WATER PURIFICATION BY AQUATIC MACROPHYTES

a literature study

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Verslag over werkzaamheden in kader van een doctoraal onderwerp Biologie voor Dr. P.J. Roos, Vakgroep Aquatische Oecologie, Universiteit van Amsterdam, onder supervisie van Dr. E.P.H. Best (werkgroep primaire en secundaire productie)

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Studentenverslag nr.1985-3

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1. INTRODUCTION

The use of aquatic macrophytes in waste water purification has been discusssed widely during the last fifteen years. Several pilot plants are into operation treating raw sewage or providing final treatment of effluents of conventional sewage plants.

The use of aquatic macrophytes for sewage purification is based mainly on the work of Seidel and Wolverton in the sixties and seventies. Seidel introduced the use of the emergent SCHOENOPLECTUS LACUSTRIS (bulrush), which supposedly breaks down organic pollutants like phenols. Wolverton suggested that harvesting a fast-growing waterweed like EICHHORNIA CRASSIPES (waterhyacinth) might remove substantial amounts of nitrogen and phosphorus from the water. Since waterhyacinth occurs only in the (sub)tropics it is not suitable for use in temperate regions.

This literature study is aimed at answering the following questions:

i. Which macrophyte is most suitable in removing organic matter, nitrogen and phosphorus from wastewater of domestic origin.
ii. What is the exact role of macrophytes in this purification process.
iii. Which (bio)chemical processes are involved in this method of wastewater treatment.
iv. Do the mechanisms as suggested by several authors, working on the topic of wastewater treatment, sufficiently explain their data.

The first chapter of this study intends to give a brief introduction only. The second chapter deals with selection of the most suitable macrophytic species and the environmental plant- relations relevant for wastewater purification. In the third chapter the usually employed sewage treatment is briefly discussed. It is compared with the removal of nitrogen and phosphorus by harvesting macrophytes. Some case-studies are discussed in the fourth chapter, of which one is elaborated in the last chapter.

2. SUITABILITY OF MACROPHYTES FOR WATER PURIFICATION

2.1. Introduction

The following aspects of water purification will be discussed in this chapter, being the selection of the most suitable macrophytic species, as to their anatomy, physiology and ecology with respect to wastewater conditions. Some details of soil characteristics, hydrology and management measures will be given too.

2.2. System

Two systems can be distinguished in using macrophytes for wastewater purification. The first one is a water-soil system, consisting of a pond, with an influent and effluent, populated with aquatic macrophytes and micro-organisms, and with intensive exchange of chemicals between water and soil. The second system, a harvest system, has a more or less impermeable bottom and, even if a substrate for macrophytic roots is present, it is more or less inert. In the water-soil system all natural processes may occur (Kickut,1980a), while in a harvest system purification is mediated only by the uptake of minerals by macrophytes and micro-organisms, during decomposition of the organic matter. In this case storage of nutrients in substrate and in micro-organisms is only temporary. Chemicals leave this system by harvesting the macrophytes or with the effluent (except for nitrogen, as will be discussed later).

2.3. Selection of plant species

2.3.1. Terrestrial, aquatic and marsh plants

Water purification systems with vascular plants mostly utilize marsh or aquatic plants. Only on a few occasions it has been proposed to use sewage for irrigation of terrestrial plants (Hunt and Lee, 1976; Palazzo,1981). However, the relation between the amount of wastewater to be treated and the required area is not advantageous, being at the highest 20 to 75 mm water per week. Since in The Netherlands precipitation is 750 mm water per year, irrigation with sewage will bring waterlogged soil conditions about, in which terrestrial plants do not grow. Another drawback is, that consumption of crops treated in this way may imply the transfer of pathogens.

Aquatic and marsh plants are far better adapted to these waterlogged, reduced and anoxic soils. They possess stems with loose parenchymatous tissue, with large, interconnected intercellular spaces (aerenchyma, cf. Esau,1977). The aerenchyma continues within the roots and its main function, besides strengthening of the stem, is the transport of oxygen. Oxygen for respiration and for the oxydation processes in the rhizosphere. In this way several components, like Fe-II-complexes, are removed, which can be toxic when available in sufficient amounts (Armstrong, 1975).

Within the different groups of aquatic macrophytes, emergents absorb their nutrients mainly from the sediment with their roots, whereas free-floating macrophytes do this only from the ambient water. Submerged plants and plants, which are rooted to the bottom with free-floating leaves, use their roots not only for anchorage purposes, as some authors suggest, but also for the uptake of nutrients

(Carignan, 1982, Twilley et al., 1977). If water purification by macrophytic nutrient absorption is aimed, it is important to know, what the main nutrient source for the proposed plant species is, either the sediment or the ambient water.

2.3.2. Growth rate

Since purification of sewage by macrophytes concerns the conversion of organic matter into inorganic nutrients and subsequent absorption of these nutrients by plants, it is important to select fast growing species, growth rate and nutrient uptake being related. As parameter for dry matter production the following two measures are often used. The PEAK STANDING CROP, being the maximum biomass per area in the growth season, and the ANNUAL PRIMARY PRODUCTION, being the difference between the maximum and minimum biomass, divided by the annual number of days. The latter is generally measured or estimated with a higher accuracy for the aboveground biomass then for the underground parts. All data vary considerably depending on latitude, season and environmental factors. Estimates for tropical freshwater plants (CYPERUS PAPYRUS) indicate an annual production of 60 to 90 tons dry wt/ha/y, while emergent freshwater plants (PHRAGMITES AUSTRALIS and TYPHA spp.) produce 50 to 70 tons dry wt/ha/y (Westlake, 1982). Production rates of the free-floating subtropical waterhyacinth are in the order of 40 to 60 tons dry wt/ha/y, whereas for terrestrial plants (forest, grassland and crops) from 20 to 85 tons dry wt/ha/y. Submerged aquatic plants in temperate freshwaters produce less, only 5 to 10 tons dry wt/ha/y (Westlake, 1982). In this paper only data on aboveground biomass are given in regard to harvesting (Table 1a). Most values refer to natural stands, sometimes composed by mixed plant communities predominated by one single species. The highest primary production is by the emergents like PHRAGMITES AUSTRALIS (reed), SCHOENOPLECTUS LACUSTRIS (bulrush), PHALARIS ARUNDINACEA (float-grass), TYPHA LATIFOLIA and TYPHA ANGUSTIFOLIA (cattails). SPARGANIUM ERECTUM, ACORUS CALAMUS and BOLBOSCHOENUS MARITIMUS have lower production rates.

All free-floating species have lower production rates than emergent macrophytes, when growing in natural stands, except EICHHORNIA CRASSIPES (waterhyacinth). Free-floating aquatic plants, like LEMNA GIBBA, use nutrients from the water only and thus their primary production will be higher in eutrophic than in oligotrophic waters, ranging from 27 to 36 ton/ha (2.7 to 3.6 Kg/m2) each summer (cf. Abdulayef,1969, after Harvey and Fox, 1973). Calculations based upon laboratory experiments with LEMNA MINOR (duckweed) give an annual production (mainly the summer season) of 56 ton/ha (5.6 kg/m2) when harvested regularly (Joy, 1969), whereas data from short-term experiments indicate lower production values (122.7 g/m2,dry weight in 8 weeks). Submerged plants have lower primary production rates than the emergent and free-floating plants (see Table 1a).

Table 1a. Primary production of several freshwater macrophytes.

Macrophytic species		Abovegr.peak standing crop (g/m^2) min	max	mean	Annual production rate ($g/m^2/y$)
ACORUS CALAMUS	(1)	605	1174	857	1071
A. CALAMUS	(2)	400	600		400- 700
BOLBOSCHOENUS MARITIMUS	(3)	500	1300		500-1400
CAREX RIPARIA	(4)	300	1300	650	-
CERATOPHYLLUM DEMERSUM	(5,6)	70	321	-	-
EICHHORNIA CRASSIPES	(7,8)	-	15400	-	1100-3300
ELODEA CANADENSIS	(9)	-	-	-	20
GLYCERIA MAXIMA	(2)	600	2600		700-3400
LEMNA GIBBA	(10)	50	150		
L. MINOR/GIBBA	(11)				1644
LYTHRUM SALICARIA	(1)	1373	2104	1616	2100
NUPHAR ADVENA	(1)	245	1175	627	780-663
NYMPHAEA ALBA	(9)				280
PHALARIS ARUNDINACEA	(1)	-	-	566	-
PHRAGMITES AUSTRALIS	(1)	654	3999	1850	1872
P. AUSTRALIS	(2)	600	3500		600-3700
P. AUSTRALIS	(4)	600	4300	1500	-
P. AUSTRALIS	(12)		2960		
P. AUSTRALIS	(13)		5726		
P. AUSTRALIS	(14)	680	1000		
POLYGONUM/LEERSIA	(1)	523	2142	1425	-
POTAMOGETON PECTINATUS	(9)	-	-	-	100
SAGITTARIA LATIFOLIA	(1)	214	649	432	1071
SCHOENOPLECTUS LACUSTRIS	(2)	800	3000		800-3100
S. LACUSTRIS	(4)	400	1600	800	-
SPARGANIUM ERECTUM	(2)	900	1600		1000-1900
TYPHA ANGUSTIFOLIA	(2)	1000	3000		1100-3400
T. ANGUSTIFOLIA	(4)	300	1800	750	-
T. ANGUSTIFOLIA	(12)		3710		
T. ANGUSTIFOLIA	(13)		3039		
T. LATIFOLIA	(2)	500	2000		600-2400
T. LATIFOLIA	(4)	400	2200	900	-
T. spec.	(1)	804	2338	1215	1420

(1) Whigham et al.(1978).
(2) Kvet and Husak (1978), monospecific reedswamp communities.
(3) BOLBOSCHOENUS MARITIMUS ssp. COMPACTUS, but B. MARITIMUS ssp.MARITIMUS only 200-1000 g/m2/y), Kvet and Husak (1978).
(4) Rodewald-Rodescu (1974).
(5) 70 g/m2 cf. Gerlaczinska (1973), after Blake and Dubois (1979)
(6) Smart (1980).
(7) Wolverton and McDonald (1979b), seven months growth period; dry weight being 5 % of wet weight.
(8) Estimate of the annual production based on several other studies; however under optimum conditions with regular harvesting 15000 g/m2/year was produced, cf.Westlake (1963).
(9) Bernatowicz (1969), after Blake and Dubois (1979).
(10) Figures for lagoon, from 15 May-26 June, cf.Rejmankova (1978).
(11) Culley and Epps (1973), with a regular harvesting even a production rate of 2740 Kg/ha/month can be reached during six months of the year year.

Table 1b. Mineral content of several freshwater macrophytes.

Macrophytic species		Nitrogen (% dry weight) min - max	Phosphorus (% dry weight) min - max
ACORUS CALAMUS	(15)	1.26-2.92	0.20-0.35
BOLBOSCHOENUS MARITIMUS	(15)	1.36-1.79	0.28-0.35
CERATOPHYLLUM DEMERSUM	(16)	1.00-2.42	0.09-0.41
C. DEMERSUM	(17)	1.39-3.94	----
C. DEMERSUM	(27)	-----	0.26
C. DEMERSUM	(6)	2.15-3.03	0.43-0.82
EICHHORNIA CRASSIPES	(18)	1.33-3.33	0.14-0.80
ELODEA CANADENSIS	(17)	1.32-3.5	----
E. CANADENSIS	(19)	2.51	0.59
GLYCERIA MAXIMA	(15)	1.29-1.82	0.18-0.31
LEMNA SPECIES	(20)	2.24-3.90	0.57-0.80
MYRIOPHYLLUM SPICATUM	(19)	1.67	0.03
M. SPICATUM	(21)	2.89	0.50
NUPHAR ADVENA	(21)	1.10-3.98	0.30-0.41
NYMPHAEA ALBA	(19)	2.82	0.42
PHALARIS ARUNDINACEA	(22)	0.89-1.51	0.15-0.25
PHRAGMITES AUSTRALIS	(15)	1.77-2.13	0.19-0.28
POTAMOGETON PECTINATUS	(19)	1.61	0.04
P. PECTINATUS	(21)	1.72	0.26
SCHOENOPLECTUS LACUSTRIS	(15)	1.03-1.77	0.23-0.34
SCIRPUS VALIDUS	(23)		0.14-0.39
SPARGANIUM ERECTUM	(15)	1.42-2.55	0.32-0.48
SPIRODELA OLIGORHYZA	(20)	5.78-6.54	1.39-1.67
S. POLYRHIZA/LEMNA GIBBA	(24)	2.97-4.16	0.62-1.14
S. POLYRHIZA/L. GIBBA	(25)	5.77	2.05
TYPHA ANGUSTIFOLIA	(15)	1.5	0.16
T. LATIFOLIA	(15)	1.43	0.22
T. LATIFOLIA	(26)	0.86-2.12	0.08-0.41

(12) Dykyjova and Veber (1978), maximum in natural stands.
(13) Dykyjova and Veber (1978), maximum in cultivation tanks
(14) Meulemans (1982), lowest standing crop in the centre of the stand and highest near the open water, measured at the end of August.
(15) Dykyjova (1978), Opatovicky fishpond (eutrophic).
(16) Gerloff (1973), after Blake and Dubois (1979).
(17) Best (1977).
(18) Data of 17 different habitats, cf. Boyd and Vickers (1971).
(19) Bernatowicz (1969), after Blake and Dubois (1979).
(20) On swine lagoon wastewater, Culley and Epps (1973).
(21) Riemer and Toth (1969), after Blake and Dubois (1979).
(22) Klopatek (1975), after Blake and Dubois (1979).
(23) Spangler, Sloey and Fetter (1976).
(24) Rejmankova (1978).
(25) In nutrient solution, (Rejmankova, 1978).
(26) Plants collected at 30 different sites cf.Boyd (1978)
(27) Boyd (1970b).

The amount of nutrients harvested is evidently determined by the concentrations of these nutrients in the harvestable plant parts (see Table 1b). Submerged plants have high nitrogen concentrations compared to other aquatic plants (Boyd, 1978). Emergents contain relatively more supporting tissues, which are always low in nitrogen. When high production rates and nutrient concentrations are taken as criteria, the following plants are most promising for wastewater purification purposes: EICHHORNIA CRASSIPES, PHRAGMITES AUSTRALIS, SCHOENOPLECTUS LACUSTRIS, TYPHA LATIFOLIA, and to slightly less extent, GLYCERIA MAXIMA, SPARGANIUM ERECTUM, NUPHAR ADVENA, LEMNA MINOR, LEMNA GIBBA.

2.3.3. Tolerance to sewage conditions

Vascular plants used for the purpose of wastewater purification purposes should have a high primary production, and high nutrient concentrations, but they should also be able to grow in heavily polluted water. The factors determining the occurrence of these plants are: climate, light, turbidity (total dissolved solids), rooting depth, water level, temperature, pH and alkalinity, nutrient concentrations of the water, oxygen consuming organic matter (BOD), water flow, nature of the substrate. The most important nutrients in this respect are chloride, nitrate, ammonia, nitrite and phosphate.

WATER TEMPERATURE varies in natural waters mainly with season within one and the same climatic zone; there is no correlation between water temperature and the occurrence of certain macrophytic species. Tropical or subtropical plants like EICHHORNIA CRASSIPES normally do not occur in our temperate climate; however it would be possible to cultivate waterhyacinths using heat waste in winter.

Emergent plants like SPARGANIUM ERECTUM, S. EMERSUM and PHRAGMITES AUSTRALIS are rather tolerant to SHADING, but their photosynthetic activity will increase if they receive more light (Haslam, 1978). Photosynthesis and growth of submerged macrophytes depend strongly on the turbidity of the ambient water. CERATOPHYLLUM DEMERSUM seems most tolerant in this respect, while ELODEA CANADENSIS grows normally in clear water (Haslam, 1978). Since in sewage turbidity is high due to the high level of total dissolved solids and algal blooms, most submerged macrophytes are unsuitable for wastewater purification purposes.

In natural freshwater systems the correlation between the occurrence of a particular species and the WATER CHEMISTRY is often high. However their preference for certain chemical conditions does not necessarily mean that they die in different suboptimum conditions. Therefore it is useless to select plant species on basis of one characteristic.

