment capacity in terms of degree of oxygenation of the root zone generated by the reeds, nutrient uptake, and release, evapotranspiration, root/rhizome proliferation influencing wastewater filtration, flow regime through the system and penetration of the media to improve infiltration and subsurface treatment.

Management can involve:

(1) Harvesting by cutting or dredging to control species development diversity, positioning and dominance. Nutrients assimilated are also removed from the system by harvesting though the effect of this on total nutrient removal is limited.

(2) Burning provides the same control as harvesting, though nutrients may be released back into the water body, and the conservation and ecological aspects of the natural wetland are seriously affected.

Both these techniques also remove carbon from the system which provides the energy source for important reactions such as denitrification and sulphate reduction. The removal of the surface layer also influences evapotranspiration, as well as the composting process which assist in controlling temperature below surface.

(3) Selective seeding and planting of candidate species will influence the natural development of the wetland and provide more controlled sites for wastewater treatment within the ecosystem.

(4) Herbicidal and insecticidal treatment to control the development of undesirable weed species, algae, and aphids etc.

(5) Hydrological manipulation will also influence the development of the vegetation and species diversity.

6.1.3 Wastewater Quality Control

The wastewater quality in terms of organic loading and presence of potential ecological toxins significantly influence the operation and efficiency of a natural or artificial wetland as a treatment option.

By manipulation of the wastewater quality the effectiveness of the wetland can be improved.

1. Pretreatment to reduce organic solids and toxins concentrations
   - septic tanks
   - anaerobic lagoons
   - facultative ponds and High Rate Algal Ponds
   - anaerobic digesters
   - conventional secondary treatment
   - screening
   - chemical treatment especially for phosphorous and heavy metals.

2. Alteration of wastewater pH status via chemical addition directly to the wastewater or incorporation of buffering capacity in the form of limestone rip-rap influent channels or media. Algal photosynthesis can cause significant changes in wastewater pH associated with CO_2 abstraction and shift in the bicarbonate balance into the high alkaline (up to pH 11) in pond systems associated with artificial wetlands, or on surface loaded designs, whilst denitrification can produce alkanility though not in direct balance with that destroyed by nitrification.

3. Alteration of wastewater O_2 status via the various pretreatment options, as well as mechanical aeration, or physical aeration created from water drops and open ponds where algal photosynthesis can produce supersaturated oxygen concentrations (>20 mg/l)

4. Addition of silt, ash, soil or peat to wastewater to improve adsorption of nutrients (N & P) toxins, heavy metals and pathogens and influence the flow regime in the system.

Alternatively, such materials may be incorporated as a pretreatment essentially filtering stage prior to the wetland.

7. SCOPE

Financial and economic analyses have been conducted to compare the following systems:

7.1 Treating raw and pre-treated raw sewage

(a) Conventional extended aeration activated sludge.

(b) Oxidation ponds incorporating anaerobic, facultative and maturation lagoons.

(c) Constructed wetlands with anaerobic pre-treatment ponds.

7.2 Constructed wetlands for the removal of nutrients from secondary treated activated sludge plant and biofilter effluents

7.3 Constructed wetlands for suspended solids removal and "polishing" of oxidation pond effluents

PART II : ECONOMIC REVIEW

8. ALTERNATIVE SYSTEMS

8.1 Alternative Systems Treating Raw and Pre-treated Raw Sewage

Two designs of a sewage treatment works capable of producing an effluent in accordance with the General Standard (Water Act No 54/1956) are compared. It is assumed that the effluent from these works may be discharged to a receiving stream where Special Standards are not compulsory. A third design of oxidation ponds has also been undertaken for comparative purposes. Effluent from a pond system would not comply with the required standards and should be irrigated and not discharged to a public stream.

Design Examples

Design criteria are still tentative and there is no certainty that the desired effluent quality will be achieved. The design examples below should be followed for the methodology and not for the actual sizing of the beds.

The designs are for a contributing population of 5 000 population equivalents (p.e.) being representative of a small community. The total flow of 750 m^3d^{-1} is based on a unit flow of 150 $lc^{-1}d^{-1}$. A unit Chemical Oxygen Demand (COD), contribution of 120 g $c^{-1}d^{-1}$ and of Total Kjeldahl Nitrogen (TKN) of 10 g $c^{-1}d^{-1}$ has also been assumed. A COD:BOD ratio of 2,0 has been used.

The sewage flow and characteristics are as below:

Flow	5000 p.e. @ 150 $l\ c^{-1}d^{-1}$	750 m^3d^{-1}
COD	5000 p.e. @ 120 g $c^{-1}d^{-1}$	500 kg COD d^{-1}
	Concentration	667 kg m.l^{-1}
TKN	5000 p.c. @ 10 g $c^{-1}d^{-1}$	50 kg TKN d^{-1}
	Concentration	67 mg l^{-1}
BOD	Load	250 kg.d^{-1}
	Concentration	333 mg.l^{-1}

It is assumed that all the works will be constructed near the coast on land with a gentle slope. Good founding conditions are assumed without significant rock or hard material being encountered.

The three alternatives are described below. The design details and assumptions are outlined in the Annexure.

(a) *Conventional Extended-Aeration Activated Sludge*

This system accords with current sewage treatment practice for small works where compliance with the General Standard is obligatory and is designed in general accordance with the criteria published by the Water Institute of Southern Africa.

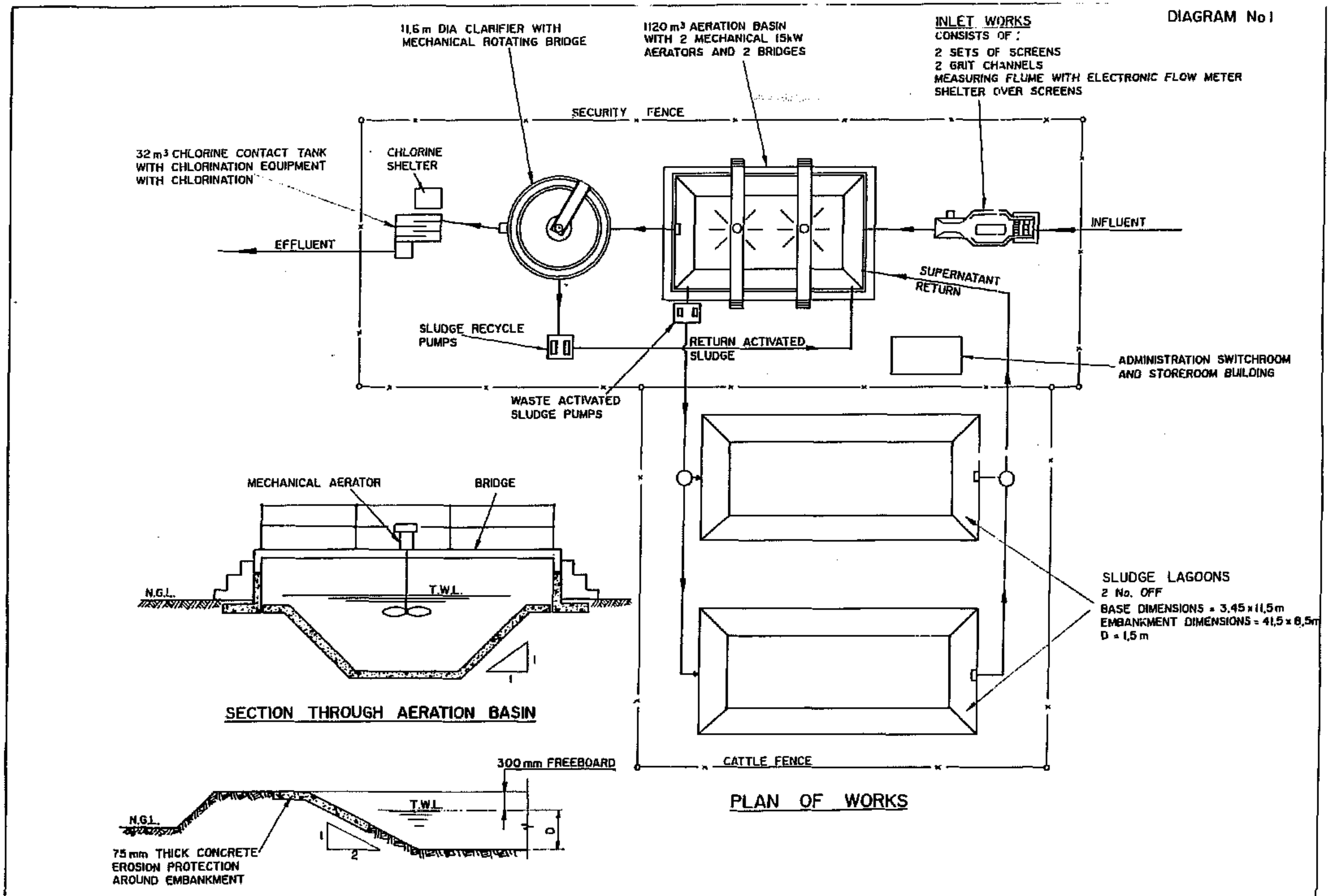
The works are illustrated schematically in Diagram 1.