POTAMOGETON PECTINATUS is highly tolerant to wastewater and industrial pollution (Haslam, 1978), but does not thrive in water polluted by lead (Westlake, 1981). SPARGANIUM EMERSUM, S. ERECTUM, SCHOENOPLECTUS LACUSTRIS, TYPHA LATIFOLIA, T. ANGUSTIFOLIA and (more or less) PHRAGMITES AUSTRALIS are most tolerant to pollution, while LEMNA ssp., NUPHAR LUTEA and GLYCERIA MAXIMA are rather tolerant (Haslam, 1978).

ROOTS are most important in water purification. Free-floating plants absorb their nutrients from the ambient water, whereas deeply rooted plants, like PHRAGMITES AUSTRALIS take their minerals up from the interstitial water. In the latter case oxygen availability influences the nutrient uptake. Submerged macrophytes normally have a small root system; they absorb their nutrients partly from the interstitial and partly from the ambient water.

Most plants mentioned live in 30-120cm deep water with no apparent preference for WATER LEVEL.

WATER FLOW under natural conditions varies considerably. PHRAGMITES AUSTRALIS prefers a slow or negligible flow, whereas POTAMOGETON NATANS occurs mainly in fast-flowing waters (Haslam, 1978). In the case of water purification systems the flow is normally slow and therefore P. NATANS, P.PERFOLIATUS and PHALARIS ARUNDINACEA are not eligible for water purification purposes.

The preference for specific SUBSTRATES is not extreme. CERATOPHYLLUM DEMERSUM, GLYCERIA MAXIMA, PHRAGMITES AUSTRALIS, ELODEA CANADENSIS, LEMNA ssp, POTAMOGETON NATANS occur often in waters with a peaty substrate, while SCHOENOPLECTUS LACUSTRUS and SPARGANIUM ERECTUM prefer sand or gravel (Haslam, 1978). More important is the fact that GLYCERIA MAXIMA grows poorly on anaerobic mud, whereas SCHOENOPLECTRUS LACUSTRIS thrives on the same substrate (Westlake, 1981).

2.3.4. Harvesting

Harvesting the aboveground biomass is a direct way to withdraw nutrients from the system. To do this successfully, certain conditions should be met. Frequency and timing of the harvest are to be chosen in such a way, that the harvesting is optimized every year. Some species should be harvested once a year, while others give better results when harvested twice a year or every two years. Harvest success should be considered as nutrient yield, i.e. the product of harvested biomass and nutrient concentration, and is therefore different for each nutrient.

Free-floating plants are easiest to harvest. The best harvesting period is at optimum growth. Removal of half the biomass provides optimum production rates. After harvesting LEMNA ssp. can be used as food for animals (Culley and Epps, 1973). In case of EICHHORNIA CRASSIPES a whole range of harvesting equipment is available (Pieters, 1978; Wolverton and McDonald, 1979a). Waterhyacinth is used as animal fodder, fertilizer,and it is fermented into biogas (Wolverton and McDonald, 1979a).

Submerged macrophytes are more difficult to harvest, especially if high yields are needed during several, subsequent years.

There is a lot of experience in harvesting emergent plants like reeds, bulrushes and cattails. After harvesting the plant material can be used for several purposes: paper product manufacturing (Rudescu, 1976), animal fodder (Pomoell, 1976), roof building, manufacturing of baskets and furniture (Seidel, 1959) and probably as energy source (Bjork and Graneli, 1978).

PHRAGMITES AUSTRALIS should be harvested once a year, being shortly after cessation of growth, but before the leaves fall (Seidel, 1976a). Some authors (Seidel, 1976a) advise to harvest SCHOENOPLECTUS LACUSTRIS two times a year, but others prefer once a year or every two years.

Cutting of the reed in summer causes a decrease in standing crop, especially for terrestrial stands; however shoot density increases, while the shoots do not reach their normal height (Dykyjova and Husak, 1973).

The effect of timing of mowing on reed has investigated also (Mochnaka-Lawacz, 1974). Mowing three times a year (15 June, 15 July and 15 September) resulted in a total harvested biomass of 570 g dry weight/m2, compared to a total biomass of 1406 g harvestable dry weight/m2 without mowing.

The effect of the harvesting frequency in natural marsh vegetation types in Wisconsin has been investigated with respect to P-concentrations and yield (Spangler, Sloey and Fetter, 1976). Highest P-concentrations were found by biweekly harvesting and lowest at one harvest a year in September, the latter serving as control (see Table 2a). Harvested biomass decreased usually with decreased frequency (Table 2b) and therefore also phosphorus yield (amount of phosphorus per m2 vegetation area) is calculated (Table 2c).

Table 2a. Phosphorus concentrations in several emergent macrophytic species in natural marshes in Wisconsin at different harvesting intervals (Spangler, Sloey and Fetter, 1976).

Macrophytic species	Phosphorus in harvested shoots (% dry weight)		
	biweekly	monthly	control
SCIRPUS FLUVIATILIS	0.62	0.43	0.15
TYPHA ANGUSTIFOLIA (site 1)	0.48	0.36	0.14
T. ANGUSTIFOLIA (site 2)	0.40	0.33	0.16
SCIRPUS VALIDUS	0.37	0.39	0.14
SPARGANIUM EURYCARPUM	0.43	0.39	not present

Table 2b. The effect of different harvesting intervals on the harvested dry matter of several emergent macrophytic species (Spangler, Sloey and Fetter, 1976).

Macrophytic species	Biomass harvested (g dry weight/m2)		
	biweekly	monthly	control
Site 1			
TYPHA ANGUSTIFOLIA	197.3	150.4	260.7
SCIRPUS VALIDUS	60.2	30.6	64.7
SPARGANIUM EURYCARPUM	35.7	37.6	not present
T O T A L	293.2	218.6	325.3
Site 2			
TYPHA ANGUSTIFOLIA	21.5	27.4	38.5
SCIRPUS FLUVIATILIS	169.3	225.7	406.7
T O T A L	190.8	253.1	445.1

Table 2c. The effect of different harvesting intervals on the total quantity of phosphorus removed (Spangler, Sloey and Fetter, 1976).

Macrophytic species	Phosphorus yield (g/m2)		
	biweekly	monthly	control
Site 1			
TYPHA ANGUSTIFOLIA	0.79	0.50	0.40
SCIRPUS VALIDUS	0.52	0.10	0.00
SPARGANIUM EURYCARPUM	0.22	0.12	0.09
T O T A L	1.53	0.72	0.49
Site 2			
TYPHA ANGUSTIFOLIA	0.13	0.13	0.11
SCIRPUS FLUVIATILIS	0.91	0.97	0.59
T O T A L	1.04	1.10	0.70

Frequency and time of harvesting are not only important in regard to nitrogen and phosphorus yield, but they affect also the biomass of reed (PHRAGMITES AUSTRALIS) and reed mace (TYPHA ANGUSTIFOLIA) stands during subsequent years. Summer cutting may result in lower yields the next season at times with small underground reserves (Husak, 1978).

Table 3. The effect of summer cutting at different levels above the bottom on biomass of PHRAGMITES AUSTRALIS (harvested on 29 July 1969) and TYPHA ANGUSTIFOLIA (harvested on 23 June 1969) in g/m2 (Husak, 1978).

Treatment	Biomass on 28 Aug. 1969	Harvested on 28 Aug. 1969	Biomass on 15 Aug. 1970	Biomass on 9 Aug. 1971
P. AUSTRALIS				
control	1,388	-	1,763	2,227
cut at 1.80 m	1,294	268	2,660	2,100
cut at 1.20 m	1,515	572	527	955
T. ANGUSTIOLIA				
control	2,039	-	2,371	2,004
cut at 1.80 m	1,949	772	1,473	2,106
cut at 0.80 m	3,009	1,195	1,466	2,805

2.3.5. Most suitable species

Submerged macrophytes like CERATOPHYLLUM DEMERSUM, POTAMOGETON ssp., MYRIOPHYLLUM SPICATUM and ELODEA CANADENSIS are not suitable for purification of raw sewage, since their growth is negatively correlated with increasing water turbidity. However, they grow well in secundary or tertiary effluent, in which most organic matter is decomposed. ELODEA CANADENSIS is already used in this respect (Radoux and Kemp, 1981a,b,c), but CERATOPHYLLUM DEMERSUM may be a better alternative due to its tolerance to highly eutrophic waters. The most suitable emergent plants are PHRAGMITES AUSTRALIS, SCHOENOPLECTUS LACUSTRIS, TYPHA ANGUSTIFOLIA and T. LATIFOLIA. These species are used for purification of wastewater since they exhibit high production rates and their photosynthesis is hardly influenced by water turbidity (De Jong, 1976; De Jong et al., 1977; Radoux, 1980b, 1982; Radoux and Kemp, 1981a,b,c, 1982, Kickut, 1980a; Osman, 1981; Spangler,Sloey and Fetter, 1976, and many others).

Like emergent plants, free-floating ones are not affected by water turbidity; rooted plants with free-floating leaves, however, may suffer from light limitation in early growth before they reach the water surface. Data on production and tolerance to highly eutrophic sewage suggest that LEMNA ssp. and EICHHORNIA CRASSIPES are the best choice within this plant group; the latter, however, does not hibernate in temperate regions.

2.3.6. Temperature and light

Plant growth is strongly influenced by temperature. Most biological processes resulting in growth have different optimum temperatures. In a temperate climate growth stops in winter and this restricts the use of macrophytes for water purification largely to the summer season. Photosynthesis depends mainly on light, but is relatively insensitive to temperature. Respiration, however, is greatly enhanced by temperature increases. Both, light and temperature govern harvestable biomass. However, it is almost impossible to modify these environmental factors to optimize water purification using macrophytes, except by the earlier mentioned use of heat waste (for instance of power plants).

2.4. Nutrients, carbon dioxide, pH and oxygen in sediments and water

2.4.1. General

Several factors influence the uptake of nutrients. In this paper only those aspects will be discussed as far as they concern wastewater purification. Carbon dioxide, pH,and oxygen, which are important for nutrient absorption and growth of the plants, as well as for decomposition and mineralization processes, will be treated too.

2.4.2. Carbon

In aerobic conditions organic compounds, like glucose, are incorporated by bacteria and decomposed into (inorganic) carbon dioxide (Hendricks and Pote, 1974):

$$6\,C_6H_{12}O_6 + 16\,O_2 + 4\,NH_3 \text{ -----> } 4\,C_5H_7O_2N + 16\,CO_2 + 28\,H_2O \quad (2.1)$$

or generally written:

$$(-CH_2O)_n + n\,O_2 \text{ -------> } n\,CO_2 + n\,H_2O \quad (2.2)$$

This carbon dioxide may be used for photosynthesis by primary producers in the water column, the availability depending on pH as follows:

$$(HCO_3^-)_2 + CA^{++} \rightleftharpoons CaCO_3 + CO_2 + H_2O \quad (2.3)$$

In alkaline waters carbon is mainly available as bicarbonate, while in acid waters it is in the form of carbon dioxide, the latter being favoured as carbon source by most plants. However macrophytic species, like MYRIOPHYLLUM SPICATUM, ELODEA CANADENSIS, POTAMOGETON CRISPUS, P. PECTINATUS, and P.LUCENS, use bicarbonate too (Westlake, 1981; Best, 1983). In wastewater the pH ranges normally from 7 to 8.

Organic matter may also be decomposed by denitrification. In this process denitrifying bacteria use nitrate as electronacceptor instead of oxygen (Osman, 1981):

$$5(-CH_2O)_n + 6\,nNO_3^- + 6\,nH^+ \text{ -----> } 5\,nCO_2 + 8\,nH_2O + 3\,nN_2 \quad (2.4)$$

In anaerobic conditions most organic matter is converted into organic acids (Cappenberg, 1975):

$$\text{org.matter} \xrightarrow{\text{bact.1}} CH_3.CH_2.COOH + CH_3.COOH + H.COOH +$$

$$+ CH_3.CHOH.COOH + CO_2 + H_2 + NH_3 + \text{other organic acids} \quad (2.5)$$

In a second stage of this process other, strictly anaerobic, micro-organisms convert these organic acids into methane (Capppenberg, 1975):

$$CH_3.COOH \xrightarrow{\text{bact.2}} CO_2 + CH_4 \quad (2.6)$$

If some oxygen is available decarboxylation of lactate may occur:

$$CH_3.CHOH.COOH + O_2 \text{------>} CH_3.COOH + CO_2 + H_2O \qquad (2.7)$$

Under anoxic conditions several electron acceptors may take over the role of oxygen, like NO3-ions (see (2.4), NO2-ions, Mn-IV-ions, Fe-III-ions, org.matter, SO4-ions, CO2 and others (Stumm and Morgan, 1981). For instance (Cappenberg, 1975):

$$SO_4^{2-} + CH_3.CHOH.COOH \xrightarrow{bact} H_2S + CH_3.COOH + CO_2 \qquad (2.8a)$$

$$SO_4^{2-} + CH_3.COOH \xrightarrow{bact} H_2S + CO_2 \qquad (2.8b)$$

2.4.3. Nitrogen

Most nitrogen in sewage is either in the form of organic nitrogen or ammonia. Plants absorb ammonia as well as nitrate ions. Several micro-organisms convert ammonia-nitrogen in a two stage process:

$$2\ NH_3 + 3\ O_2 \text{------->} 2\ NO_2^- + 2\ H_2O + 2\ H^+ \quad \text{(NITROSOMONAS)} \qquad (2.8)$$

$$2\ NO_2^- + O_2 \text{------->} 2\ NO_3^- \quad \text{(NITROBACTER)} \qquad (2.9)$$

These processes, together called NITRIFICATION, consume a lot of oxygen. The end product, nitrate, is used by plants for their nutrition or converted into gaseous nitrogen (N2) in certain conditions. The latter, purely chemical, process, DENITRIFICATION, normally occurs at low pH, while sewage has a pH of 7 to 8. Nevertheless denitrification by micro-organisms occurs in sewage treatment fields (Osman, 1981):

$$5(-CH_2O)_n + 6\ nNO_3^- + 6\ nH^+ \text{----->} 5\ nCO_2 + 8\ nH_2O + 3\ nN_2$$

(PSEUDOMONAS) (=(2.4))

These micro-organisms use nitrate (or nitrite) as electron acceptor, in anaerobic conditions oxidizing organic matter. At pH 5.5 and a temperature of 10 degrees Celcius the rate of this process is slow and only NO and N2O are produced. At pH > 6 N2 is formed (Osman, 1981).

Ureum is an important part of organic nitrogen in sewage. It can be decomposed with the help of the enzyme urease, normally present in plants, fungi and bacteria:

$$O=C(NH_2)_2 + 2\ H_2O \text{---->} H_2CO_3 + 2\ NH_3 \qquad (2.10)$$

The so-formed ammonia is lost partly to the air by volatilization, and partly converted into nitrate by nitrification ((2.7) and (2.8)).

2.4.4. Phosphorus

In domestic sewage phosphorus is present in organic or inorganic form, with detergents forming its main source (up to 70%). In this case most of the phosphorus is:

$$P_2O_7^{4-} \text{ (pyrophosphate) or } P_3O_{10}^{5-} \text{ (tripolyphosphate)} \quad (2.11)$$

which both may hydrolyze easily to (ortho)phosphate.
In water always an equilibrium exists btween:

$$H_2PO_4^{-} \rightleftharpoons HPO_4^{2-} + H^{+} \rightleftharpoons PO_4^{3-} + 2\,H^{+} \quad (2.12)$$

At low pH dihydrogenphosphate is dominating; at pH = 6.8 the amount of dihydrogenphosphate is equal to that of monohydrogenphosphate and only at high pH PO4--- is available. Plants can take up all forms, but they prefer dihydrogenphosphate.

With calcium-ions phosphate can precipitate as hydroxyl-apatite (Stumm and Morgan, 1981):

$$5\,Ca^{2+} + 3\,PO_4^{3-} + OH^{-} \rightleftharpoons Ca_5(PO_4)_3OH \qquad K_{eq} = 10^{+56} \quad (2.13)$$

Even in a saturated solution of $CaCO_3$ hydroxyl-apatite will be formed:

$$5\,CaCO_3 + H^{+} + 3\,HPO_4^{2-} + H_2O \rightleftharpoons Ca_5(PO_4)_3OH \qquad K_{eq} = 10^{+16} \quad (2.14)$$

Apatite should precipitate easier then CaCO3 in a solution of CaCO3 and phosphate in alkaline conditions. At high pH, like in the case of rapid algal growth, both hydroxyl-apatite and calciumcarbonate precipitate. The latter can react (see (2.14)) with monohydrogenphosphate forming hydroxyl-apatite. This occurs only under alkaline conditions, because otherwise no dihydrogenphosphate would be available (optimum pH = 10.5). Apatite stays often colloidal and at a decrease in pH it will hydrolyze into calcium-, phosphate- and hydroxyl-ions. The latter process apparently occurs mainly, since the outer layer of the hydroxyl-apatite is covered with the more soluble Ca2HPO4(OH)2. Thus, a lot of apatite is to be expected in sediments; however even in calcareous soils only 14 to 33% of the phosphorus is present in this form. The main part (54 to 75%) is bound to alumina or iron, forming iron- (or alumina-)hydroxide-phosphate or iron-oxide-phosphate complexes, of which the actual composition depends on pH (Golterman, 1973).

Inorganic phosphate may also precipitate as FePO4.2H2O (strengite) under certain conditions (Kickut, 1980a; Stumm and Morgan, 1981).

Besides precipitation in more or less stable compounds, ortho-phosphate can also be adsorbed to soil particles. Generally anions can loosely be adsorbed to negatively charged particles. Phosphate is adsorbed more readily then sulfate, nitrate or chloride.

In acid soils phosphate will be adsorbed to some extent to alumina- or iron-hydroxides of a sorbens (this should not be confused with precipitation). The latter bond is stronger then that between phosphate and soil particles, and it depends less on pH and the anion concentration, since chloride-, nitrate- and sulphate-ions do not compete, however H2O, hydroxyl-, fluoride-, bicarbonate-, arsenate-, silicate- and molybdate-ions do (Van der Heide, 1977).

Certain chemicals as fluorides, bicarbonates, oxalate, citrate, humic acids or lignin can prevent phosphate precipitation (with iron- or alumina-ions). They mobilize phosphate from the metal-phosphate complex. Organic acids do this with the alumina-, iron- and calcium-ions, thus these complexes go into solution.

In an aquatic environment (with interactions between the soil and the overlying water) most of the phosphate is in the soil (especially under natural conditions). In certain conditions it can be mobilized and return to the overlying water. In contrast to nitrogen, phosphate can not be exchanged from the soil/water system to the air.

2.4.5. Soil

Besides the mentioned (bio)chemical processes in the soil, other properties of the soil itself are also important. The PERMEABILITY of the soil for water (Kf) is of great importance. This characteristic depends on several other soil properties like particle size, content of relativily large organic particles, the presence of root channels and on activity of worms. For example the Kf of loamy sand is 4 * 10 exp(-6) m/s and of silty clay 2 * 10 exp(-8) m/s. Most soil horizons have a different permeability; thus vertical percolation is controlled by the most impermeable horizon having the lowest Kf. A "root horizon' can have a Kf of 10 exp(-3) after three years growth of emergent plants like reed, independent of the original soil composition (Kickut, 1980a). The final permeability and period of time to reach this Kf depend on plant species (Kickut, 1980a).

Thus a low or high permeability is required for the purpose of water purification, depending on the use of submersed, floating(-leaved) or emergent plants, and the size of their rootsystem. Submerged and floating(-leaved) macrophytes absorb their nutrients partly or completely from the ambient water, while emergents do this of the interstitial water. Therefore the latter ones require extensive infiltration and percolation in cases when sewage has to be purified. In order to keep this (interstitial) sewage separated from the groundwater, a less permeable horizon, lying beneath the "root horizon", is needed with Kf < 10 exp(-6) m/s (Kickut, 1980a). At a slightly sloping "impermeable" horizon the water flows initially vertically and subsequently in horizontal direction along the surface of the "impermeable" layer, enabling the so-formed effluent to be collected at the lowest point.

2.4.6. Oxygen in sediments and water

The availability of oxygen in the soil is important for many (bio)chemical processes. Nitrification occurs aerobically, while denitrification requires anaerobic conditions. Both, aerobic and anaerobic conditions occur in the water, depending on many factors. For instance, algal blooming may cause anoxic conditions, and in deep, meromictic waters stratification occurs temporarily, leaving little or no oxygen in the hypolimnion. The oxygen concentration in the water is affected by temperature, reaeration at the water surface, respiration, photosynthesis, and, especially in the case of water purification, input of organic matter.

The oxygen concentration in the interstitial water is mostly very low or zero. Soils without plant growth and a high water infiltration rate are often anoxic. Even soils covered by terrestrial vegetation, with no special adaptations to waterlogged conditions, are mostly devoid of oxygen. In an emergent vegetation, however, oxygen is easily transported to the rootsystem, through the aerenchymatic tissues (Esau, 1977). Part of the oxygen is consumed by plant respiration, part by oxidation of iron(II)-ions (and manganese(II)-ions) thus limiting the bilogical availability of iron. This phenomenon is known in rice, ERIOPHORUM ANGUSTIFOLIUM, reed and many other plants, which live usually in reduced soils (Ohle, 1934; Armstrong, 1975; Green, 1977). On the outside of the root-endodermis of emergent plants is therefore often some rust detectable (Armstrong, 1967a,b). Under reducing conditions iron(II) would be absorbed rapidly, causing a toxic Fe(II)-level in the plant (Martin, 1968).

Not all available oxygen is required for the oxydation of iron. For reed an oxygen transport of 5 to 47 g O2/m2/d was estimated, biomass of the underground plant parts being 500 to 2500 g dry weight/m2 (Kickut, 1980a). Plants will normally respire 5 to 18 g O2/m2/d of this surplus by their roots, whereas the rest is used in other (bio)chemical oxidations.

In waterlogged rice, cv. NORIN,37, for instance, the oxygen flux (radial oxygen loss, cf. Armstrong) was high near the root apex amounting to 183 ng/cm2 root-surface/min (Armstrong, 1964; 1967a). Thus, soils occupied by rice or emergent macrophytes is composed by aerobic and anaerobic compartments with transitions in between (Kickut, 1980a). As a result a mosaic pattern of high and low redoxpotentials develops, in which all sorts of different (bio)-chemical processes occur. Organic acids will be formed like acetic acid, lactic acid, succinyl acid, citric acid and others. These acids will mobilize iron by reducing FeIII- into FeII-ions. The latter ions are easily transported to aerobic micro-areas, where FeII-ions are oxidized to FeIII, forming different complexes with phosphate, particularly iron-oxide-phosphate-complexes.

3. WATER PURIFICATION

3.1. Requirements to water purification

In evaluating water purification the differences between, and the actual composition of influent and effluent are important to consider, especially, if the effluent is drained into the surface water. Several governmental institutes in The Netherlands and in Europe have formulated short- and long-term requirements. In general, the composition of the raw sewage varies considerably. A more or less average composition of domestic sewage is given in Table 4. Heavy metals and other toxic substances are not included in this table.

Table 4. Average composition of domestic sewage (in The Netherlands).

Parameter	Concentration (mg/l)
Total solids	600- 900
Dissolved substances	700-1000
Suspended solids	400- 700
Max.sedimentation$_{20}$	200
BOD_5 (1)	300- 500
COD (2)	600-1100
Nitrogen:	
N-total (as N)	70- 115
N-organic	30- 50
NH_3-inorg.	40- 65
NO_3/NO_2	0- 2
Phosphorus:	
P-tot.	15- 30
P-org.	5- 10
P-inorg.	10- 20
Chlorides	200

(1) BOD_5^{20} is the amount of oxygen (mg/l) necessary for bacterial oxidation of all organic waste in 1 l sewage during 5 days at 20 degrees Celcius.
(2) Chemical Oxygen Demand: the amount of oxygen (mg/l) necessary for the total chemical oxydation of 1 l sewage.

The influent of a sewage treatment plant (RWZI) is raw sewage, which is purified in one way or the other. The effluent is drained into the surface waters. Therefore it is feasible to use the same requirements for the (final) effluent as for surface waters in respect to water quality (see Table 5).

Table 5. Examples of target (long-term) and preliminary (short-term) requirements to surface waters (Anon., 1975) and the requirements for basic quality (Anon., 1981).

Parameters	Preliminary boundary values	Target values	Basic quality
Temperature	25 °C	-	< 25 °C
Oxygen	> 50 %	-	> 5 mg/l
pH	6.5 - 8.5	6.5 - 8.5	6.5 - 9.0
Suspended solids	80 mg/l	25 mg/l	-
Turbidity	0.5 m	1.0 m	> 0.5 m
Kjeldahl-N (1)	3 mg/l	1 mg/l	< 2 mg/l
NH3-N	2.0 mg/l	0.5 mg/l	< 1 mg/l
NO2-N	1.0 mg/l	-	< 10 mg/l (2)
NO3-N	4 mg/l	2 mg/l	
PO4-P (total)	0.3 mg/l	0.05 mg/l	0.2 mg/l
Conductivity	1.00 ms/cm	0.75 ms/cm	-
BOD_5^{20}	< 5 mg/l	< 3 mg/l	< 5 mg/l

(1) Kjeldahl-N is the total amount NH3-N and organic nitrogen, analyzed according to Kjeldahls method.
(2) This requirement is not compulsory if total Kjeldahl-N = 2 mg/l or less.

3.2. Conventional sewage purification

3.2.1. Wastewater treatment methods

A sewage treatment system consists usually of several processes separated with respect to site and/or time. Older treatment systems consist of two purification steps, whereas more modern ones of three (including phosphate removal).

The first step, the PRIMARY SEWAGE TREATMENT, removes all large particles by sedimentation. This is accompanied by skimming of the oils and fats by flotation. The primary sludge, produced in this process, may be used for agricultural purpose, after drying in the air.

During the SECONDARY TREATMENT all biodegradable substances are decomposed by biological oxidation. Nitrate, sulfate, phosphate, carbonate and water are the main products of this process. Several methods for this process are used like trickling filters, activated sludge, and oxidation ditches.

In a TRICKLING FILTER (FIXED BED) lava slags are used as sites for attachment of micro-organisms. Conditions are aerobic, although no special precautions are taken for oxygen supply. Bacteria use the organic matter in the partly treated sewage as carbon source for their rapid growth. The sludge, mainly composed by flocks of bacteria, floats in the water and it settles down in a separate tank.

In an ACTIVATED SLUDGE tank, on the other hand, the bacteria are floating free in the sewage water. Extensive oxygen supply causes rapid bacterial growth and high reduction rates of organic matter. After separating the sludge from the water in a sedimentation tank, part of it is mixed with the influent to keep enough micro-organisms in the activated sludge tank. The remaining sludge is mineralized in an anaerobical digester.

In an OXIDATION DITCH the large particles are usually not allowed to settle down before biodegradation is completed. The rapid water flow through this arena-like ditch prevents sedimentation of the sludge. In this case loading is mostly followed by a period of biodegradation. The oxidation ditch can not be loaded as heavily as the other two systems, but purification from organic compounds is the highest. All three systems provide a rather well mineralized secondary effluent, but they fail to remove the main part of inorganic nutrients like nitrate and phosphate. In table 6 the results of different treatments are given. During the first two steps reduction of BOD is high; however, for removal of the inorganic minerals a third step is needed.

Table 6. Estimates of sewage purification in three different steps. Purification is expressed as percentage of the influent concentration.

Purification	BOD_5^{20} (% influent)	N_{tot} (% influent)	P_{tot} (% influent)
After the first step	25-40	10	20
After the second step	max. 95	40	30
After the third step	-	- ??	90-95

In the third step nitrogen is removed largely by ammonia-stripping in case of a high ammonia-concentration. Often nitrification and subsequent denitrification are used. However, phosphate removal is the main process in this final purification step. This is accomplished by chemical precipitation. Precipitation can be done simultaneously with the second step processes or, with better results, separately. The following chemicals are used for the precipitation of phosphate: iron-III-chloride, iron-III-sulphate, alumina-III-sulphate and calciumhydroxide (lime). Application of iron- or alumina-ions causes the formation of iron- or alumina-phosphates. These metal-phosphates are colloidal and two times the equivalent amount is needed to let it precipitate rapidly (Dirkzwager and Karper, 1971). Precipitation will occur simultaneous with the flocculation of the metal-hydroxides. The final result depends on pH and temperature.

At a pH higher than 10.5 lime is used to remove phosphates, causing precipitation of phosphates as hydroxyl-apatite ($Ca_{10}(PO_4)_6(OH)_2$). Concomitantly precitation of calciumcarbonate occurs, as both calciumcarbonate and hydroxyl-apatite consist of fine crystals, a small amount iron-III-ions is needed for quantitative separation, the quantity depending on the hardness of the water to be treated, but it is many times less than using iron-III-ions alone. Third step treatment with lime causes a high pH in the effluent; since the water is soft, neutralizing requires only a small amount of acid (Dirkzwager and Karper, 1971).

3.2.2 Sludge

Handling of sludge is one of the largest problems of conventional wastewater treatment. Primary sludge is the particulate material which settles down during the first step of the wastewater treatment; secondary sludge is formed in the second purification step. Within the latter two categories can be discerned, namely, humic-sludge, from oxidation beds, and surplus-sludge, from an activated sludge tank. Chemical sludge is formed in the third purification step, when phosphate precipitation occurs after biodegradation of the organic matter. Mixed sludge is the result of phosphate precipitation simultaneously with the second purification step. Sludge consists for more than 90% of water. Its treatment starts with anaerobic digestion, followed by dehydration, untill the dry weight is at least 30% of the original sludge mass. The total amount of sludge varies, depending on the purification methods used. For instance, using lime only for phosphate precipitation enormous amounts of chemical sludge are produced, which are far less when lime is applied together with iron-III-salts. The composition of the sludge varies widely. Chemical sludge contains considerable amounts of heavy metals, especially of non-domestic origin. Sludge problems are very complex and its treatment brings enormous costs about (up to 50% of the total costs of the whole purification process).

3.2.3 Recent methods

Several more recent methods will briefly be discussed in this study.

The first one involves the use of pure oxygen instead of air in the aerobic purification treatment. Advantages are better mineralization, less sludge of better quality and lower annual costs. However, this method is rather complicated and causes less nitrification and more corrosion than normal.

The deep-shaft method uses gravitation for optimum aeration of wastewater. The sewage is saturated with air by falling down a long pipe, providing optimum degradation of organic matter.

Anaerobic digestion of sludge is preferable above anaerobic digestion of raw sewage. Recently these digesters became frequently applied in The Netherlands.

Even more recently a method was suggested to remove phosphates from the secondary effluent without any sludge production using a whirl-bed. This whirlbed is caused by a waterstream flowing upwards into a container, which is partly filled with filter-sand. Water pH is enhanced by the addition of natriumhydroxide to the stream and thus phosphate crystals are bound to the sand. The phosphorus can be regained after drying of the latter mixture.

3.3. Purification using aquatic macrophytes

3.3.1. Introduction

Aquatic macrophytes are widely used in wastewater treatment, mostly in combination with conventional methods (Blake and Dubois, 1979; Boyd, 1970a; Copelli et al., 1981; Culley and Epps, 1973; Cornwell et al., 1977; Corradi et al., 1981; Demoulin, Dubois, Goeyry, 1981; Finlayson, 1983; Gersberg, Elkins, Goldman, 1983; Ghetti et al., 1981, 1982; Greiner and De Jong, 1982; Goldman and Ryther, 1976; Harvey and Fox, 1973; De Jong, 1976; De Jong, Kok and Koridon, 1977; Kickut, 1975, 1976, 1980a, 1980b; Kok, 1974; Kok and de Jong, 1975; Kurpas, 1980; Lakshman, 1979; McNabb, 1976; Mitchell and Williams, 1982; Nuemann, 1970; Osman, 1981; Ower, Cresswell, Bate, 1981; Palazzo, 1981; Pietsch, 1980; Radoux, 1980a, 1980b, 1982; Radoux and Kemp, 1981a, 1981b, 1981c; Reddy, 1983); Schmitz et al., 1982; Seidel, 1976a, 1976b; Serfling and Mendola, 1979; Spangler, Sloey, Fetter, 1976; Sutton and Ornes, 1975, 1977; Tilton and Kadlec, 1979; Wolverton, Barlow and McDonald, 1976; Wolverton and McDonald, 1975, 1979a,b).