Raw sewage entering the system will receive preliminary treatment in the inlet works comprising a manually raked bar screen, two constant velocity horizontal flow grit channels and a measuring flume. The flume will be equipped with a flow meter having a rate of flow indicator and a totaliser. A basic shelter will be provided over the screens to provide the attendant with some protection from sun, rain and wind.

After the inlet works the screened and degritted sewage will pass to an aeration basin of 1 244 m^3 total effective volume with an hydraulic residence time of 36 hrs. The reactor will be rectangular in plan with small vertical walls, sloping sides and horizontal floor. Two platform mounted low speed surface aerators of 11 kW nominal rating each will be provided.

A single Dortmund type tank with a diameter of 10,0 m will be used. At the design peak rate of flow of 94 $m^3.h^{-1}$ the upflow rate will be 1,19 $m.h^{-1}$. At the design MLSS of 3,73 $kg.m^{-3}$ this gives a sludge flux of 7,61 $kg.m^{-2}.h^{-1}$ which is satisfactory. The maximum rate of pumping for the return activated sludge will be 20 *l*/s.

Clarified effluent will be chlorinated with a vacuum chlorinator system supplied by a gas bottle. A small shelter will be provided to protect the gas bottles from the elements. The chlorinator and service water will be housed in a separate cubicle. A chlorine contact tank providing 1 h retention at average daily flow will be constructed. Final effluent will gravitate to the receiving stream.



ACTIVATED SLUDGE PLANT

Waste activated sludge will be pumped directly from the aeration basin by means of two self priming centrifugal pumps, operating on timers. At the design sludge age of 25 days, 53 m^3 of mixed liquor will be wasted daily to two storage lagoons of 820 m^3 nominal volume each. The lagoons will be of earth embankment construction with a concrete apron slab cast at the water line. Each lagoon will provide approximately one year's sludge storage. Supernatant from the lagoons will gravitate back to the aeration basin.

A small building of approximately 90 m^2 will be provided to accommodate switchgear, equipment store, operator's room and a wash room.

No provision is made for surfaced roads and landscaping other than surface grading, terracing and grassing of embankments. The main site will be security fenced and cattle fencing provided around the sludge lagoons.

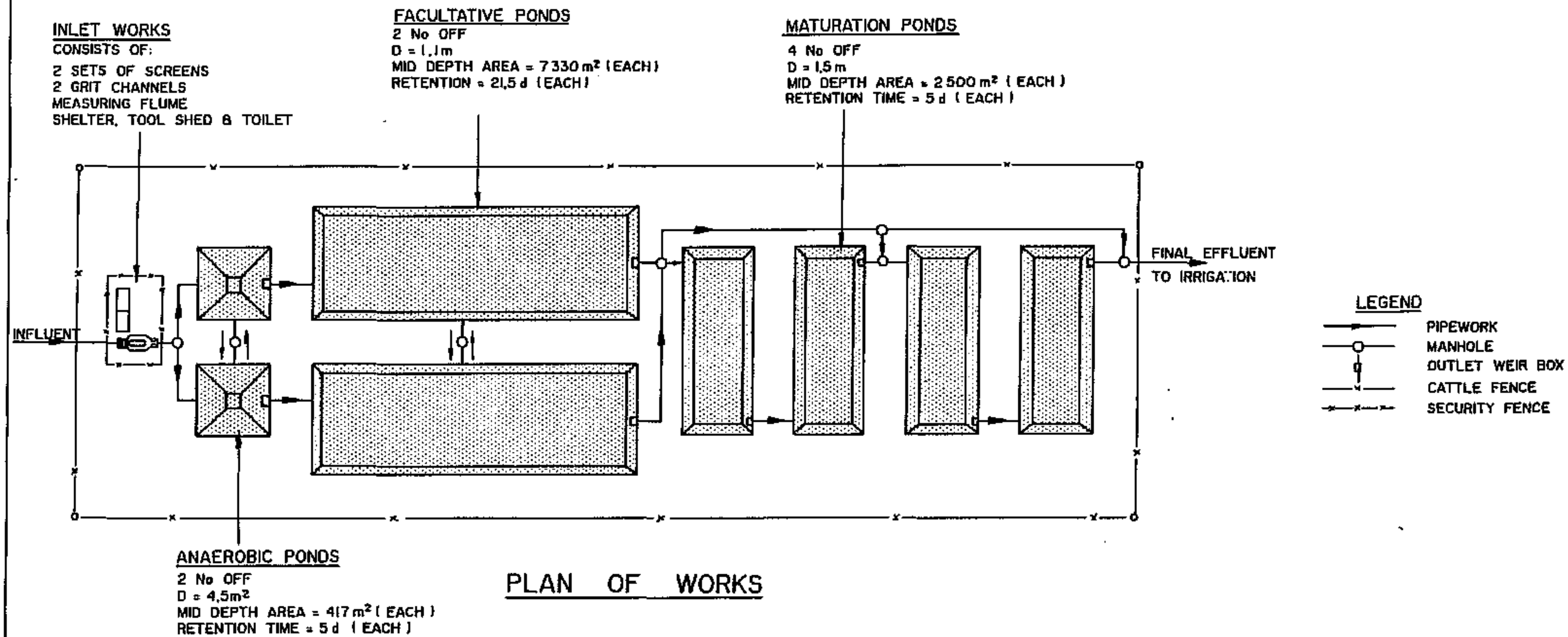
The works are illustrated schematically in Diagram 1.

(b) *Oxidation Pond System*

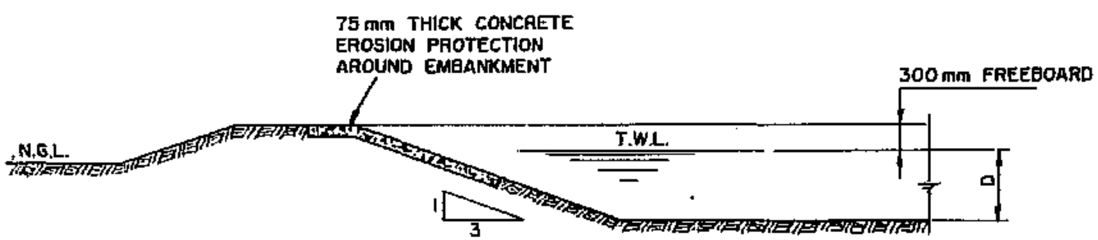
This system incorporates the typical anaerobic/facultative/maturation pond arrangement for the treatment of raw domestic sewage. The design of the ponds is generally in accordance with design criteria of the Watertek Division of CSIR. The works are illustrated schematically in Diagram 2.

The inlet works will be constructed as for the extended aeration plant and will include bar screens and a measuring flume but not grit channels. As it is assumed that no power is available on site for this system a mechanically operated flow meter will be installed. The shelter over the screens, as previously proposed will be extended to include an implement store and toilet cubicle. The total area of the building would be approximately 30 m^2. No other buildings will be provided on site.

Two anaerobic ponds will be provided with a nominal liquid depth of 4,5 m and a nominal volume of 1 890 m^3 each. Both ponds combined will provide a hydraulic space time of 5 days at the average daily flow. A system of inlet pipework will enable either pond to be isolated for cleaning and maintenance. The anaerobic ponds, as with the other ponds in the system, will be constructed with embankment slopes of 1:3 and would be concrete lined at water level.



PLAN OF WORKS



TYPICAL SECTION THROUGH POND EMBANKMENT

OXIDATION POND SYSTEM

Two facultative ponds will be constructed in parallel with a mean liquid depth of 1,2 m and a surface area of 4 050 m^2 each. The total hydraulic space time would be 15,4 days at an estimated organic loading rate of 220 kg BOD_5/ha/d for a mean minimum water temperature of 15°C. The ponds would be constructed such that either may be removed from service for cleaning or both may be operated in series as required.