The use of aquatic macrophytes for wastewater treatment has several advantages. Macrophytes affect the hydrology, form attachment sites for micro-organisms, transport oxygen into the soil, when rooted, and remove inorganic nutrients from bottom and ambient water. When compared to conventional purification methods, some processes are similar, while others are different. In both cases the organic matter should be decomposed by bacteria. This occurs, under controlled conditions depending on treatment type, whereas in the case of macrophytes hardly any control occurs except loading.

3.3.2. Theoretical estimate of purification possibilities based on the harvesting of aquatic macrophytes

When merely the harvesting of aquatic macrophytes is used for water purification purposes, only relativily small amounts of organic matter, nitrogen and phosphorus are removed. In Table 7 the best results as to nitrogen are given, while Table 8 shows the best possibilities for phosphorus removal. Especially the vegetation area required per i.e. (1) is high. Phosphorus removal by plant harvesting is relatively quite poor, compared to the area needed for conventional wastewater treatment.

(1) i.e. is an inhabitant equivalent, indicating a certain amount of BOD and Kjeldahl-N (NH_3-N and org.N), estimated to be produced during 24 hours by an inhabitant of the country concerned. In The Netherlands one 1 i.e. is mostly 54 g BOD, 10 g N, and 3.5 g P-tot. More exact is the formula Q/180(2.5 BOD + 4.57), with Q the number m^3 wastewater/24 hours.

Table 7. Nitrogen removal by harvesting freshwater macrophytes.

Macrophytic species	Harvest (g dw/m2/y)		N (% dw)		N yield (g/m2/y)	N (i.e./m2)	Area needed (m2/i.e.)
P.AUSTRALIS	1000	(1)	2	(2)	20	0.0055	183
	3000	(3)	2		60	0.0165	61
	5700	(4)	2		114	0.0312	32
S.LACUSTRIS	500	(1)	1	(2)	5	0.0014	730
	500		1.8		8.8	0.0024	417
	3000	(5)	1		30	0.0082	122
	3000		1.8		54	0.0148	68
T.ANGUSTI-FOLIA	1000		1.5	(2)	15	0.0041	243
	3000	(6)	1.5		45	0.0123	81
T.LATIFOLIA	750		1.4	(2)	10.5	0.0029	348
LEMNA MINOR + L.GIBBA	1644	(7)	3	(8)	49.3	0.0132	76
	1644		4.5	(9)	74.0	0.0203	49
	1644		5.6	(10)	92.1	0.0252	40
E.CRASSIPES	15400	(11)	1.3	(12)	200.2	0.0548	18
	15400		3.3	(12)	508.2	0.1392	7

(1) De Jong (1976); harvest in July.
(2) Dykyjova (1978); minimum and maximum values.
(3) Dykyjova and Veber (1978); maximum in natural stands.
(4) Dykyjova and Veber (1978); maximum in cultivation tanks
(5) Kvet and Husak (1978); maximum aboveground peak standing crop
(6) Dykyjova and Veber (1978); the maximum in cultivation tanks, being similar to that in natural stands.
(7) Culley and Epps (1973); from laboratory experiments a harvest of 2740 Kg dw/ha/month was estimated for a six months season.
(8) Rejmankova (1978); varying during the growth season.
(9) Harvey and Fox (1973).
(10) Rejmankova (1978); in nutrient solution.
(11) Wolverton and McDonald (1979b); production from April through October by an averge standing crop of 220 t/ha.
(12) Boyd and Vickers (1971); minimum and maximum values.

Table 8. Phosphorus removal by harvesting freshwater macrophytes (13).

Macrophytic species	Harvest (g dw/m2/y)	P (% dw)	P yield (g/m2/y)	P (i.e./m2)	Area needed (m2/i.e.)
P.AUSTRALIS	1000 (1)	0.2 (2)	2	0.0016	639
	3000 (3)	0.2	6	0.0047	213
	5700 (4)	0.2	11.4	0.0089	112
S.LACUSTRIS	500 (1)	0.23 (2)	1.2	0.0009	1111
	500	0.34 (2)	1.7	0.0013	751
	1000 (5)	0.23	2.3	0.0018	555
	1000	0.34	3.4	0.0027	358
T.ANGUSTI-FOLIA	1000	0.16 (2)	1.6	0.0013	798
	3000 (6)	0.16	4.8	0.0038	266
T.LATIFOLIA	750	0.22 (2)	1.7	0.0013	774
LEMNA MINOR	1644 (7)	0.8 (7)	13.2	0.0103	97
+ L.GIBBA	1644	2.05 (10)	33.7	0.0264	38
E.CRASSIPES	15400 (11)	0.57 (12)	87.8	0.0687	15
		0.80 (12)	123.2	0.0964	10

(13) All subscripts as in Table 7.

4. CASE-STUDIES

4.1. Introduction

Many reports on the use of freshwater macrophytes for wastewater purification exist. They vary from experimental studies, on laboratory scale as well as on pilot plant scale, to using whole wetlands for this purpose. In this chapter the most relevant studies will be reviewed. Finally, potential application will be discussed.

4.2. Experiments

4.2.1. Free-floating macrophytes

4.2.1.1.(Sub)tropical species

Since 1948 application of the free-floating EICHHORNIA CRASSIPES for wastewater purification has been investigated (Pieterse, 1977,1978). This (sub)tropical waterweed is a fast grower, has a rapid nutrient uptake and is easy to harvest (Boyd, 1970a; Wolverton and McDonald, 1979b and others). Wolverton and coworkers have investigated this topic extensively (Wolverton and McDonald, 1975, 1979a,b; Wolverton, Barlow and McDonald, 1976).

The reduction in BOD, Kjeldahl-N and tot-P was studied in 4.5 l containers filled with either raw sewage or secondary effluent, the composition of raw sewage being: BOD = 72 mg/l, Kj-N = 16.1 mg/l, tot-P = 5.60 mg/l , and of the secondary effluent: BOD = 21.6 mg/l, Kj-N = 1.76 mg/l, tot-P = 4.50 mg/l. Purification in the containers with plants was far better than in the control containers (Table 9).

Table 9. Reduction in BOD, N and P under laboratory conditions by floating-leaved macrophytes (Wolverton and McDonald, 1975).

	Raw sewage		Secondary effluent			
	+ plants	control	+ plants	control	+ plants	control
	7 days		7 days		14 days	
	EICHHORNIA CRASSIPES					
BOD_5^{20}	97 %	61 %	77 %	6 %	-	-
Kjeldahhl-N	92 %	18 %	75 %	13 %	89 %	15 %
tot-P	60 %	13 %	87 %	11 %	99 %	25 %
	ALTERNANTHERA PHILOXEROIDES					
BOD_5^{20}	92 %	68 %	94 %	48 %	98 %	60 %
Kjeldahl-N	97 %	18 %	61 %	10 %	76 %	14 %
tot-P	50 %	13 %	44 %	15 %	62 %	41 %

The growth rates of EICHHORNIA CRASSIPES plants, cultivated on secondary effluent of a trickling filter sewage plant and in natural stands, were compared (Cornwell et al., 1977). In this case the growth rate was doubled compared with that in natural stands (in Florida an area-doubling time of 6.2 days is usual in the period 15 April-13 May). A positive correlation was found between the reduction of N and P, and both pond depth and residence time.

Nitrogen removal:

$$NR = 0.327 \times SA + 6.95 \quad \text{(correlation coefficient 0.92)} \qquad (4.1)$$

in which NR = % tot-N removed
SA = pond surface area per flow unit, in $ft^2 \times 10^3 \times d / am.gal \times 10^6$

For phosphorus removal:

$$PR = 0.238 \times SA - 8.77 \quad \text{(correlation coefficient 0.96)} \qquad (4.2)$$

in which PR = % tot-P removed
SA = pond surface area per flow unit, in $ft^2 \times 10^3 \times d / am.gal \times 10^6$

Equations (4.1) and (4.2) converted into metric units gives:

$$NR = 13.324 \times SA + 6.95 \qquad (4.3)$$

$$PR = 9.697 \times SA - 8.77 \qquad (4.4)$$

in which SA is in $m^2 \times d / m^3$

$1000\ ft^2 \times d / gal \times 10^6 = 0.024543\ m^2 \times d / m^3$

(1 am.gal = 3.78533 l).

A constant ratio of 26:1 (on M-basis) was found between N and P removed, while in EICHHORNIA CRASSIPES itself a ratio of 20:1 and in the influent 8.7:1 occurred. In this case N was assumed to be the growth-limiting factor. The highest P-removal was 44%, which was found in the shallowest pond (0.34 m), with the longest residence time (48 h) and an influent of 3.44 mg tot-P/l. The highest nitrogen removal was 80 % in the same pond and the same residence time, with an influent of 13.68 mg tot-N/l. Using equation (4.1), it was calculated that, with a pond depth of 0.34 m, 5.1 acres are required for an 80% removal of nitrogen in 1 mgd secondary effluent, or 2.1 ha for 80% N removal in 3,800 m3 secondary effluent/d. This means that less than 1 m2 is required for 80 % removal of nitrogen from the secondary effluent, that is produced by treatment of 1 i.e. raw sewage.

According to Ower, Cresswell and Bate (1981) the highest N-uptake by E. CRASSIPES, is 1.25 mg N/g FW/d in medium containing 36 mg/l N and 6.53 mg/l P. At higher P-concentrations N-absorption declined. P-uptake was strongly correlated with the concentration of phosphorus in the water. The highest P-uptake was 0.06 mg P/g FW/d in water with 26.1 mg/l P and 36 mg/l N, being 21 times less than the N-uptake (on weight basis).

4.2.1.2.Duckweeds

Several other free-floating macrophytes are used for wastwewater treatment due to their high growth rates, like LEMNA MINOR, LEMNA GIBBA and SPIRODELA POLYRHIZA.

The N- and P-removal by L. MINOR was studied (Harvey and Fox, 1973). For this the plants were cultivated in the effluent of a secondary treatment plant, for ten days without any renewal of the 22 l medium, at a temperature of 24 degrees Celcius, a light intensity of 11,000 lux, a photoperiod of 12/12 L/D, the growth surface being 0.05 m2, and with a water depth of 0.45 m. Tot-Kj-N- and tot-P-removal were highest in the tanks with L. MINOR, resulting in low N- and P-concentrations in the effluent (Table 10).

Table 10. Water purification with LEMNA MINOR (Harvey and Fox, 1973).

Nutrient conc. (mg/l)	After 10 days treatment			Removal in 10 d (%)
	influent	control	effluent	
Tot-Kj-N	4.4	6.5	0.7	87
NO_3	8.4	9.1	4.9	39
NO_2	0.04	0.08	0.22	-400
Tot-P	6.1	5.1	2.0	67

In case of SPIRODELA OLIGORHIZA, it was estimated that a weekly harvest of half the biomass of plants cultivated in wastewater from a swine lagoon would give a yield of 2,800 kg DW/ha/month. Expressed as harvestable nutrients, this is 168 kg N/ha/month and 56 kg P/ha/month, amounting over a five month summer period to 84 g N/m2/y and 28 g P/m2/y (Culley and Epps, 1973). These calculations are based on the nutrient contents of 5.7 to 6.5 % DW for N, 1.3 to 2.8 % DW for P (Culley and Epps, 1973), and a doubling time of about seven days (measured for LEMNA; Joy, 1969).

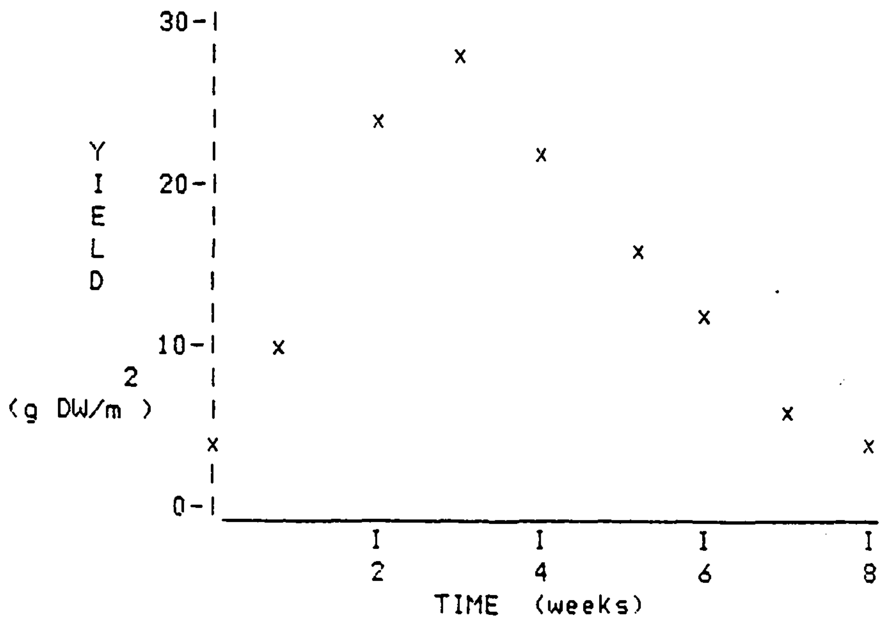
The phosphorus removal capacity of a mixture of LEMNA MINOR and LEMNA GIBBA was studied (Sutton and Ornes, 1975). The first experiment was designed to evaluate the influence of sewage concentration on the growth of a mixture of LEMNA GIBBA and LEMNA MINOR. The duckweeds were cultivated for two weeks in 12 l containers with a surface area of 536 cm2, starting with an inoculum of 10 g FW. The medium consisted for 0 to 100 % of secondary sewage effluent from an air sludge oxidation sewage plant, after chlorination. The plants received 47 % of full sunlight. Biomass increased with higher sewage concentrations, until the latter was 25 % of the undiluted secondary sewage. The P-concentration in the duckweed tissue was highest in the 100 % sewage solution. P-removal was best in the most diluted solution (Table 11).

Table 11. Phosphorus removal from solutions consisting for 0 to 100 % of secondary effluent by LEMNA MINOR and LEMNA GIBBA during a two week small-scale experiment (Sutton and Ornes, 1975).

Conc. of effluent (%)	P-conc. at t=0 d (mg/l)	P-conc. at t=14 d (mg/l)	P-removal (%)	Yield (g DW/m2)	P-tissue (% DW)
0				3.2	0.30
6	0.12	0.01	92	3.5	0.33
12	0.25	0.06	76	3.9	0.39
25	0.50	0.21	58	4.1	0.50
50	0.99	0.53	47	4.1	0.89
75	1.49	1.06	29	4.1	1.11
100	1.99	1.71	14	4.1	1.24

These experiments with duckweeds were continued on a larger scale, being cultivation of an inoculum of 110 g FW in 760 l containers with an area of 1.66 m2, at 35 % sunlight. This time the secondary sewage effluent had not been chlorinated. This FW represented 3.1 g dry weight per square meter. In harvesting half the biomass each week, and replacing lost water by pond water, a yield varying in time was found. Yield was the highest in the third week of culturing, being 28 g/m2, or 4 g/m2/d) and decreased subsequently, presumably because of nutrient depletion (Fig.1).

Fig. 1. Weekly yield of batch cultures of LEMNA GIBBA and LEMNA MINOR cultured in secondary effluent for eight weeks (Sutton and Ornes, 1975).



The total P-concentration in the sewage effluent ranged from 1.42 - 4.28 mg/l P, of which 90 % was removed during the first four weeks. Further reduction up to 97 % occurred the next four weeks (Fig.2).