Four maturation ponds with a liquid depth of 1,2 m and a surface area of 1 700 m^2 each will be provided. The hydraulic space time in each pond will be approximately 3 days at the average design flow. Effluent from the maturation ponds will be irrigated to land and will not be chlorinated. No provision has been allowed in the scheme for any irrigation facilities such as pipework or diesel engine driven pumps as may be required.

The entire site will be cattle fenced with a small section of security fencing around the inlet works and implement store.

(c) *Constructed Wetlands with Anaerobic Pre-treatment Ponds*

The inlet works, implement store and toilet facilities would be the same as that previously proposed for the pond system treating raw sewage.

After screening and metering the flow would be divided equally between two anaerobic ponds. Both ponds will have a liquid depth of 4,5 m and a nominal volume of 1 890 m^3. The combined hydraulic residence time would be 5 days at the average flow rate of 750 $m^{-3}.d^{-1}$. The ponds will be constructed with earth embankments, unlined, with a concrete apron at the water line all as previously described for the pond system.

Anaerobically pre-treated sewage will gravitate to a system of four artificial wetlands, each with a bed surface area of 4 250 m^2. The loading on the combined beds would be 75 $l/m^{-2}.d^{-1}$ and 150 kg $BOD_5/ha^{-1}.d^{-1}$ for average hydraulic and organic load respectively. The beds will be constructed with earth embankments with concrete aprons to a level of 300 mm below the bed surface. It is assumed that sub-surface permeability and water table depth are such that an impermeable lining is not required.

The inlet zone will be constructed with a concrete channel across the full width of the beds with 'V' notch weirs to ensure even distribution of influent. The channel will discharge over an inlet trench approximately 1,0 m wide by 0,6 m deep filled with 50 to 100 mm crushed stone.

The bed media will be imported gravel graded 19 mm to 12 mm and will be 600 mm nominal depth. The beds will be constructed with a horizontal base. The beds would be planted with rhizomes of common reed (*Phragmites australis*) at a density of 2 rhizomes/m^2.

The outlet zone will comprise a stone filled trench (50 to 100 mm stone) approximately 1,0 m wide with a 150 mm diameter submerged collector drain. The collector drain in each bed will discharge to an outlet control structure incorporating an adjustable weir to vary the liquid level in the bed. The interconnecting pipework and distribution pipework for the beds will be arranged to permit the isolation of one bed at a time for cleaning and maintenance.

Treated effluent from the beds will be chlorinated either with a vacuum chlorinator system supplied by a gas bottle or if no power is available by dosing with hypo-chlorite. A chlorine contact tank providing 30 min retention at average daily flow would be constructed. Thereafter the final effluent would gravitate to the receiving stream.

The entire site will be cattle fenced with security fencing being erected around the inlet works and chlorination facilities only.

The works are illustrated schematically in Diagram 3.

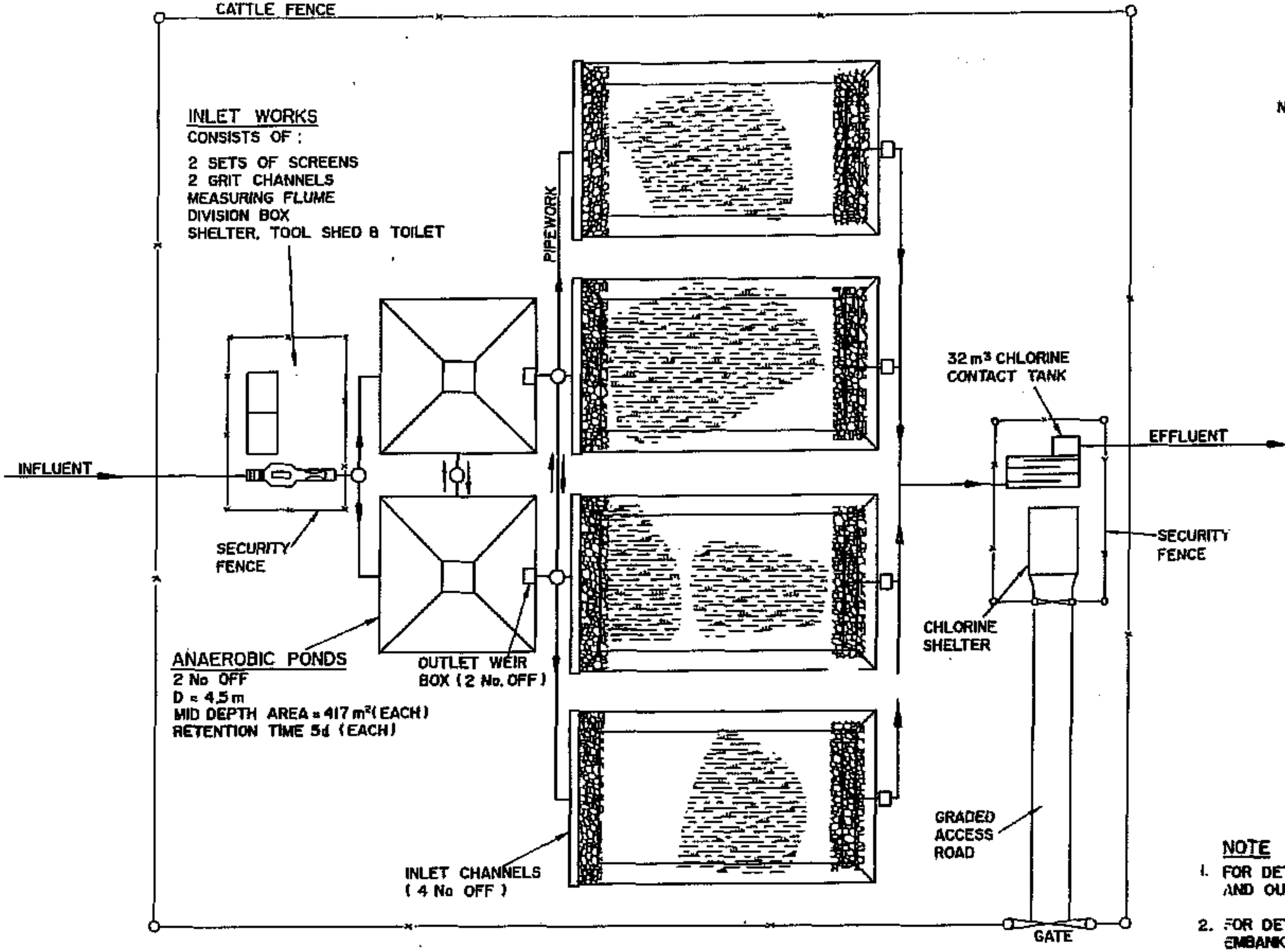
8.2 Artificial Wetlands for Nutrient Removal from Secondary Treated Activated Sludge Plant and Biofilter Effluents

The proposed layout of the scheme is illustrated in Diagram 4.

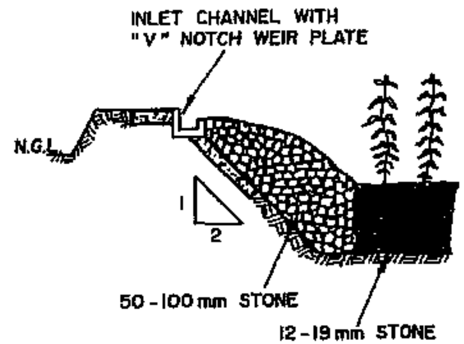
Secondary effluent from an activated sludge plant or biofilter works, will flow to a division chamber and there after gravitate to two equally sized artificial wetlands. Unlike the previously described wetlands these units will operate in a vertical flow mode.

The surface of the bed will be flooded by the incoming effluent to provide as uniform a distribution as possible. The alternative would be to provide an overhead irrigation system with a complex system of distribution pipes and spray nozzles.

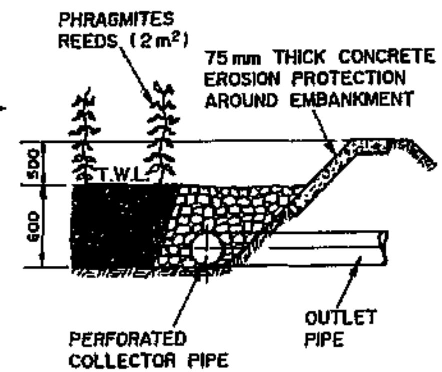
DIAGRAM No 3



PLAN OF WORKS



TYPICAL SECTION THROUGH INLET EMBANKMENT



TYPICAL SECTION THROUGH OUTLET EMBANKMENT

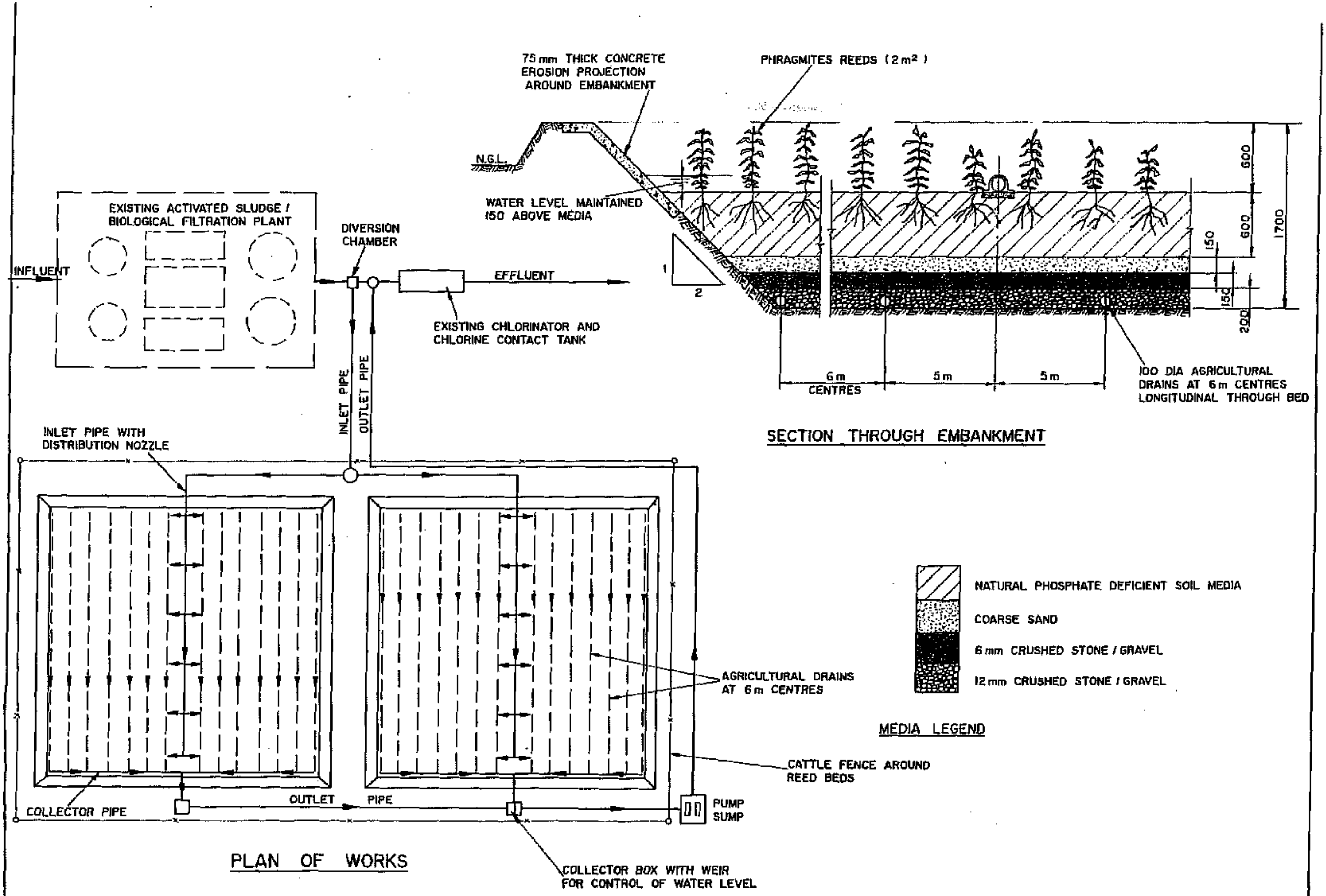
NOTE

1. FOR DETAILS OF REED BED INLET AND OUTLET EMBANKMENTS, SEE FIG. 3.
2. FOR DETAILS OF ANAEROBIC POND EMBANKMENTS SEE FIG. 2.

REED BEDS

4 No. OFF
BASE DIMENSIONS = 35 m x 68 m
SURFACE DIMENSIONS OF 12 TO 19 mm
GRAVEL BASE = 37,5 m x 6,5 m
EMBANKMENT DIMENSIONS 39,5 m x 67,5 m

WETLANDS WITH ANAEROBIC PRETREATMENT



WETLANDS FOR NUTRIENT REMOVAL

The beds will have a surface area of 3 750 m^2 each and under average flow conditions will be loaded at a rate of 100 $l/m^{-2}.d^{-1}$. The inlet pipework will be arranged such that each bed may be isolated for cleaning and maintenance. Under these conditions the operating bed will be loaded at 200 $l/m^{-2}.d^{-1}$.

The beds will be constructed with earthen embankments with a total internal depth of 1,7 m. Concrete aprons would be cast on the embankments above media level to protect the surfaces from erosion. The substrata will be constructed in layers comprising a base course 200 mm deep of 12 mm stone, a 150 mm layer of 3 to 6 mm stone, a 150 mm layer of coarse sand and a 600 mm depth of phosphate deficient soil media or ash. *Phragmites* reeds will be planted in the bed at a density of 2 rhizomes/m^2.

Longitudinal 100 mm diameter agricultural drains will be laid throughout the length of the beds at 6 m centres within the gravel base layer. The drainage pipes will discharge into a 150 mm diameter collector drain and thereafter into an effluent control structure with adjustable weir plates for controlling the liquid depth and hence retention time.

The wetlands will be cattle fenced throughout. A small store would be provided for labourer requirements.

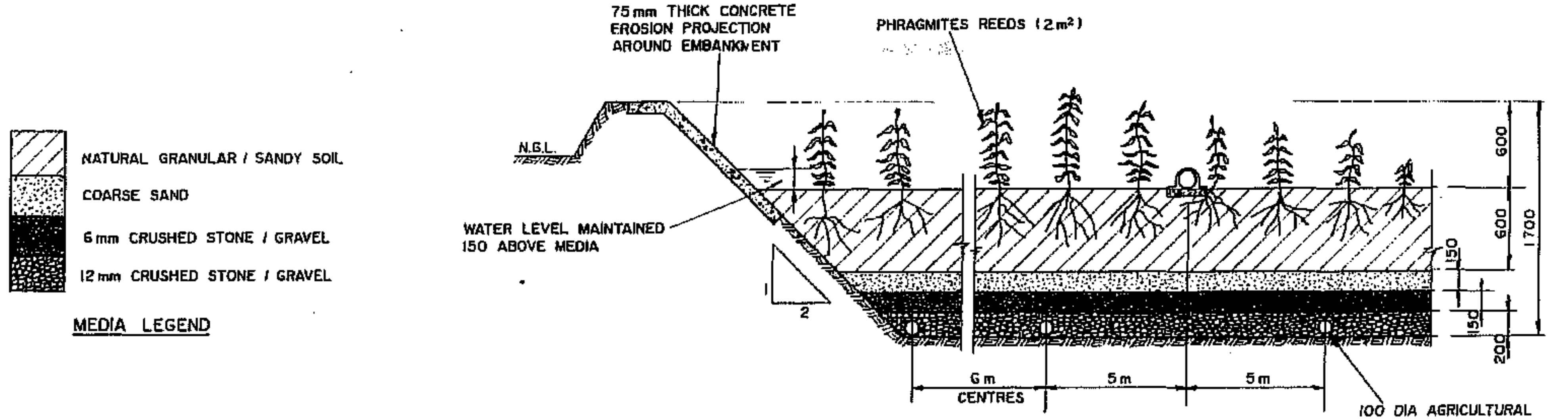
8.3 Artificial Wetlands for Suspended Solids Removal and "Polishing" of Oxidation Pond Effluent

Wetlands constructed for the treatment of oxidation pond effluent would be the same in every respect to the units proposed for treating activated sludge/biofilter effluents (Section 2.2); with the exception that media within the beds would be of a more granular nature. The average loading rate would be 100 $l\ m^{-2}.d^{-1}$ as for the previous system.