Fig. 2. Total-P concentration of sewage effluent and of LEMNA GIBBA/LEMNA MINOR cultivated in batches with static secondary effluent for eight weeks, harvesting half the biomass each week (Sutton and Ornes, 1975).

```
          3.5-I                   o-o-o sewage effl.    I-10
              xo                  x-x-x duckweed tissue I
P             I    x                                    I       P
              I                                         I
C             I                                         I-8     C
O         2.5-I                                         I       O
N             I                                         I       N
C             I                                         I       C
              I         x                               I-6
              I                                         I       L
E         1.5-I    o                                    I       E
F             I                                         I       M
F             I                                         I-4     N
L             I              x                          I       A
              I         o                               I
          0.5-I                   x                     I
              I              o         x    x      x    x-2
(mg/l)        I                   o                     I    (mg P/g DW)
              I                        o    o      o    o
            0-I_________________________________________I 0
                        I         I         I           I
                        2         4         6           8
                           TIME   (weeks)
```

A curvilinear relationship was found between the P-conc. of the LEMNA-tissue and the ortho-P conc. in the secondary effluent with a maximum value of 9.7 mg P/g DW at an ortho-P-conc. of 2.1 mg P/l (Sutton and Ornes, 1975):

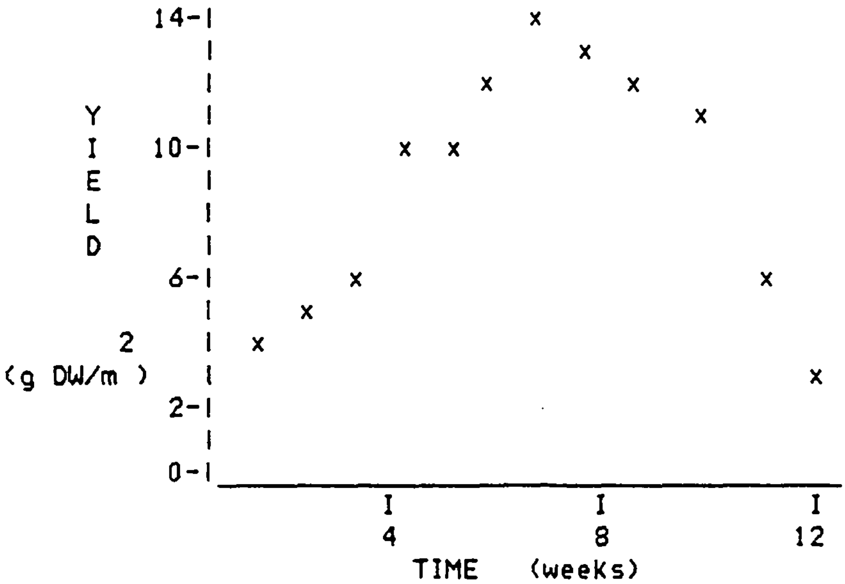
$$y = 1.336 + 8.102x - 1.963x^2 \qquad (4.5)$$

in which y = P-conc. plant tissue (mg P/g DW)
x = o-P-conc.sec.effl. (mg P/l)
with correlation coeff. $r = 0.9839$

From the maximum yield in the third week and the P-conc. of the duckweed tissues (during the same week) a removal by harvesting of 14 mg P/m2/d could be reached with an average of 8 mg P/m2/d. Since the N-conc. in the water were not given, similar calculations can not be carried out for nitrogen.

SPIRODELA POLYRHIZA was also studied as means for wastewater purification (Sutton and Ornes, 1977). For this the plants were cultivated in 760 l containers on secondary effluent from an air sludge oxidation system after chlorination; an inoculum of 100 g FW/1.66 m2 container surface (1.7 g DW/m2) was grown at a temperature of 23.9 to 28.5 degrees Celcius, and an illumination of 35 % full sunlight. Half the biomass was harvested every week during this twelve week experiment. The highest yield was 13.5 g DW/m2 or 1.9 g/m2/d, during the seventh week, being an average of 1.2 g/m2/d for the twelve week period (Fig. 3).

Fig. 3. Weekly yield of batch cultures of SPIRODELA POLYRHIZA cultured in secondary effluent for twelve weeks (Sutton and Ornes, 1977).



Also in this case a curvilinear relationship was found between the P-conc. of the SPIRODELA-tissue and the P-conc. in the secondary effluent with a maximum value of 9.4 mg P/g DW at an ortho-P-conc. of 2.05 mg P/l:

$$y = 3.469 + 5.770x - 1.409x^2 \qquad (4.6)$$

in which y = P-conc. plant tissue (mg P/g DW)
x = o-P-conc.sec.effl. (mg P/l)
with correlation coeff. $r = 0.8818$

At P-conc. higher than 2.05 mg P/l no further P-accumulation will occur in the plant tissue. This concentration is low compared to values found in raw sewage, being 15 to 30 mg P/l (Table 4).

Table 12. P-concentration in secondary sewage water, in which SPIRODELA POLYRHIZA was grown for 12 weeks with weekly harvesting (Sutton and Ornes, 1977)

Time (weeks)	P-conc. In water (mg/l)	P-conc. In plants (% DW)
0	3.53	0.70
1	2.53	0.82
2	2.13	0.86
3	1.63	0.88
4	1.22	0.89
5	0.95	0.82
6	0.82	0.75
7	0.60	0.78
8	0.49	0.66
9	0.31	0.47
10	0.16	0.44
11	0.13	0.35
12	0.09	0.32

From the maximum yield in the seventh week and the tissue P-conc., a maximum P-removal of almost 15 mg P/m2/d was calculated, the minimum and average values being 1.6 and 8.8 mg P/m2/d, respectively.

The growth rate of LEMNA GIBBA was also studied in fishponds and under lab. conditions (Rejmankova, 1978). It was done in dense stands of PHRAGMITES AUSTRALIS and TYPHA ANGUSTIFOLIA, where light was limiting. Growth was found negatively correlated with plant density. High N- and P-conc. were measured in the mixed population of LEMNA GIBBA and SPIRODELA POLYRHIZA from nutrient-rich ponds, of 3 to 5 % and 1 %, respectively. Transplantation of these duckweeds from their original, eutrophic habitat to experimental nutrient solution caused an increase in N- and P-conc. to, respectively, 6 % and 2 % DW. Regrettably, no nutrient concentrations of the fishponds and experimental solution were given.

A relation between biomass and growth rate for LEMNACEAE was found to depend on temperature, light and inoculum as follows (Rejmankova et al., 1979):

$$CGR = -6\,(\log W_o)^2 + 9.38 \log W_o + 3.19 \qquad (4.7)$$

at $t = 20.9\,^oC$ and PAR = 10.6 MJ/m2/d
in which CGR = crop growth rate (g/m2/d)
Wo = total biomass at t=0 (g/m2)

and:

$$CGR = 2.79\,(\log W_o)^2 + 5.78 \log W_o + 0.13 \qquad (4.8)$$

at $t = 5.8\,^oC$ and PAR = 5.9 MJ/m2/d)

A curvilinear relationship between concentration of N and P in the water and in the duckweeds was established, similar to that of Sutton and Ornes (1975, 1977). The following equations were found in experiments at which the N- and P-concentrations ranged up to 40 and 30 mg/l, respectively:

$$Ns = 59.138 - 39.187 / (Nv + 1) \quad (4.9)$$

$$Ps = 16.986 - 13.962 / (Pv + 1) \quad (4.10)$$

in which Ns = N-conc. in the water (mg/l)
Nv = N-conc. in the plants (mg/g DW)
Ps = P-conc. in the water (mg/l)
Pv = P-conc. in the plants (mg/g DW)

With these equations it was calculated, that for certain *minimum* N- and Pconcentrations in the water constant N- and P-contents occur in the plants, the highest ones being 6.0 % N and 1.7 % P on DW basis. From equations (4.7),or, at lower temperature and irradiation (4.8), with (4.9) and (4.10), respectively, the nitrogen (EN) and phosphorus elimination (EP) can be calculated as follows (Rejmankova et al., 1979):

$$EN = CGR \times Ns \quad (4.11)$$

$$EP = CGR \times Ps \quad (4.12)$$

Calculating the P-balance of a culture vessel of the large scale experiment of Sutton and Ornes with L. MINOR and L. GIBBA (Sutton and Ornes, 1975), it is to be expected that all P is divided over the duckweed tissue and the water.

LEMNA GIBBA and L. MINOR

tot-P at t=0 in 760 l (1.66 m2):

in water	3.3 mg P/l x 760 l water	= 2.508 g tot-P
in duckweeds	9 mg P/g x 5.1 g tissue	= 0.045 g tot-P
		2.553 g tot-P

total-P at t=8 weeks in 760 l (1.66 m2):

in water	0.25 mg P/l x 760 l water	= 0.190 g tot-P
in duckweeds (sum of weekly harvests x weekly P-content + 4.6 g (duckweed left over after 8 weeks) and this all x 1.66 m2)		= 0.752 g tot-P
		0.942 g tot-P

This calculation indicates a loss of 2.553 - 0.942 g P = 1.611 g P for a 760 l culture vessel.
In case of SPIRODELA (Sutton and Ornes, 1977) similar losses occurred, as clear from the following P-budgets:

SPIRODELA POLYRHIZA

tot-P at t=0 in 760 l (1.66 m2):

in water	3.53 mg P/l x 760 l wat	=	2.683 g tot-P
in duckweeds	7 mg P/g x 1.7 g tissue	=	0.012 g tot-P
			2.695 g tot-P

tot-P at t=8 weeks in 760 l (1.66 m2):

in water	0.09 mg P/l x 760 l water	=	0.068 g tot-P
in duckweeds (sum of weekly harvests x weekly P-content + 4.6 g (duckweed left over after 8 weeks) and this all x 1.66 m2)		=	1.190 g tot-P
			1.258 g tot-P

Here 2.695 - 1.190 g = 1.437 g P is missing per culture vessel.

Summarizing, the following can be concluded from the data on duckweeds so far. SPIRODELA OLIGORHIZA thrives on swine lagoons with water of unknown chemical composition (Culley and Epps, 1973). LEMNA MINOR (Harvey and Fox, 1973; Sutton and Ornes, 1975), LEMNA GIBBA (Sutton and Ornes, 1975) and SPIRODELA POLYRHIZA (Sutton and Ornes, 1977) grow well on secondary effluents. The biomass of LEMNA MINOR and L. GIBBA does not increase further above ortho-P conc. > 0.50 mg/l, the P-content of the plant being highest at a P-conc. of 2 mg/l (Sutton and Ornes, 1975). In SPIRODELA POLYRHIZA, which is usually richer in P than LEMNA GIBBA and L. MINOR, but develops a lower biomass, a similar P-yield is possible. P-contents upto 2 % DW were found for L. GIBBA and S. POLYRHIZA (Rejmankova, 1978).
In contrast with the square equations (4.5) and (4.6) of Sutton and Ornes (1975) for P, Rejmankova, Kvet and Rejmanek (1979) found a curvilinear relationship (4.10) between water and tissue P-conc. which seems more logical. Equations (4.5) and (4.6) indicate P-contens of duckweeds to decrease for P-conc. > 2 mg/l, while (4.10), on the contrary, shows that no further P-accumulation will occur. This difference between (4.5) and (4.10) is probably caused by the smaller range in P-conc. in the water used by Sutton and Ornes (1975).

4.2.2. Emergent macrophytes

Three emergent macrophytic species were grown in a greenhouse in winter, namely IRIS VERSICOLOR L., SCIRPUS VALIDUS Vahl., and SCIRPUS ACUTUS Muhl. (Spangler, Sloey and Fetter, 1976). The plants were planted in 7 cm pea-sized gravel in plastic lined basins of 0.80 x 0.90 m, filled with primary effluent, at daylight with an additional illumination of 2,152 - 3,228 lux at night (the type of the light source was not mentioned). Only small differences in nutrient removal were found between the basins with plants and the controls (Table 13). P-removal was the highest at the five days retention period, but the presence of plants showed hardly any effect for all parameters measured. No absolute data were given the composition of the primary effluent used in the experiments.

Table 13. Effect of some emergent macrophytes (IRIS VERSICOLOR, SCIRPUS VALIDUS and SCIRPUS ACUTUS) on primary effluent in a greenhouse experiment (Spangler, Sloey and Fetter, 1976).

Retention period	Reduction (%)				
5 days	control	IRIS	S.ACUTUS	S.VALIDUS	S.VALIDUS
BOD_{5}^{20}	97	98	98	98	97
COD	89	89	87	86	83
ortho-P	52	58	68	76	70
tot-P	76	80	84	83	80
dissolved solids	60	54	60	51	44
3 days	control	IRIS	S.ACUTUS	S.VALIDUS	S.VALIDUS
BOD_{5}^{20}	86	94	92	96	95
COD	75	73	89	85	85
ortho-P	2	8	41	63	49
tot-P	-4	34	45	62	54
dissolved solids	28	21	25	13	13
1.5 days	control	IRIS	S.ACUTUS	S.VALIDUS	S.VALIDUS
BOD_{5}^{20}	86	89	90	88	81
COD	54	49	61	57	29
ortho-P	-1	-3	28	57	30
tot-P	32	30	59	60	51
dissolved solids	19	12	2	-9	-14

The optimum concentrations for growth and maximum nutrient content of some emergents were studied in hydroponic cultures (Dykyjova, 1978). The nutrient solution used had the following composition (Dykyjova and Veber, 1978):

$CO(NH_2)_2$	600.0 mg/l	H_3BO_3	6.18 mg/l
$Ca(NO_3)_2.4H_2O$	800.0 mg/l	$MnSO_4.H_2O$	2.23 mg/l
$MgSO_4$	963.0 mg/l	$CuSO_4.5H_2O$	2.49 mg/l
KH_2PO_4	680.0 mg/l	$ZnSO_4.7H_2O$	2.87 mg/l
$Fe_2(SO_4)_3.9H_2O$	28.1 mg/l	$CoCO_3.7H_2O$	2.81 mg/l
EDTA-complex	88.6 mg/l	$(NH_4)_2MoO_4$	1.96 mg/l

This nutrient solution was used in several concentrations, being 0 - 50 - 100 - 150 - 200 %. Biomass production was the highest in the 50 % concentration in TYPHA LATIFOLIA and PHRAGMITES AUSTRALIS. N-content of the shoots was highest in the 50 % (TYPHA LATIFOLIA) or 100 % (PHRAGMITES AUSTRALIS) nutrient medium. P-content was more or less constant. The underground parts contained most nitrogen in the 150 % solution. ACORUS CALAMUS and BOLBOSCHOENUS MARITIMUS showed a higher shoot production than in natural habitats. When grown in 300 %, solution most species showed chlorotic leaves or a dying-off of the leaves and/or shoots. The highest accumulation of nutrients per area was found in three years old plants of TYPHA LATIFOLIA in 100 % solution. The total biomass of 8,231 g DW/m2 contained 156.2 g N/m2 and 37.5 g P/m2, of which the underground biomass amounting to 3,860 g DW/m2, contained 102.7 g N/m2 and 26.3 g P/m2. The toxicity of the very concentrated nutrient solution of 300 %, resulting in chlorosis and die-off of leaves and shoots, may have been caused by too high micronutrient concentrations (Dykyjova, 1978).

TYPHA LATIFOLIA and SCIRPUS VALIDUS were also tried for wastewater treatment under Canadian conditions (Lakshman, 1979). For this plants were grown in a growth chamber under fluorescent light, 10,800 lux at 1 m, a 14/10 L/D photoperiod, at a temperature of 25 degrees Celcius and a relative humidity of 30 %. As substrate pea sized gravel was used to eliminate nutrient exchange. Each tray of 0.91 x 0.84 x 0.46 m contained six plants, which increased to about nine in four weeks. At the beginning of each run the trays were filled with 227 l untreated sewage , which stayed in the tray until total-P reduction was about 90 %. After draining, a new run was started with the same plants. The P-conc. in the sewage ranged from 3.9 to 29.0 mg P/l and total-Kjeldahl-N from 10.3 to 44.0 mg N/l (see also Table 4). The first runs showed only small differences between the trays with and without plants. After several runs a distinct effect of the macrophytes, especially S. VALIDUS, could be seen, being a reduction of both total-P and total-Kjeldahl-N. In the later runs of the experiment effluents from the control tray contained more total-P than the influent. Similar results occurred in the T. LATIFOLIA trays. Short retention periods and saturation of the sediment, which acted as P-source, probably cause this effect (Table 14a). No increases were found in total-Kjeldahl-N, but high loads and/or relatively short retention times gave decreased reduction percentages (Table 14b). Although in this experiment plant biomass was harvested periodically, no data were given.

Table 14a. The reduction in total-P in containers with raw sewage, planted with SCIRPUS VALIDUS (bulrush) and TYPHA LATIFOLIA (cattail) with different retention times (Lakshman, 1979).