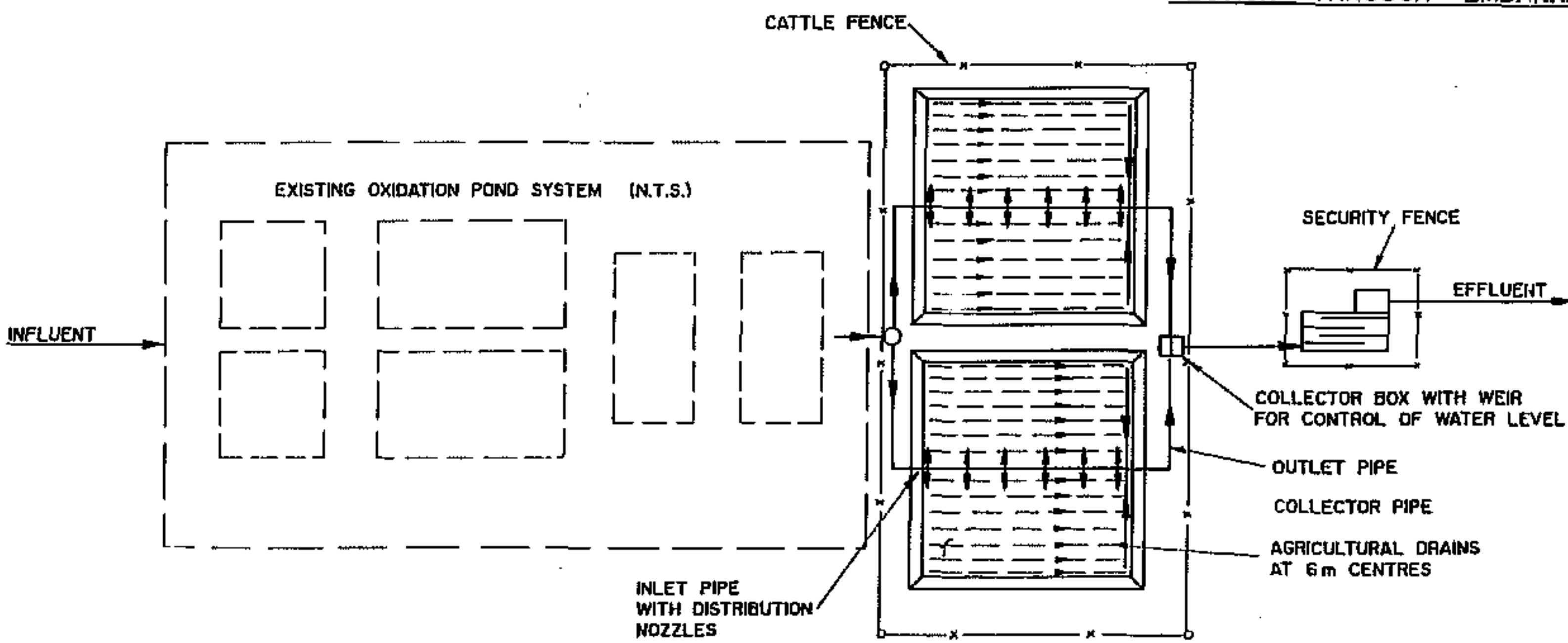
The site will be cattle fenced throughout with security fencing being provided around the chlorination facilities.

The proposals are illustrated schematically in Diagram 5.

DIAGRAM No 5



SECTION THROUGH EMBANKMENT



PLAN OF WORKS

WETLANDS FOR EFFLUENT POLISHING

9. COST ESTIMATES

9.1 The capital costs have been estimated using tendered rates for similar work in neighbouring areas. Where necessary, particularly for wetland construction, rates have been derived after discussions with recognised civil engineering contractors familiar with this type of work. Summarised schedules of quantities and prices have been prepared for each alternative. Capital costs are inclusive of contract price adjustment up to and including the construction period, contingencies, engineering expenses and overheads.

9.2 Cost estimates have been based on the assumption that the work will be undertaken by a contractor from the private sector after calling for public tenders. The cost benefits, or advantages that may be derived from labour intensive construction techniques have not been considered at this stage.

9.3 All structures and buildings have been priced on the basis of sound engineering construction with reinforced concrete and brickwork respectively for designs to normally accepted codes of practice.

The costs of pipework have been calculated assuming the use of Class 18 fibre cement, with the exception of pipework built into concrete which would be hot dipped galvanised steel.

9.4 With the extended aeration activated sludge plant we have assumed that power and potable water (borehole) would be provided at the boundary of the works. It must be recognised that in practice this would be site specific and the actual provision of power and water to the works may represent a significant portion of the costs.

All electrical cabling, switchgear and water distribution pipework within the site boundaries have however been included in the estimates.

It is assumed that the proposed wetlands treating effluent are constructed adjacent to an existing works and there is adequate land area available to construct the ponds.

For other alternative ponds and wetlands it has been assumed that no power is available.

9.5 Excavation quantities and prices assume that all sites are reasonably level and will be in typical soil materials without excessive rock or hard excavation. For comparative purposes 'rock' and 'hard' volumes have been estimated at 10% and 30% of the bulk excavation quantities respectively.

9.6 It is assumed that the gravel/crushed stone media required for the constructed wetlands treating raw sewage will be available from commercial sources within 10 km of the site. The availability of natural material local to site or increased haulage distance for commercial stone will have a significant impact upon the wetland construction cost.

With the wetlands constructed for nutrient removal and polishing oxidation pond effluent it is assumed that phosphate deficient media or granular material is available from natural sources within 10 km of the site.

It is also assumed that sufficient *Phragmites* reeds for the wetlands are available from natural vleis within 10 km of the site.

9.7 In determining capital costs it is assumed that land is available free of charge and no purchase cost has been included in the estimates.

9.8 In order to compare the different process alternatives we have allowed for the following maintenance and replacement factors in the analyses.

- All civil works, a maintenance cost of 0,5% per annum of present capital cost with replacement required after 45 years.
- Mechanical items, a 10% per annum maintenance factor with replacement every 10 years.
- Electrical equipment, a 5% per annum maintenance factor with replacement every 15 years.
- Earthworks and ponds, a 0,5% per annum maintenance factor with replacement every 30 years.

We have not allowed any annual maintenance costs for the wetlands as this does not seem realistic. We have however allowed for the cost of re-excavating the beds, screening and washing the media in gravel beds, replacing phosphate deficient media, reinstating the beds and replanting reeds every ten years. It is not possible to predict the life of an artificial wetland, i.e. the period within which hydraulic transmissivity will reduce to the point where the beds can no longer perform the required function. Long term data from operational experience is required.

9.9 We have allowed for staffing of the different process alternative in accordance with the requirements of the Government Gazette (RSA) dated 27 December 1985. The rates for the different classes of operator and labourers have been given to us by the Department of Works of a neighbouring State. We have assumed a medium sensitivity environment.

10. ECONOMIC COMPARISONS

10.1 Alternative Systems

Capital Cost

The estimated present day costs for the alternatives for treating raw sewage as well as those for improving secondary effluents of poor quality are tabulated hereunder.

Table 7: Alternative Systems Treating Raw Sewage

	Activated Sludge (Rand)	Oxidation Ponds (Rand)	Wetlands with Anaerobic Ponds (Rand)
Net Total Civils	672 000	618 000	1 121 000
Net Total Mechanicals	173 000	35 000	35 000
Net Total Electricals	41 000		
Allow for Contingencies	89 000	65 000	116 000
Allow for Price Adjustment	133 000	98 000	173 000
Engineering Fees, etc	219 000	149 000	157 000
	1 327 000	965 000	1 602 000

Present Worth Comparisons

The present worth of each scheme has been calculated for the projected cash flow over a period of 30 years. It has been assumed that the systems will operate at full load over this whole period. A complete range of discount rates has been used to take into account different economic conditions.

Table 8: Summary of Present Worths (R x 1000)

Discount Rate		0,0%	2,0%	4,0%	6,0%	8,0%	10,0 %
a)	Activated Sludge	7 724	6 069	4 945	4 160	3 595	3 177
b)	Oxidation Ponds	4 605	3 662	3 023	2 576	2 254	2 014
c)	Wetlands with Anaerobic Ponds	6 210	5 000	4 172	3 590	3 168	2 852
Wetlands with Nutrient Removal		5 257	4 129	3 361	2 824	2 437	2 151
Wetlands for Effluent Polishing		4 948	3 884	3 161	2 656	2 291	2 021

The discount rate does not affect the relative worth of the four schemes that are compared.

The oxidation pond system has the lowest present worth. This is not surprising as the quality of the effluent from an oxidation/maturation pond system will not comply with the General Standard as set out in Government Gazette Notice No 991 of 18 May 1984. The presence of algae will raise the concentration of suspended solids and with it the chemical oxygen demand and oxygen absorbed values to between 2 to 3 times the permitted standard. E.coli counts of less than 1 000/100 m*l* are the best that can be expected. The cost of additional wetlands to improve the effluent to an acceptable standard will bring the present worth of this system to values very similar to that for Alternative (c) being the constructed wetland preceded by anaerobic ponds.