Run	Retention period (days)	Initial tot-P conc. (mg/l)	Final tot-P-conc. (mg/l) % reduction between brackets: control	bulrush	cattail	cattail
1	35	16.8	0.2 (99)	0.2 (99)	0.2 (99)	0.6 (96)
2	33	19.0	0.7 (96)	0.9 (95)	1.1 (94)	1.4 (93)
3	12	9.7	5.9 (39)	0.5 (95)	0.5 (95)	0.2 (98)
4	16	13.4	8.3 (38)	1.5 (89)	0.5 (96)	1.6 (88)
5	28	8.2	4.6 (44)	0.8 (90)	0.7 (91)	0.8 (90)
6	26	4.6	1.5 (67)	1.5 (67)	1.1 (76)	0.9 (80)
7	33	15.6	4.0 (74)	0.1 (99)	3.6 (77)	8.2 (47)
8	21	11.6	8.0 (31)	1.2 (90)	0.8 (93)	3.4 (71)
9	19	29.0	16.2 (44)	0.7 (98)	0.5 (98)	5.6 (81)
10	34	17.6	11.6 (34)	0.8 (95)	1.3 (93)	13.6 (23)
11	35	8.2	1.7 (79)	0.6 (93)	0.4 (95)	0.7 (91)
12	13	3.9	1.5 (62)	1.5 (62)	0.6 (85)	0.7 (82)
13	6	9.5	5.8 (39)	2.5 (74)	1.9 (80)	2.1 (78)
14	14	11.5	15.0 (-30)	0.8 (93)	6.0 (48)	18.0 (-57)
15	14	12.0	20.2 (-68)	6.6 (45)	4.0 (67)	11.8 (2)
16	14	9.0	20.8 (-131)	3.2 (64)	12.5 (-39)	11.9 (-32)
17	14	16.4	24.5 (-49)	3.7 (77)	22.2 (-35)	11.6 (29)
18	14	15.6	27.1 (-74)	13.7 (12)	32.1 (-106)	27.7 (78)
19	34	17.0	7.4 (56)	1.0 (94)	14.9 (12)	1.8 (89)
20	29	6.8	2.9 (57)	1.0 (85)	0.9 (87)	0.7 (90)

Table 14b. The reduction in total-Kjeldahl-N (TKN) in containers with raw sewage, planted with SCIRPUS VALIDUS (bulrush) and TYPHA LATIFOLIA (cattail) with different retention times (Lakshman, 1979).

Run	Retention period (days)	Initial tot-P conc. (mg/l)	Final tot-Kjeldahl-N-conc. (mg/l) % reduction between brackets			
			control	bulrush	cattail	cattail
1	35	30.0	2.2 (93)	2.6 (91)	1.1 (96)	1.9 (94)
2	33	34.4	2.3 (93)	2.0 (94)	2.7 (92)	0.4 (99)
3	12	26.0	14.0 (46)	6.0 (77)	4.0 (85)	1.6 (94)
4	16	26.4	18.4 (30)	3.2 (88)	1.7 (94)	1.8 (93)
5	28	31.2	10.8 (65)	2.8 (91)	4.0 (87)	2.8 (91)
6	26	31.2	6.0 (81)	1.6 (95)	11.2 (64)	4.4 (86)
7	33	35.2	24.0 (32)	2.4 (93)	10.4 (70)	4.4 (88)
8	21	37.6	17.6 (53)	2.0 (95)	4.0 (89)	5.2 (86)
9	19	44.0	26.4 (40)	3.2 (93)	6.0 (86)	8.4 (81)
10	34	40.0	28.0 (30)	1.7 (96)	16.0 (60)	22.0 (45)
11	35	27.6	8.4 (70)	1.2 (96)	2.7 (90)	1.9 (93)
12	13	10.3	4.0 (61)	1.3 (87)	1.8 (83)	1.8 (83)
13	6	10.3	8.4 (18)	2.7 (74)	5.9 (43)	5.6 (46)
14	14	25.8	17.6 (32)	2.8 (89)	8.4 (67)	12.4 (52)
15	14	21.6	21.2 (2)	2.8 (87)	14.4 (33)	16.4 (24)
16	14	24.0	20.5 (15)	4.0 (83)	13.5 (44)	11.8 (51)
17	14	25.8	22.2 (14)	9.0 (65)	18.3 (29)	15.6 (40)
18	14	31.0	28.0 (10)	15.0 (52)	26.0 (16)	21.0 (32)
19	34	34.0	18.4 (46)	1.0 (97)	11.6 (66)	1.6 (95)
20	29	22.8	8.2 (64)	0.9 (96)	1.8 (92)	1.8 (92)

An exponential relationship was found between absorption of P and N by the plant/gravel/bacteria system and the initial quantities of these nutrients (Lakshman, 1979):

For P-removal:

$$Mat = Mi\ (1 - (1.94)\exp(-0.18t)) \qquad (4.13)$$

in which t = time (d)

Mat = nutrient quantity, absorbed by the plant/gravel/bacteria system (g or kg)

Mi = initial nutrient quantity (g or kg)

And for total-Kjeldahl-N removal:

$$Mat = Mi\ (1 - (1.45)\exp(-0.125t)) \qquad (4.14)$$

The number of days required to reach a desired level of purification can easily be determined by rewriting (4.13) and (4.14) into:

$$PR = 100 - (194)\exp(-0.18t) \qquad (4.15)$$

in which PR = % P-removal (= 100 x Mat/Mi)

And for total-Kjeldahl-N:

$$NR = 100 - (145)\exp(-0.125t) \qquad (4.16)$$

in which NR = % N-removal (= 100 x Mat/Mi)

PR and NR depend only on time. Solving equations (4.15) and (4.16) for t, it was calculated, that PR is negative if t < 3.68 days. This would indicate, that the trays act as nutrient source during the first days after recharging. Therefore the abovementioned equations ((4.13), (4.14), (4.15), (4.16)) do not give a proper description of nutrient removal during the first days. No quantitative relation is given by (4.13) and (4.14) between nutrient removal and plant harvest. The constants used in Lakshmans equations were found by regression analyses of all runs. The average value of the thus-calculated constants for bulrush and cattails were used, carrying in them all other conditions of these experiments (Lakshman, 1979).

Three emergent macrophytic genera: TYPHA, PHRAGMITES and SCIRPUS were also tried for wastewater purification under Australian conditions (Finlayson and Chick, 1983). PHRAGMITES AUSTRALIS and a mixture of TYPHA DOMINGENSIS and T. ORIENTALIS were grown, respectively, in trenches of 20 m length, SCIRPUS VALIDUS on a trench of 15 m length; all trenches had a width of 1.8 m, were lined with black plastic, and filled with 0.2 cm red gravel to a depth of 50 cm. Abattoir effluent was pumped with a mechanical aerator and then allowed to percolate through the gravel substrate from 10 March 1981 until 9 April 1981 (autumn). The average calculated retention time was 2.7 d in the TYPHA-trench, 3.6 d in the case of the PHRAGMITES-trench, and 3.0 d in the one of SCIRPUS. The effluent was concentrated by high evaporation, 32 % for TYPHA, 49 % for PHRAGMITES, and 45 % for SCIRPUS,and diluted by rainfall (two times). Purification was best in the SCIRPUS-trench, especially the reduction of Kjeldahl-N, which was partly oxidized to nitrate. In all trenches a considerable P-reduction occurred. The overall results are given in Table 15.

Table 15. Nutrient concentrations in in- and outflow of three trenches used for purification of abattoir effluent, one being planted with a mixture of TYPHA DOMINGENSIS and T. ORIENTALIS, one with PHRAGMITES AUSTRALIS, and one with SCIRPUS VALIDUS (Finlayson and Chick, 1983).

Nutrient conc.	T. DOMINGENSIS + T. ORIENTALIS		P. AUSTRALIS		S. VALIDUS	
(mg/l)	inflow	outflow	inflow	outflow	inflow	outflow
Kj.-N	99.3	85.1	94.7	69.7	98.1	43.6
NO3-N	0.08	0.51	0.10	0.16	0.08	2.76
NH4-N	31.2	30.4	34.4	30.2	33.6	15.,4
P-tot	14.6	6.9	13.9	8.7	14.6	5.7
ortho-P	7.2	3.9	7.8	5.6	7.7	3.1

The purification in general seems rather poor, however; reduction of suspended solids was quite good. The SCIRPUS- and PHRAGMITES-trenches produced aerobic effluent, but the TYPHA-trench was sometimes anaerobic.

Looking in a different way at the data by not giving the concentrations, but nutrient in- and output, the results are much better, the main reason being the high evaporation rate (Table 16).

Table 16. Nutrient in- and output of three trenches used for the purification of abattoir effluent, one planted with TYPHA DOMINGENSIS and T. ORIENTALIS, one with PHRAGMITES AUSTRALIS, and one with SCIRPUS VALIDUS. Means of one month (Finlayson and Chick, 1983).

	Total-N		Total-P	
	/trench	/m2	/trench	/m2
TYPHA DOMINGENSIS and T. ORIENTALIS				
Input (g)	1553	16.0	228	2.3
Output (g)	901	9.3	74	0.8
Reduction (%)	42		68	
PHRAGMITES AUSTRALIS				
Input (g)	1564	12.1	230	1.8
Output (g)	589	4.5	74	0.6
Reduction (%)	62		68	
SCIRPUS VALIDUS				
Input (g)	1040	12.8	155	1.9
Output (g)	270	3.3	33	0.4
Reduction (%)	74		79	

4.2.3. Other experiments

A study was done to follow the fate of radioactively labelled N and P in reservoirs with macrophytes (Reddy, 1983). This was done to investigate the tentative use of eight reservoirs of 20 ha each for treatment of highly eutrophic agricultural drainage water. The reservoirs were situated in central Florida. The eight reservoirs were simulated galvanized, plastic vessels of 1.2 m length, 0.6 m width, and 0.6 m depth. In each vessel 0.15 m thick sediment was installed consisting of calcareous marly clay loam with 0.30 % N. The experiment was carried out in duplicate, in a greenhouse, at 21 degrees Celcius The vessels were planted with either HYDROCOTYLE UMBELLATA (pennyworth; 78.7 g/m2), or EICHHORNIA CRASSIPES (waterhyacinth; 165.6 g/m2), or with a mixture of TYPHA LATIFOLIA (cattail; 365.8 g/m2) and EGERIA DENSA (elodea; 122.5 g/m2). The control vessels were devoid of macrophytes. One series of reservoirs was enriched with labelled NH4-N, the other with labelled NO3-N (2.0 atom % N15-nitrogen), the total inorganic N-load being 8.46 g N/m2. The nutrient concentrations in water, sediment and plants were used to calculate the N- and P-removal rates, respectively, as follows:

$$C(t) = C(0) \times (1 - \exp(-kt))$$

in which: t = time (d)
C(0) = initial conc. of N and P, respectively
C(t) = conc. N and P, respectively, after t days
k = constant, calculated using least-square fit

Table 17. Biomass production and nutrient uptake by macrophytes, cultivated on agricultural drainage water (Reddy, 1983).

Macrophytic species	Production rate (g DW/m2/d)	Nutrient uptake rate (mg/m2/d)	
		N	P
HYDROCOTYLE UMBELLATA	4.20	190	50
EICHHORNIA CRASSIPES	4.26	200	24
TYPHA/EGERIA	3.60	120	4
TYPHA LATIFOLIA	2.92	50	1
EGERIA DENSA	0.67	70	3
Control (algae)	0.76	20	3

Also the preference for NH4-N and NO3-N was studied. HYDROCOTYLE UMBELLATA and TYPHA LATIFOLIA showed a strong preference for NH4-N, while EICHHORNIA CRASSIPES, EGERIA DENSA and the algae in the control vessel accumulated NO3-N and NH4-N in equal amounts during the 27 days experiment, during which 4.0 g labelled N/m2, plus 0.46 g N/m2 from wastewater and sediment was administered. The nitrogen mass balance (Table 18) showed high disappearance rates of NH4-N in the presence of all macrophytes, lower ones in case of NO3-N, which was partly explained by the incorporation in macrophytic tissues. Only small amounts of the labelled nitrogen remained in the water excepting the control vessels. Volatilization of NH4-N and nitrification-denitrification, which were not measured, were probably responsible for the major N-losses. The volatilization of ammonia occurred probably to higher extent in case of EGERIA DENSA and the controls than in the other vessels, due to high pH. In case of labelled NH4-N addition, ammonia was largely recovered as nitrate, due to nitrification. Circulation of the overlying water by pumping supplied sufficient oxygen for nitrification; however, usually the waters overgrown with floating macrophytes contain less oxygen. Nitrification only occurred at pH $<$ 9, whereas denitrification took mainly place in the sediment, where redox-potentials of -100 to 50 mV were found (Reddy, 1983).

Table 18. Mass balance of labelled N in vessels with macrophytes, growing for 27 days on agricultural drainage water. The first series received 4.0 g labelled NH4-N/m2 and 4.0 g unlabelled NO3-N, the second series 4.0 g labelled NO3-N and 4.0 g unlabelled NH4-N (Reddy, 1983).

Macrophytic species	Labelled NH4-N (% added)			
	water	sediment	plant	unaccounted
HYDROCOTYLE UMBELLATA	0.0	8.9	67.3	23.8
EICHHORNIA CRASSIPES	3.4	8.5	41.2	46.9
TYPHA/EGERIA	0.1	8.0	43.8	48.1
Control (algae)	21.0	20.9	4.6	53.5
	Labelled NO3-N (% added)			
HYDROCOTYLE UMBELLATA	0.0	6.2	13.0	80.8
EICHHORNIA CRASSIPES	11.5	5.9	39.3	43.3
TYPHA/EGERIA	0.1	28.5	23.8	47.6
Control (algae)	35.8	30.9	4.3	28.9

Removal of P was highest in the controls, where precipitation with Ca-complexes occurred at high pH. In case of TYPHA and EGERIA a similar situation was found with more P in the water. Highest P-absorption by the plants was found in the HYDROCOTYLE-vessel, followed by EICHHORNIA. P mass balances are given in Table 19.

Table 19. Mass balance of unlabelled P in vessels with macrophytes growing for 27 days on agricultural drainage water. Both series contained water with 5 mg P/l (Reddy, 1983).

reservoir system	P in water (in %)		P not in water (in %)	
	soluable	insoluble	in plants	unaccounted
HYDROCOTYLE UMBELLATA	27.6	13.7	64.5	-5.8
EICHHORNIA CRASSIPES	27.5	36.5	28.6	7.4
TYPHA/EGERIA	29.3	11.1	4.4	55.2
TYPHA LATIFOLIA	-	-	1.0	-
EGERIA DENSA	-	-	3.4	-
Control (algae)	4.5	4.8	3.4	87.3

4.3. Pilot plants

Spangler, Sloey and Fetter used a pilot plant to investigate purification of secondarily treated wastewater using emergents (see also section 4.2.2.). In several small ponds (9.29 m2) and a bigger one (46.45 m2) they grew SCIRPUS VALIDUS; two basins in 1973, and three in 1974). Besides these SCIRPUS VALIDUS ponds, two others were planted with IRIS VERSICOLOR and one with SCIRPUS FLUVIATILIS (Spangler, Sloey and Fetter, 1976). The plants were planted in gravel with a depth of 0.70 m in the large pond and 0.15 m in the smaller ponds. The control pond contained only gravel. The flow rates were not kept constant, but they resulted in an average retention time of five h. Even with these short retention times, BOD decreased considerably, however also in controls (Table 20). The oxygen conc. never dropped below 2.0 mg/l in the SCIRPUS VALIDUS ponds, although it did in the controls. Anaerobiosis was only measurable in the water above the gravel.

The effect of harvesting on the performance of the ponds was studied also. Hardly any difference in nutrient removal rates was found before and after harvesting the ponds.

Table 20. Pilot plant for the purification of secondarily treated wastewater consisting of ponds with SCIRPUS VALIDUS on gravel, before and after harvesting the aboveground biomass. The average retention time was five h.(Spangler, Sloey and Fetter, 1976).