10.2 Constructed Wetlands Treating Secondary Effluents

The total costs of constructed wetlands to treat secondary effluents, for nutrient removal and for effluent polishing is tabulated below. The two systems differ principally in design in that the nutrient removal option has been calculated for vertical downwards flow from a flooded surface bed in order to ensure that all the effluent passes through the phosphate deficient media zone. Horizontal flow through the root zone has been assumed for the effluent polishing system.

Table 9: Wetland Systems Treating Secondary Effluents

	Wetlands for Nutrient Removal (Rand)	Wetlands for Effluent Polishing (Rand)
Net Total Civils	614 000	603 000
Allow for Contingencies	61 000	60 000
Allow for Price Adjustment	92 000	90 000
Engineering Fees, etc	95 000	94 000
	862 000	847 000

Too little is known as to the adsorptive capacities of phosphate deficient media the period before saturation and loss of adsorptive capacity is reached. For the economic comparisons we have assumed this will be ten years. We have also assumed the use of clinker which has a high adsorptive capacity and is very porous. The use of clays which have good adsorptive properties would for hydraulic reasons increase the size of the beds enormously although not necessarily the cost provided local clays could be suitably used.

The effluent polishing system is to improve the quality of secondary effluents from biofilter plants or from an oxidation pond system. It has been designed as an 'add-on' to an existing oxidation pond system and not in combination with such a system as differing results could be expected.

Present worth comparisons were not prepared for this proposal as the upgrading of oxidation pond effluent is not generally practised. Numerous investigations have been conducted overseas using, chemical precipitation/sedimentation, dissolved air flotation, filtration and micro-screening. In view of the intensive use of pond systems in this country a more comprehensive evaluation of wetlands for this application may be warranted.

11. DISCUSSION

There is still a great deal to be learnt and understood concerning the very complex reactions taking place within an artificial wetland system. Design criteria are at this stage very tentative and the required effluent quality objectives may not be met at the design loading rates. Experience overseas in this regard has been most erratic. The costs of the wetland systems are relatively high if suitable porous media has to be imported from commercial sources. Should local circumstances be favourable great savings can be made in minimising excavation and making best possible use of the local resources in order to achieve the required design.

Despite the imponderables, artificial wetland systems nevertheless have a place in sewage treatment technology. They are not suitable for treating raw sewage but can be used successfully to treat raw sewage which has either passed through an anaerobic pond system or some form of primary treatment ie: with septic tanks. The construction should wherever possible be appropriate making maximum use of local materials and resources.

Factors not taken into account in the design of these pond and wetland systems are the water losses which will occur into the main soil body. These losses may be very significant where the ponds are constructed over semi-permeable materials of very low natural moisture content. Initial filling of the systems may take many months or even years in saturating the local soil body. In European practice use has been made of geomembranes to line the pond systems. These would become prohibitively expensive and could not be justified unless the effluent has a high economic value.

12. CONCLUSION

Artificial wetlands are complex biological physical systems that are as yet little understood. In consequence design criteria are tentative only. The successful application of one set of criteria on a particular site does not mean that the same set will be applicable elsewhere. Nor should they be regarded as an alternative low cost sanitation system as they pre-suppose a water borne sewerage scheme with a concomitant water supply.

ANNEXURE

EXTENDED AERATION ACTIVATED SLUDGE SYSTEM TREATING RAW SEWAGE

Design Parameters

Design Flow (ADF): 750 m3/d

Peak Factor: 3,0 x ADF

Temperature: Maximum 24°C
Minimum 15°C

Sewage Characteristics:	mg/l	Load (kg)
COD (1,8 BOD_5)	720	540
TKN	55	41
PO4	12	9

Elevation: 145 m above sea level

Diluted Sludge Volume Index: 175

Design Sludge Age: 25 days

Aeration

Assuming low speed surface aerators

Aerator efficiency	1,8 $kg.kWh^{-1}$ at Standard	Alpha 0,80
N/No @ DO 2,0	0,410	Beta 0,90

Average O_2 Demand	kg/d	kg/h
Carbonaceous	353	14,7
Nitrogenous	136	5,7
Total	489	20,4

Power: Required: 21,0 kW
Installed: 22,0 kW (2 x 11 kW aerators)

Sludge Storage Lagoons

Lagoon Volume (m^3)	818
Liquid Depth (m)	1,5
Total No of Lagoons	2
Total Volume (m^3)	1636

Approximately one year storage of sludge per lagoon

OXIDATION POND SYSTEM TREATING RAW SEWAGE

Design Parameters

Population	- 5 000 pe
Flow/pe	- 150 $l.pe^{-1}.d^{-1}$
Average Daily Flow	- 750 $m^{-3}.d^{-1}$
BOD5/pe	- 60 $g.pe^{-1}.d^{-1}$
Concentration	- 400 mg BOD_5/l
Peak Flow Factor	- 3 x ADF

Anaerobic Ponds

Assume retention time to be 5 days and pond depth of 4,5 m (liquid depth).

Total mid-depth area $$A = \frac{Qt}{D} = \frac{750\ m^3/d \times 5\ d}{4{,}5\ m} = \underline{834\ m^2}$$

Therefore construct two ponds in parallel each with wall lengths of 30,5 x 30,5 m and a volume of 1890 m^3.

At the design temperature of 15°C the BOD_5 reduction in the anaerobic ponds is assumed to be 40%. The maximum average BOD_5 contribution to the facultative ponds is thus

$$0{,}6 \times 400\ mg/l = \underline{240\ mg/l}$$

Facultative Ponds

Assuming reaction rate constant (K_1) for BOD_5 removal at 20°C = 0,3 d^{-1} then reaction rate at design temperature at 15°C is:

$$K_{1(T)}12°C = 0{,}3 \times 1{,}05^{15-20} \text{ (from Arrenhuis } K_{1(T)} = K_{1(20)}Q^{T-20}\text{)}$$

$$= 0{,}235$$

Assuming First Order Kinetics:

$$\frac{Le}{Li} = \frac{1}{1 + K_{1(T)}t}$$

where Li and Le are influent and effluent BOD_5 concentrations respectively (mg/l)

$$\frac{60\ mg/l}{240\ mg/l} = \frac{1}{1 + 0{,}235\ t}$$

Therefore $\underline{t =}$ $\underline{12{,}8\ days}$

Surface area of ponds for an assumed liquid depth of 1,2 m

= 8 000 m^2

length = 130 m; breadth = 65 m

Check organic loading

750 m^3/d x 240 mg/l = <u>180 kg BOD_5/d</u>

Area loading = $\frac{180}{0,8}$ = <u>225 $kg/ha^{-1} \cdot d^{-1}$</u>

Construct two ponds of 4 000 m^2 surface area each operating in parallel with 1,1 m liquid depth.

Maturation Ponds

Determine reaction rate constant (K_b) for coliform removal assuming

K_b is 2,6 d^{-1} at 20°C

At design temperature of 15°C:

$$K_{b(T)} = K_{b20}(1,19)^{T-20}$$

and $K_{b(T)} = 1,09\ d^{-1}$

Assuming Ni = 4 x 10^7 faecal coliforms/100 mg in raw sewage in bacterial concentration leaving the facultative pond Ne_{Fac} is:

$$Ne_{Fac} = \frac{Ni}{(1 + K_b t_{AN})^2 (1 + K_b t_{Fac})}$$

$$= \frac{4x\ 10^7}{(1 + 1,09 \times 2,5)^2 (1 + 1,09 \times 12,8)}$$

Ne_{Fac} = <u>1,9 x 10^5 faecal coliforms/100 ml</u>

Consider a series of n maturation ponds each with a residence time t of 5 days. Concentrations of coliforms leaving nth pond (Ne_{MAT}) is:

$$Ne_{MAT} = \frac{Ne_{Fac}}{(1 + K_b t)^n}$$

$$= \frac{1,9 \times 10^5}{(1 + 1,09 \times 5)^n}$$

For n = 4

Ne_{MAT} = 110

With a hydraulic retention time of 5days the surface area of each pond, assuming a depth of 1,5 m would be 2 500 m^2

---oOo---

WETLAND DESIGN WITH ANAEROBIC PRE-TREATMENT PONDS TREATING RAW SEWAGE

Design Parameters

Population	- 5 000 pe
Flow/pe	- 150 l/pe/d
Average Daily Flow	- 750 m^3/d
BOD_5/pe	- 60 g/pe/d
Concentration	- 400 mg BOD_5/l
Peak Flow Factor	- 3 x ADF

Anaerobic Ponds

Assume retention time to be 5 days and pond depth 4,5 m (liquid depth).

$$\text{Total mid-depth area } A = \frac{Qt}{D} = \frac{750 \text{ m}^3/\text{d} \times 5 \text{ d}}{4{,}5 \text{ m}} = 834 \text{ m}^2$$

Therefore construct two ponds in parallel each with wall lengths of 30,5 m x 30,5 m and a volume of 1 890 m^3

At the design temperature of 15°C the BOD_5 reduction in the anaerobic ponds is assumed to be 40%. The maximum average BOD_5 contribution to the wetlands is thus

$$0{,}6 \times 400 \text{ mg/l} = \underline{240 \text{ mg/l}}$$

Hydraulics

Assuming flow through fully saturated media is defined by Darcy's Law

$$Q = K_s A S \quad \text{.............................. (i)}$$

Q = Flow/unit time
K_s = Coefficient of permeability
A = Cross sectional area of bed perpendicular

European experience suggests that unit flow velocity Q/A should not exceed 8,6 m/d to avoid disruption of the root/biological structure. Assuming this value to be valid, equation (i) reduces to:

$$S = \frac{8{,}6}{K_s} \quad \text{.............................. (ii)}$$

Crushed stone or gravel media permeability will be in range of 1 to 100 cm/s depending on physical characteristics and percentage fines (Terzaghi). Assuming reasonably clean crushed stone and permeability of 10 cm/s:

$$S = \frac{8{,}6}{10 \times 3\,600 \times 24 \times 10^{-2}}$$

$$= 0{,}001 \text{ m/m } (0{,}1\%)$$

For clean gravel hydraulic resistance is low and beds are often constructed with horizontal foundation. Long term permeability of the beds is unknown although overseas literature suggests a value of 0,3 cm/s to be reasonable. With this permeability and a horizontal foundation, a degree of overland flow is to be expected as the bed matures, unless the phratic line can be drawn down by means of the outlet control structure.

Process Design

a) Assuming First Order Kinetics
Assuming biological reaction to approximately first-order plug flow kinetics:

$$\frac{Ce}{Co} = e^{-(kTt)} \quad \text{(iii)}$$

where t = residence time in system, days

$$t = \frac{\text{available void space (Vv)}}{\text{average flow rate (Q)}}$$

Vv = volume of voids, m^3
= nV
n = porosity of bed as decimal fraction
V = total volume of system, m^3
Q = average flow, m^3/d
Ce = effluent BOD, mg/l
Co = influent BOD, mg/l
K_T = first order temperature dependant constant, d^{-2}

Assuming reaction rate constant to follow Arrhenius Relationship:

$$K_T = K_{20}(1{,}1)^{T-20} \quad \text{(iv)}$$

where K_{20} = reaction rate constant at 20°C
T = design temperature, °C
K_T = reaction rate constant at design temperature, d^{-1}

Limited information indicates that K_{20} may be related to porosity (Reed, 1988):

$$K_{20} = K_o\,(37{,}32\,n^{4{,}27}) \quad \text{(v)}$$

where K_o = optimum reaction rate constant for fully developed bed, (d^{-1})

A tentative value for K_o (Reed, USA) is 1,839 d^{-1} for systems treating municipal wastewater. The validity of this assumption under South African conditions is unknown.

Assuming crushed stone media with a porosity of 0,3:

$$K_{20} = 1{,}839\ (37{,}31 \times 0{,}3^{4{,}272})$$

$$= \underline{0{,}45\ d^{-1}}$$

correcting for design temperature:

$$K_T = 0{,}45\ (1{,}1)^{15-20}$$

$$= \underline{0{,}28\ d^{-1}}$$

Substituting in (iii) for effluent BOD_5 of 15 mg/l

$$\frac{15}{240} = e^{(-0{,}28t)}$$

$$t = \frac{-ln\ \frac{15}{240}}{0{,}28}$$

$$\text{and} \quad t = \underline{9{,}9\ \text{days}}$$

The bed volume required would be:

$$V = \frac{tQ}{n}$$

$$= \frac{9{,}9 \times 750}{0{,}3}$$

$$= \underline{24\ 750\ m^3}$$

For bed depth of 0,6 m this relates to surface area of 4,1 ha. This is excessive.

The first order kinetics rate constant is very sensitive to temperature. If effluent BOD_5 were 25 mg/l and design temperature 20°C the retention time would be 5,0 days and surface area 2,1 ha.

(b) Alternative Design (Oxygen Available)

Emergent aquatic plants can transmit between 5 and 45 g O_2/d/m^2 of wetland surface, depending upon oxygen status in root zone.

Assuming conservative rate of 20 g O_2/m^2/d under South Africa conditions and oxygen requirement is 1,5 x BOD then:

O_2 required = Lo .... (vi)

and O_2 available = $\frac{(TrO_2)As}{1000\ g/kg}$ .... (vii)

where O_2 = oxygen required or available kg/d
Lo = organic loading, kg BOD/d
TrO_2 = oxygen transfer rate
= 20 g/m^2/d
As = surface area, m^2

O_2 required = 1,5 x 750 m^3/d x 0,4 kg/m^3

= <u>450 kg/d</u>

Thus O_2 available = $\frac{20\ g/m^2/d \times As}{1000\ g/kg}$ = 450 kg/d

= <u>22 500 m^2 (2,25 ha)</u>

The loading rate would be 33 l/m^2/d and 133 kg BOD/ha/d

Overseas researchers suggest that a factor of safety be applied to this value (x2 recommended). As no account is taken of organic reduction by anaerobic processes this additional allowance is questionable and local studies suggest that higher loading is acceptable.

(c) Alternative Design (Kickuth Model)

Kickuth (West Germany) determines bed area (Ah)from:

Ah = 5,2 Qd (lnCo - lnCe) .... (viii)

Substituting design data:

Ah = 5,2 x 750 (ln400 - ln15)

= <u>12 805 m^2 (1,3 ha)</u>

The equivalent loadings would be 59 l/m^2/d and 230 kg BOD_5/ha/d

Wetlands in Germany have been constructed with a soil media. The applicability of Kickuth model to gravel beds is unknown. Kickuth's statements and data have also been questioned by a number of researchers.

(d) Surface Loading from Daspoort (Pretoria) Pilot Studies

Initial Study (1987/88)

Initial studies on a pilot plant with a settled sewage feed at Daspoort gave the following long term averages.

Influent Settled Sewage

Hydraulic loading rate	100 $l.m^{-2}.d^{-1}$ (superficial area)
COD concentration	276 $mg.l^{-1}$
Suspended solids	88 $mg.l^{-1}$
Equivalent BOD loading rate	153 $kg.ha^{-1}$

Effluent

COD concentration	63 $mg.l^{-1}$
Suspended solids concentration	16 $mg.l^{-1}$

Design Summary

(i) Hydraulic

Cross sectional area limiting through flow to 8,6 $m^3/m^2/d$

$$A \text{ section} = \frac{750}{8,6} = 87 \text{ m}^2$$

with 0,6 m deep media width of inlet zone

$$W = \frac{87}{0,6} = 145 \text{ m constructed in four cells}$$

(ii) Organic Loading

Accept a loading rate of 150 kg/BOD/ha/d.

Bed area required	=	$\frac{240 \text{ kg BOD/d}}{150 \text{ kg } BOD_5\text{/d/ha}}$
	=	<u>1,2 ha</u>
Length of bed	=	$\frac{12000}{145}$
	=	83 m
with bed slope	=	0,1%
Total fall	=	83 mm
Take up in increased depth		say 0,7 m min

REFERENCES

Alexander, W.V. (1985). *Phosphate removal from effluents.* Paper presented at the Symposium on the Impact of Phosphate on South African Waters (22 November) CSIR, Pretoria. 20 p.

Ashton, P.J. (1979). The production and potential uses of macrophytes grown in wastewater. Council for Scientific & Industrial Research Reprint RW794, Pretoria.

Bernatowicz, S., Lesczynski, S. and Tyczynska, S. (1976). The influence of transpiration by Emergent plants on the water balance in lakes. *Aquatic Botany* 2, 275-288.

Boon, A.G. (1986). Report of a visit by members and staff of WRC to Germany (GFR) to investigate the root-zone method for treatment of water. Revised and reprinted 1986, Water Research Centre, Stevenage.

Breen, P.F., Chick, A.J. and Mitchell, D.S. (1989). Wastewater treatment system. Australian Provisional Patent Application No PJ0245.