Parameters	PRE-HARVEST				
	infl.	control		SCIRPUS VALIDUS	
	conc. (mg/l)	conc. (mg/l)	reduction (%)	conc. (mg/l)	reduction (%)
BOD	38.5	4.7	87.8	4.5	88.2
COD	41.6	30.8	25.8	36.0	13.4
NH3	1.5	2.0	-35.7	1.2	20.9
tot.org-N	0.7	0.9	-26.3	0.7	56.8
NO3	ND (*)	ND (*)	ND (*)	ND (*)	ND (*)
total-P	22.6	18.2	19.5	21.5	4.7
diss.solids	902	930	-3.1	910	-0.9
coliforms (x 1000)	485	29.5	93.9	49.5	90
turbidity (JTU)	8.6	1.8	79.3	2.0	77.4

ONE WEEK AFTER HARVEST

Parameters	PRE-HARVEST				
	infl.	control		SCIRPUS VALIDUS	
	conc. (mg/l)	conc. (mg/l)	reduction (%)	conc. (mg/l)	reduction (%)
BOD	65.6	8.8	86.5	5.3	92.0
COD	ND (*)	ND (*)	ND (*)	ND (*)	ND (*)
NH3	0.4	0.2	40.5	0.1	83.4
tot.org-N	ND (*)	ND (*)	ND (*)	ND (*)	ND (*)
NO3	6.6	3.7	44.5	9.7	-47.1
total-P	21.0	18.1	13.8	15.9	24.5
diss.solids	758.0	704.0	7.2	696	9.5
coliforms (x 1000)	2546	49.9	98.0	58.3	97.7
turbidity (JTU)	23.2	3.1	86.7	9.7	90.7

(*) Not done.

The same authors investigated P-removal by different harvesting regimes applied to emergent plants in natural marshes (Spangler, Sloey and Fetter, 1976) (see also sections 2.3.4. and 4.2.2.). The highest yields, both in dry weight and P, were reached with frequent harvesting. In the mentioned pilot plant emergents were harvested four times, with approximately one month intervals. Harvesting SCIRPUS VALIDUS caused a P-removal of 3.5-3.8 g/m2, while only 1.1 g P/m2 was harvested in case of SCIRPUS FLUVIATILIS (Table 21). The latter species is therefore less suitable for purification purposes.

Harvesting SCIRPUS VALIDUS removes 3.5 g P/m2, which equals 35 Kg P/ha or 27 i.e./ha (compare with Table 8).

Table 21. P-yield by harvesting shoots of two ponds with SCIRPUS VALIDUS and one pond with SCIRPUS FLUVIATILIS in a pilot plant (Spangler, Sloey and Fetter, 1976).

Harvest date	P-yield (g/m2)		
	S. VALIDUS	S. VALIDUS	S. FLUVIATILIS
17 June	1.53	1.86	0.58
19 July	1.32	1.06	0.33
8 Aug.	0.30	0.61	0.16
9 Sept	0.36	0.30	0.06
total	3.51	3.83	1.13

Most P found in the underground parts and in the gravel substrate (Table 22). In winter this was largely washed out (Spangler, Sloey and Fetter, 1976). The gravel substrate appeared not capable to bind the P more permanently.

Table 22. P-distribution in a pilot plant with SCIRPUS VALIDUS on gravel (Spangler, Sloey and Fetter, 1976).

Date	17 June		23 September		4 December	
S.VALIDUS	g P/m2	%	g P/m2	%	g P/m2	%
Shoots harv. at date	1.86	14.1	0.30	1.6	0.00	0.0
Shoots harv. since last date	0.00	0.0	1.67	8.9	0.00	0.0
Standing shoots	0.82	6.2	1.74	9.2	0.58	7.3
Rhizomes	1.42	10.8	3.12	16.5	2.30	28.9
Roots	0.35	2.6	3.41	18.0	2.68	33.6
P in biomass	4.45	33.7	10.24	54.2	5.56	69.8
P in gravel	8.75	66.3	8.65	45.8	2.41	30.2
Total P	13.20	100	18.89	100	7.97	100
Control pond (no plants) P in gravel	7.91	100	5.18	100	0.38	100

Seidel tested the use of bulrushes (SCHOENOPLECTUS LACUSTRIS) and reed (PHRAGMITES AUSTRALIS) for wastewater purification purposes. Several small sewage plants are designed according to her ideas (Seidel, 1976b), and a few of them will be discussed here. In Westport, USA, a small sewage plant was built, of which the exact dimensions were not described. Raw sewage is infiltrated in a reed-planted pond, hydrologically separated from the underlying soil. The bottom of the pond is covered with large gravel, in which drainage pipes are placed. Smaller-sized gravel and sand as top layer are used as filter and substrate for ten reed plants per m2. The short retention time of the reed pond (several minutes) is long enough to withdraw the solids largely from the water. After this initial treatment, the effluent is governed into three successive basins planted with bulrushes with the same plant density. In the latter ponds the average retention time is half a day. Usually one m2 reed and two m2 bulrush pond are sufficient for the purification of one m3 domestic sewage. Transport between the successive ponds occurs only due to gravity; during this process intensive aeration takes place. The decrease in BOD is at least 80 % (Table 23).

Table 23. Decrease in BOD in a small reed/bulrush sewage treatment system operating in Westport, USA, during 1973, and designed according to Seidels' ideas (Seidel, 1976b).

Dates in	BOD		
1973	influent (mg/l)	effluent (mg/l)	decrease (%)
22 March	97	5	94
18 April	101	7	93
11 May	85	10	88
6 June	87	19	78
13 June	86	25	71
2 July	83	8	90
26 July	65	23	65
8 August	65	19	71
15 August	69	7	90
22 August	83	8	90
30 August	67	5	91
5 September	95	13	86
12 September	92	6	93
27 September	90	14	84
4 October	92	10	89

The effluent from a plant nursery is treated in a small system in Western Germany. The population consists of 15 persons and the total sewage production is three m3 per day. The raw sewage is infiltrated in a reed pond of 7.5 m2, where the solids are withdrawn largely. Final purification occurs in two bulrush ponds of 11 m2. The retention time in the reed pond is 5 to 10 min. and in the bulrush pond 8 to 10 h. (Seidel, 1976b). The decrease in BOD was quite high (Table 24). No data on N and P were given.

Table 24. Decrease in BOD in a small reed/bulrush sewage plant for the purification of sewage of a nursery in Western Germany, designed according to the ideas of Seidel. Average data of one year (Seidel, 1976b).

Water type	BOD (mg/l)	Turbidity (cm)
Influent (raw sewage)	360	0
After reed treatment	70	7
After bulrush treatment 1	14	30
After bulrush treatment 2	7	40
After bulrush treatment 3	2.5	52

In 1978 a pilot plant for wastewater purification was started in Viville (Arlon, Belgium). Five series of four ponds were used, each of 600 l, with a surface area of 0.96 m2 (Radoux, 1980b, 1982; Radoux and Kemp, 1981a, 1981b, 1981c). In each pond series water transport occurred by gravity (cascades). The average composition of the water was:

COD = 75 mg/l (30-450)
total-N = 10 mg/l (5-25)
total-P = 3.5 mg/l (2-6)

The bottom of all tanks was covered with quartz. In case it was planted with emergent plants, 7 cm of water was standing above this inert "soil", while ELODEA CANADENSIS was grown in 35 cm water depth.

In the experiments of 1979 (July - October) optimum retention times were determined by supplying different loads to three series of tanks, in which each series was succesively planted with TYPHA LATIFOLIA, PHRAGMITES AUSTRALIS, CAREX ACUTA and ELODEA CANADENSIS (Radoux and Kemp, 1981a). From preliminary studies it was known that TYPHA LATIFOLIA grew better in wastewater conditions, than SPARGANIUM ERECTUM (Radoux, 1980b). Water entered the system by percolation, providing a water flow through the quartz soil. The decrease in COD was not affected considerably by loading (170 i.e.to 675 i.e.); it depended, however, strongly on season. In the range of 170 to 340 i.e., N-removal was high, 90 to 95 %; an exception formed October, when the N-removal was less efficient. In the series with the highest loading purification results were quite good in July, but it decreased during the rest of the year. P-removal depended more on loading and it decreased in the course of the season. Longer retention times, by increasing the number of tanks per series, generally increased the removal of N, P and COD, except for P in the tank with PHRAGMITES AUSTRALIS and the highest loading.

In 1980 three series of four tanks were used, of which one series without plants (Radoux, 1982; Radoux and Kemp, 1981c). The other two series of four tanks were subsequently planted with TYPHA LATIFOLIA, PHRAGMITES AUSTRALIS, CAREX ACUTA and ELODEA CANADENSIS (the latter is not mentioned in Radoux, 1982). One unplanted series served as control. The water circulated through the first series (with macrophytes) by infiltration followed by percolation (a horizontal flow through the quartz), creating aerobic and anaerobic patches. No horizontal flow occurred in the substrate of the other two series, where the water flowed largely above the quartz. The experiment lasted 123 d. (May to October). The retention time for each tank was two days, resulting in a six days retention time for one series of three tanks (in Radoux and Kemp, 1981c an overall retention time of ten days is mentioned).

Table 25. N-balance in a pilot sewage plant in Viville (Belgium) in 1980 (Radoux, 1982; Radoux and Kemp, 1981c). Three series of four tanks were compared: one without plants and the other two with TYPHA LATIFOLIA in the first tank, PHRAGMITES AUSTRALIS in the second, CAREX ACUTA in the third, and ELODEA CANADENSIS in the fourth one, with and without percolation through the substrate. Retention time two days per tank.

Total-N	Planted		Not planted
(g/m2/123 d)	percolation	no percolation	no percolation
Influent	44.21	17.68	17.68
In system:			
Water ambient	0.15	0.07	0.12
interst	0.11	0.20	0.65
Underground biomass (*)	27.34	8.48	11.44
Aboveground biomass	13.03	6.66	-
TOTAL	40.63	15.41	12.21
Effluent	3.58	2.27	5.47
Removal (%)	92 %	87 %	69 %

(*) micro-organisms, roots and rhizomes, if present

Table 26. P-balance in a pilot sewage plant in Viville (Belgium) in 1980 (Radoux, 1982; Radoux and Kemp, 1981c). See also Table 25.

Total-P	Planted		Not planted
g/m2/123 days	percolation	no percolation	no percolation
Influent	14.93	5.97	5.97
In system:			
Water ambient	0.09	0.09	0.05
interst	0.23	0.13	0.09
Underground biomass (*)	9.11	3.13	3.74
Aboveground biomass	2.06	1.02	-
Effluent	3.44	1.61	2.09
Removal (%)	77 %	73 %	65 %

(*) micro-organisms, roots and rhizomes, if present

The purification was similar in tanks with macrophytes and percolation, and in tanks with plants, but without percolation. The former was even better, since the loading of the percolation ponds was 2.5 times higher. Recalculating the data for conditions of equal loading, the TYPHA LATIFOLIA- tank without percolation (76%) functionated better than the tank with percolation. This may be due to the fact TYPHA LATIFOLIA has aboveground roots in the water, absorbing more nutrients in the tank without percolation. PHRAGMITES AUSTRALIS and CAREX ACUTA had higher N-removal rates in the series of tanks with percolation, resulting in a better overall result (Radoux and Kemp, 1981c). P-removal was similar; however ELODEA CANADENSIS played a more important role in this case, since it removed 50 % of the influent.
A comparison of two series of treatment ponds with the same loading, one with and one without plants, showed better water purification in the planted ponds (Table 25 and Table 26). The difference was caused mainly by the first tank with TYPHA LATIFOLIA, where a N-removal of 76 % occurred (Radoux and Kemp, 1981c). The N-removal by ELODEA CANADENSIS was not impressive, although percolation increased it. P-removal was higher in the ELODEA-tank with percolation, being 16 % vs. 10 % with and without percolation, respectively.
The final effluent of the percolated tanks contained:

COD = 24 mg/l (69 % removal)
total-N = 0.5-1.2 mg/l (with hardly any NH3 and NO2)
total-P = 0.1-1.7 mg/l

A comparison of these results with Table 5, indicates a good performance for purification of COD (no reduction in the unplanted series of tanks) and N, vs. reasonable performance in case of P. However, several marginal notes have to be made. Loading of the ponds was low, and nutrient concentrations (COD, N and P) were rather low for domestic sewage, the latter being caused by dilution of the raw sewage with river water of the Samois river before it was purified experimentally. Also, these experiments were carried out in the growth season, whereas a large washout of P in the sediments can be expected during winter and spring. No data were given of the performance on the Viville pilot plant in winter.

The use of Lemnaceae and EICHHORNIA CRASSIPES for purification of pretreated (in lagoons) pig manure was investigated in a pilot plant (Corradi et al., 1981; Coppelli et al., 1981; Ghetti et al., 1981). In Reggio Emilia (Northern Italy) four plastic-lined ditch-shaped ponds were built with a depth of 0.65 m, planted with EICHHORNIA CRASSIPES and a mixture of LEMNA MINOR and LEMNA GIBBA. The surface areas of the four ponds (1 to 4) were respectively 54, 49, 50, and 45 m2.
The composition of the pretreated pig manure was:

NH_4-N	230 - 280 mg/l	(average for the second period 249)
org.-N	30 - 60 mg/l	
tot.-P	40 - 55 mg/l	
PO_4-P	30 - 40 mg/l	(average for the second period 35.9)
COD	600 - 1000 mg/l	(average for the second period 713)
BOD	300 - 700 mg/l	

The pretreated water was used as influent for the macrophytic ponds. In the first period, 5 May to 14 July 1980, pond 3 and 4 were used both planted with the mixture of LEMNA MINOR and LEMNA GIBBA. Water entering pond 3 at one side and leaving it at the other, flowed (by gravity) to the inflow of pond 4 for a second treatment. Biomass was about 800 g FW/m2 in both duckweed ponds at the start of the experiments. On 15 July LEMNA MINOR and LEMNA GIBBA were removed from pond 3. Pond 1, 2, and 3 were planted with EICHHORNIA CRASSIPES and pond 4 was the only pond containing duckweed. During this second period, 15 July to 13 October, water flowed subsequently through pond 1, 2, 3 (waterhyacinth), and 4 (duckweed). On 14 October all waterhyacinths were removed and pond 3 was planted with duckweeds again, until 9 December, when it started to freeze. EICHHORNIA CRASSIPES needs high irradiance and water temperature, and was therefore only used during the summer months.
It is difficult to give a simple summary of the results, due to the changes in plant species in the ponds, the changing number of ponds in operation and the changing loading and chemical composition of the influent. The harvested biomass, however, gives some insight. Fifty percent of the biomass was harvested weekly to anticipate nutrient limitation.

Table 27. Biomass data on duckweeds (LEMNA MINOR and LEMNA GIBBA) cultivated for 218 days in ponds with pretreated pig manure in Northern Italy, from 5 May to 9 December, 1980. All variables on dry weight basis (Corradi et al., 1981).

Biomass production rate:	
average	16.82 g/m2/d
min.	4.71 g/m2/d
max.	35.71 g/m2/d
Harvested biomass:	
average	6.88 g/m2/d
min.	0.76 g/m2/d
max.	20.23 g/m2/d
total (*)	1500 g/m2/y
Reproduction rate:	
average	0.10 g/g/d
min.	0.02 g/g/d
max.	0.24 g/g/d
N:	
average content	4.7 %
N-yield	0.323 g/m2/d
N-yield (*)	70.5 g/m2/year
P:	
average content	1.1 %
P-yield	0.076 g/m2/d
P-yield (*)	16.5 g/m2/y

* A year assumed to consist of 218 days.

EICHHORNIA CRASSIPES was grown in May and June in metal tanks with heated water of 20 to 27 degrees C. The biomass production of this plant after being planted in pond 1, 2, and 3, is given in Table 28. The biomass production in basin 1 was low, due to the high loading of wastewater (Table 29). It proved necessary to change regularly the plants in basin 1 for those from basin 2 and 3.

Table 28. Waterhyacinth (EICHHORNIA CRASSIPES) grown in three successive ponds with pretreated pig manure in Northern Italy from 15 July until 13 October, 1980 (Copelli et al., 1981).

	Biomass (g DW/m2)		Production (g DW/m2/d		Total production in 91 d. g/m2/91 d
	mean	(range)	mean	(range)	
Basin 1	188	(145-230)	7.0	(2.5-26.1)	637
Basin 2	369	(274-369)	25.3	(6.4-63.5)	2302
Basin 3	328	(236-420)	28.4	(8.2-52.2)	2584
Whole system	292	-	19.8	-	1802

Table 29. Purification of pretreated pig manure by harvesting EICHHORNIA CRASSIPES in three successive ponds in Northern Italy, from 15 July to 13 October, 1980 (Copelli et al., 1981).