Breen, P.F. and Chick, A.J. (1989). Wastewater treatment using artificial wetlands: the hydrology and performance of horizontal and vertical flow systems. Proceedings. Australian Water & Wastewater Association, 13th Federal Convention, The Institution of Engineers, Australian National Conference Publication No 89/2, 167-171.

Brix, H. (1987). Treatment of Wastewater in the rhizosphere of wetland plants - the root zone method. *Wat Sci Technol* 19 (1/2), 107-118.

Cooper, P.F. and Boon, A.G. (1987). The use of *Phragmites* for wastewater treatment by the root zone method. The UK approach. In: K R Reddy and W H Smith (ed). Aquatic Plants for Water Treatment and Resource Recovery. Magnolia Publ Inc, Orlando, Florida.

Davies, T.H. (1988). Reed bed treatment of wastewaters. A european perspective. *Water, Sydney,* 15, 32-33+39.

Drews, R.J.L.C. (1983). Pond systems for the purification and disposal of domestic wastewater from small communities. NiWR, CSIR, Pretoria. Guide K69.

Ellis, B.G. and Erickson, A.E. (1969). Transformation of various phosphorus compounds. In: Soils. Report to Michigan Water Resources Commission.

Gearheart, R.A., Finney, B.A., Wilbur, S., Williams, J. and Hull, D. (1985). The use of wetland treatment processes in water reuse. In: Proceedings Water Reuse Symposium III, Vol 2, August 26-31, 1984, San Diego, 617-638.

Gersberg, R.M., Elkins, B.V., Goldman, C.R. (1983). Nitrogen removal in artifical wetlands. *Water Research,* 17, (9), 1009-1014.

Gersberg, R.M., Elkins, B.V., Goldman, C.R. (1985). Wastewater treatment by artificial wetlands. *Water Sci Technol* 17 (4), 443-450.

Godshalk, G.L. and Wetzel, R.G. (1978). Decomposition in the littoral zone of lakes. In: *Freshwater Wetlands: Ecological Processes and Management Potential.* Good, R.E., Whigham, D.F. & Simpson, R.L. (Eds). Academic Press, New York. 131-143.

Good, B.J. and Patrick, W.H. Jr (1987). Root-water-sediment interface processes. In: R. R. Reddy and W.H. Smith (ed) Aquatic plants for water treatment and resource recovery. Magnolia Publ Inc, Orlando, Florida.

Hensman, L.C. (1985). The use of algae for the removal of phosphorous from secondary wastewater effluents. Ph.D. Thesis. University of Pretoria.

Herskowitz, J. (1986). Town of Listowel artificial marsh project. Final report. Proj No 138 RR, Ontario, Min Environment, Toronto, Sept 1986.

Ingram, H.A.P. (1983). Hydrology, in Ecosystems of the World. Vol 4A Mires: Swamp, Bog, Fen and Moor, A.J.P. Gore, (ed) Elsevier, Amsterdam, 67-158.

IsKandar, I.K. (1981). Modelling Wastewater Renovation Land Treatment. (Ed) John Wiley & Sons U.S.A.

Kickuth, R. (1980). Abwassereinigung in Mosaikmatrizen aus aeroben und anaeroben Teilbezirken. *Verhandl Verein österreichischer Chemiker*, Abwassertechniches Symposium, Graz, 639-665.

Kickuth, R. (1983). Einige Dimensionierungsgrundsätze für das Wurzelraumverfahren. In: Sekoulov, I. und Wilderen, P. (Hrsg): Abwasserreinigung mit Hilfe von Wasserpflanzen. Techn Univ Hamburg-Harburg.

Kickuth, R. (1984). Das Wurzelraumverfahren in der Praxis. *Landschaft & Stadt*, 16, 145-153.

Lawson, G.J. (1985). Cultivating reeds (*Phragmites australis*) for root zone treatment of sewage. Contract Rep WRC. (ITE Proj 965. Stevenage, October 1985.

Linacre, E.T. (1976). Swamps. In: vegetation and the atmosphere, Vol 2, case studies, J.L. Monteith (ed) Academic Press London 329-347.

Maesener, J. de, Paelinck, H., Verheven, R. and Hulle, D. van (1982). Use of artificial reed marshes for treatment of industrial wastewater and sludge. In: Studies on Aquatic Vascular Plants.

Mitchell, D.S., Breen, P.F. and Chick, A.J. (1990). Artificial wetlands for treating wastewaters from single households and small communities. In: *Constructed Wetlands for Water Pollutions Control*. Cooper, P.F and Findlater, C. (Eds)

Reed, S.C., Diener, C.J. and Weyrick, P.B (1986). Nitrogen removal in cold regions trickling filter systems. SR/86/2 Cold Regions Regions Research & Engineering Laboratory, Hannover, New Hampshire.

Reed, S.C., Middlebrook, F.J. and Crites, R.W. (1988). Natural systems for waste management and treatment. McGraw Hill Book Company.

Richardson, C.J. (1985). Mechanisms controlling phosphorus retention capacity in freshwater wetlands. *Science* 228: 1424-1427.

Rheinheimer, G. (1974). Aquatic Microbiology, John Wiley & Sons, London.

Rogers, K.H., Breen, P.F. and Chick, A.J. (1990). Hydraulics, Root Distribtuion and phosphorous removal in experimental wetland systems. Pres. Int. Conf. Constructed Wetlands in Water Pollution Control. Cambridge, England. Sept.

Rogers, F.E.J., Rogers, R.H. and Buzer, J.S. (1985). Wetlands for wastewater treatment with special reference to municipal wastewaters, Witwatersrand University Press. Johannesburg, 122.

Rönsch, B. (1985). Wurzelraum-Klaranlagen nach Kickuth *Spenge-Wallenbrück, 46.*

Seidel, K. (1976). Macrophytes and water purification. In: *Biological Control of Water Pollution.* Tourbier, J. & Pierson, R.W. (eds). Univ of Pennsylvania Press, Philadelphia.

Seidel, K (1978). Gewässerreinigung durch höhere Pflanzen. *Garten Landsch,* 88, 9-17.

Steiner, G.R. and Freeman, R.J. (1988). Configuration and substrate design considerations for constructed wetland wastewater treatment. Pres Int Conf Constructed Wetlands for Wastewater Treatment. June 13-17, Chattanooga, Tennessee. 1988.

Stowel, R.M., Ludwig, R., Colt, J and Tchobanoglous, G (1981). Concepts in aquatic treatment system design. *Journal of the Environmental Engineering Division.* ASCE, 107, 919-940.

Tchobanoglous, G. and Culp, G.L. (1980). Wetland systems for wastewater treatment: an engineering assessment. USA Environment Protection Agency, Office of Water Programme Operations, Series Water EPA 430/9-80-007, Washington.

Watson, J.T. et al. (1988). Performance expectations and loading rates for constructed wetlands. Prepared for the Int Conf Constructed Wetlands for Wastewater Treatment, June 13-17, Chattanooga, Tennessee.

Wolverton, B.C. (1987). Artificial marshes for wastewater treatment. In: K.R. Reddy & W.H. Smith (eds). Aquatic plants for wastewater treatment and resource recovery. Magnolia Publ Inc, Orlando, Florida, 141-152.

Wood, A and Rowly, M (1987). Artificial wetlands for wastewater treatment. In: Walmsley, R.D. and Botten, M.L. (Compilers). Proceedings of a Symposium on Ecology and Conservation of Wetlands in South Africa. Occasional Report Series No 28, Ecosystem Programmes. FRD, CSIR Pretoria, 198-204.

Wood, A and Hensman, L.C. (1988). Research to develop engineering guidelines for the implementation of constructed wetlands for wastewater treatment in southern Africa. Paper presented at an Int Conf Constructed Wetlands for Wastewater Treatment, Chattanooga, Tennessee, 13-17 June.

Wood, A. (1989). Research to assess the potential of artificial wetlands for wastewater treatment in southern Africa. Paper presented at the First WISA Biennial Conference & Exhibition, Cape Town, 30 March.

Wood, A., Scheepers, J. and Hills, M. (1989). Combined artificial wetland and high rate algal pond for wastewater treatment and protein production. *Wat Sci Tech,* 21, 659-668.

Wuhrman, K. (1972). Stream purification. In: Water Pollution Microbiology, 1, R. Mitchell (ed). John Wiley, New York.

Zirschky, J. (1986). Basic design rationale for artificial wetlands. Contract Rep. 68-01-7108. EPA, Washington, June 1986.

WRC (1990) European Design and Operations Guidelines For Reed Bed Treatment Systems Pres. Int.Cof. "Use of Constructed Wetlands for Water Pollution Control" Cambridge. England, September 28.

Water Act No 54, 1956.