Total-N	Input (mg N/m2/d)	Removed by harvesting (mg N/m2/d)
Basin 1	7800	260
Basin 2	5900	1480
Basin 3	2400	1100
Total system		
15 July - 15 Sept.	2800	940
15 July - 13 Oct.	2500	840
Total-P	**Input (mg P/m2/d)**	**Removed by harvesting (mg P/m2/d)**
Basin 1	1250	50
Basin 2	1090	280
Basin 3	530	290
Total system:		
15 July - 15 Sept.	430	210
15 July - 13 Oct.	390	190

Not only by harvesting biomass, but also by sedimentation large quantities of P and N were removed from the water (Table 30). No data on nitrification and denitrification were given .

Table 30. Sedimentation in three successive ponds planted with Waterhyacinth (EICHHORNIA CRASSIPES) in Northern Italy (Copelli et al., 1981).

Sedimentation	Basin 1	Basin 2	Basin 3
Total sedimentation (g/m2/d)	8 - 15	6 - 15	4 - 10
Tot-N in sediment (mg/m2/d)	256 -480	114 -285	40 -100
Tot-N in sed.per 91 d. (g/m2)	23.3-43.7	10.4-25.9	3.6-9.1
Tot-P in sediment (mg/m2/d)	184 -345	84 -210	36 - 90
Tot-P in sed.per 91 d. (g/m2)	16.7-31.4	7.6-19.1	3.3-8.2

Thus, culturing ofduckweeds and waterhyacinth is possible on pretreated pig manure; harvesting part of the biomass every week removes considerable amounts of nitrogen and phosphorus. If LEMNA MINOR and LEMNA GIBBA are grown in spring and fall and EICHHORNIA CRASSIPES only in summer even better results are reached (Ghetti et

al., 1981).
An annual harvestable production of 2700 g DW/m2 can be reached, when using duckweeds from April to 15 July, followed by waterhyacinth until october, compared to 1500 g/m2 for duckweeds only, and 1900 g/m2 for waterhyacinth only.

4.4. Natural marshes

The use of natural marshes for wastewater treatment has been investigated by several authors (Sloey et al., 1978; Spangler et al. 1976; Tilton and Kadlec, 1979; Schmitz et al., 1982).

A considerable decrease in BOD was found in a natural marsh in Spring Creek, Calumet County, Wisconsin (Spangler, et al., 1976). During summer and fall 67 % P-removal was found, possibly by precipitation and uptake by the marsh vegetation. In spring, however, large quantities of P left the marsh with the effluent.

A freshwater wetland southwest of Houghton Lake, Michigan (USA) was used for tertiairy treatment of wastewater (Tilton and Kadlec, 1979). The area, which received wastewater was mainly occupied by CAREX spp. and SALIx spp.. A pilot study was carried out. Volumes, varying between 33,840 m3 (summer, 1976) and 23,520 m3 (summer, 1977) of unchlorinated secondary effluent were pumped on 6.5 ha of the wetland with a total area of 710 ha. The water level varied between 5 and 10 cm in wet summers, and 90 cm below the soil surface in dry summers. The contact with groundwater was negligible because of the impermeable nature of the organic soil. The nutrient loading was moderate; purification of N and P was good (Table 31).

Table 31. Tertiairy treatment of wastewater in a natural freshwater wetland from 25 May to 26 September 1976 (Tilton and Kadlec, 1979). Average values for the season. The output values were not corrected for background levels of nutrients. Mass balance for purification within one hectare.

Nutrient	Conc.			Mass		
	input (g/l)	output (g/l)	Removal (%)	input (g/m2)	output (g/m2)	Removal (%)
(NO3 + NO2)-N	0.36	0.01	99	1.6	0.01	99
NH4-N	0.08	0.03	63	0.3	0.07	77
tot.diss-P	0.41	0.11	73	1.7	0.09	95

The total plant biomass was not significantly higher after the treatment period, but the morpholocical dimensions of TYPHA LATIFOLIA changed. The N-content was the same, but the P-content had doubled. In 1977 the discharges occurred on another area than in 1976; although the effluent had higher nutrient levels, the nutrient removal rates were similar to those in 1976. However, an area of two ha was used in 1977, in contrast with one ha in 1976. Denitrification alone was sufficient to account for the total N-removal. Nevertheless, of this N micro-organisms and macrophytes must have absorbed nitrate also.

Ammonium-ions were probably removed partly by uptake by the plants and algae and partly by exchange for cations. Part of the latter was used by micro-organisms for nitrification after initial adsorption to the peat soil . P was largely removed by adsorption to the soil, but higher P-contents of the plants indicate that P was also partly assimilated by the plants. No nutrient balance was calculated, since the nutrient input by wastewater discharge was small compared with the nutrients already present in the system.

In Belgium a natural marsh near Cussigny was used for wastewater purification for more than 30 years (Schmitz et al., 1982). Raw domestic sewage and wastewater with high iron and zinc concentrations of a galvanic production process were treated in this case. Loadings of the whole area of four ha were 150 to 300 l/s (324 to 648 l/m2/d), the retention time being only 13 to 22 h. The influent contained 20-100 mg BOD/l. The marsh effluent, however, contained only 2 mg BOD/l and the nitrate concentration had decreased with 99 % compared to that of the influent. The effluent had a quality similar to that of drinking water, except for the rather high metal concentrations.

Although natural marshes are sometimes used for the purpose of wastewater purification for many years, it may be risky to continue this or to start new projects. Natural marshes can handle some nutrient overloading, but changes are to be expected in the species composition of flora and wildlife in general (Sloey et al., 1978). Overestimation of the "self-purifying" capacity of surface waters and the resulting problems, lead to the suggestion, that one might better use artificial wetlands and marshes for wastewater purification. Artificial marshes, especially those without contact with ground water, can better be controlled and do not disturb nature.

4.5. Small commercial treatment systems

4.5.1. Solar Aquacell

In the City of Hercules, California, a Solar Aquacell AWT Lagoon system was built in which EICHHORNIA CRASSIPES, duckweeds and micro-organisms were used for the purification of wastewater (Serfling and Mendola, 1979). This project was started in 1979 with a capacity of 1,330 m3/day, a total capacity of 7,600 m3/day being planned on 2.0 to 3.2 ha or 4.05 ha including buildings, facilities etc. The final effluent was calculated to require a retention time of six to seven days to be of tertiairy quality. Since in 1979 the project was still in the building phase, no results have been goiven so far.

4.5.2. Purification ponds and ditches

In The Netherlands a wastewater plant using macrophytes was started in 1967 by the Federal Commission for the IJsselmaarpolders (RIJP) to treat the sewage of a campsite. In two years time the scale was doubled and the system has been used ever since (Kok, 1974; Kok and De Jong, 1975; De Jong 1976; De Jong et al., 1977; Greiner and De Jong, 1982). The first experimental pond (field 1) had an area of one ha and an irregular shape. Since maintenance was difficult, the total area was enlarged to 1.75 ha (field 2) shaped as ditches of three m width. The water depth of field 1 was meant to be 0.4 m, but infiltration into the soil made it 0.2 m. The soil consists of calcareous clay to a depth of 1.0 m. Although the plant was not meant to be experimental, yet some investigations were carried out during

the first years of operation. Of the twelve ditches in total some were planted with SCHOENOPLECTUS LACUSTRIS, others with PHRAGMITES AUSTRALIS, with artificial plastic plants or left bare.
The experimental data on field 1, planted with S.LACUSTRIS, were collected in 1969. The influent was composed by sewage (after presettling in a separate ditch), and lake water as diluent to maintain a desired water level (Kok, 1974; De Jong et al., 1977). The water course was 600 m, and the retention time 10 d. Attention was paid particularly to the hydrology of the system. The composition of the water coming into the system is given in Table 32.

Table 32. Composition of the influent of a bulrush pond (field 1) used for wastewater purification, being a mixture of sewage, lake-water and rain, each having different nutrient concentrations (Kok, 1974).

Water	BOD (mg/l)	COD (mg/l)	N (mg/l)	P (mg/l)	Susp. solids (mg/l)
Sewage	200-400	400-1000	20-160	6-115	205 (1)
Lake	10- 25	40- 80	2	0.3	-
Rain	< 5	-	-	-	-

(1) Mean value given, the range being 65 - 400 mg/l; the effluent contained 1 - 94 mg/l, av. 9.8 mg/l

The infiltration decreased from 20 mm to 7 mm/d in, respectively, 1967 and 1973- 1974. In 1969 it was 9 mm/d (= 9 l/m2/d), whereas the evapotranspiration of water and plants together was 5 mm/d. The average precipitation (rain) during the summer of 1969 was less than 3 mm/d (Table 33). Purification was calculated after analyzing the mixture of presettled sewage and lake water (influent), and the effluent for BOD, COD, Kjeldahl-N, total-P, suspended solids and bacteriological quality, of which the latter and COD are not given here (Tables 34a, 34b, 34c).

Table 33. Hydrological parameters of a bulrush pond with a surface area of one ha in 1969 (average values in l/m2/d, calculated after Kok, 1974). Influent = sewage + lake water + rain. In Table 32 the conc. of BOD, COD, N and P of the influent are given. Effluent = total influent - evapotranspiration - infiltration (the infiltration constant being 9 l/m2/d).

Week no.	Sewage (l/m2/d)	Lake water (l/m2/d)	Rain (l/m2/d)	Total infl. (l/m2/d)	Evapo-transp. (l/m2/d)	Effluent (l/m2/d)
26	5.4	14.3	1.1	20.8	2.4	9.4
27	11.4	8.6	3.1	23.1	2.6	11.5
28	16.3	-	1.9	18.2	4.6	4.6
29	16.3	-	-	16.3	7.4	-0.1
30	24.3	-	-	24.3	8.3	7.0
31	16.9	-	1.9	18.8	7.4	2.4
32	8.9	-	1.3	10.2	11.3	-10.1
33	6.6	2.1	1.0	9.7	3.4	-2.7
34	6.0	-	12.7	18.7	2.4	7.3
35	4.7	-	6.9	11.6	4.4	-1.8
av.	11.7	2.5	3.0	17.2	5.4	2.8

Table 34a. The fate of BOD in a bulrush pond (field 1) in 1969 (De Jong et al., 1977).

Week no.	BOD				
	Influent (mg/l)	Effluent (mg/l)	Removal (%) (1)	Influent (g/m2/d)	Effluent (g/m2/d) (2)
26	285	12	95.8	5.7 (3)	0.113
27	329	6	98.2	6.6	0.069
28	331	8	97.6	5.4	0.037
29	167	7	95.8	2.7	--- (4)
30	347	18	94.8	8.4	0.126
31	399	19	95.2	6.7	0.046
32	276	17	93.8	2.5	--- (4)
33	234	7	97.0	2.1	--- (4)
34	127	7	94.5	0.8	0.051
35	76	5	93.4	0.4	--- (4)
av.	257	11	95.6	4.1 (5)	

(1) Removal = (conc.effl./conc.infl.) x 100 %.
(2) The effluent of a certain week corresponds with the influent of that same week (total infl. of Table 33).
(3) BOD in g/m2/d = conc. BOD (g/l) x (sewage + lake water) (l/m2/d).
(4) No values, effluent being negative (Table 33).
(5) 4.1 g/m2/d = 2870 kg/ha/season, a season being 10 weeks = 70 days; according to Kok (1974): 2536 kg/ha.

Table 34b. The fate of Kjeldahl-N in a bulrush pond in 1969 (De Jong et al., 1977.

Week no.	KJELDAHL - N				
	Influent (mg/l)	Effluent (mg/l)	Removal (%)	Influent (g/m2/d)	Effluent (g/m2/d)
26	100	14	86.0	2.1	0.132
27	120	18	85.0	2.8	0.207
28	120	25	79.2	2.2	0.115
29	124	34	72.6	2.0	---- (1)
30	120	67	44.2	2.9	0.469
31	158	75	52.5	3.0	0.180
32	98	55	43.9	1.0	---- (1)
33	82	41	50.0	0.8	---- (1)
34	41	24	41.5	0.8	0.175
35	23	14	39.1	0.3	---- (1)
av.	99	37	59.4	2.0	

(1) No values, effluent being negative (Table 33).

Table 34c. The fate of total-P in a bulrush pond during 1969 (De Jong et al., 1977).

Week no.	Total-P				
	Influent (mg/l)	Effluent (mg/l)	Removal (%)	Influent (g/m2/d)	Effluent (g/m2/d)
26	18	3	83.3	374	28
27	19	4	78.9	439	46
28	18	6	66.7	328	28
29	16	7	56.3	261	----(1)
30	23	14	39.1	559	98
31	23	18	21.7	432	43
32	17	16	5.9	173	----(1)
33	15	14	6.7	146	----(1)
34	9	10	-11.1 (2)	168	73
35	6	6	0.0	70	----(1)
mean	16	10	34.8	295	

(1) No values, effluent being negative (Table 33).
(2) Negative, probably, since P is washed out.

Field 2, created in 1970, is composed by twelve ditches each with a length of 375 m and a width of 3m. These ditches are easy to maintain and enable the execution of several parallel experiments. Although several ditches were planted on purpose with bulrush or reed, others which were intended to stay bare, became occupied by algae and submerged macrophytes in the course of summer. Table 35 reflects the performance of these ditches.

Table 35. Chemical composition of water in purification ditches (field 2) planted with bulrush, reed or unplanted, with a residence time of approximately 17 days, measured on July 13 1971 (De Jong, et al. 1977).

Ditch	Distance from inlet (m)	Kj-N (mg/l)	NO3-N (mg/l)	NH4-N (mg/l)	Tot.-P (mg/l)	COD (mg/l)
Bulrush	0	130	0.0	105	19	500
	75	100	0.0	90	16	243
	150	26	0.0	22	6	86
	250	2	0.0	0	0.44	80
	effluent	3	0.0	0	0.24	67
Reed	0	130	0.0	105	19	500
	75	114	0.0	100	17	424
	150	53	0.0	43	9.50	188
	250	12	0.0	4	1.90	133
	effluent	1	0.0	0	0.14	60
Unplanted	0	130	0.0	105	19	500
	75	40	0.1	23	5.2	305
	150	29	0.0	14	3.3	281
	250	11	0.0	3	0.9	153
	effluent	2	0.0	0	0.15	83

A comparison was made between groundwater samples and samples taken from filters under the ditches (Table 36). In this way it was proven, that there occurred hardly any nutrient enrichment of the soil below the pond.

Table 36. Comparison of groundwater samples and samples taken under the purification ditches (De Jong, et al., 1977).

Sample	NH4-N (mg/l)	Kjeldahl-N (mg/l)	NO3-N (mg/l)	Total-P (mg/l)	Ortho-P (mg/l)
Ditch					
Min.	0.2	2.7	0.0	0.28	0.01
Max.	4.9	9.9	0.1	1.03	0.20
Control					
Min.	0.3	0.7	0.00	0.27	0.00
Max.	5.1	6.9	0.04	1.78	0.15

4.5.3. Infiltration fields

The same Dutch organization as used the pond and ditch system, the Federal Commission for the IJsselmeerpolders (RIJP), has built another wastewater purification plant with freshwater macrophytes (Greiner and De Jong, 1982). This plant differs from the older one in having a water infiltration system as essential part of the purification process, in contrast to the earlier used aboveground water-flow system. In the Lauwerszee-area (in the NW of The Netherlands, near the Waddensea) wastewater produced by recreational activities is treated by four infiltration fields, after presettling in a presettling/distribution ditch. The latter has a clay bottom and its walls are made of adobe; this combination differs greatly from the bottom of the infiltration fields (Table 37).

Table 37. Soil properties of infiltration fields used for wastewater purification in the Lauwerszee-area (Greiner and De Jong, 1982).

Parameter		
Particle size	($m \times 10^{-6}$)	105-150
Lutum content	(% DW)	1.3
Humic substances	(% DW)	0.1
Iron conc.	(mg/g DW)	2.9
Alumina conc.	(mg/g DW)	2.7
Calcium conc.	(mg/g DW)	11.5
P-conc.	(mg/g DW)	0.12
Permeability	(m/24 h)	2 - 3

A hydraulic load of 20 to 30 mm/24 h was aimed, equalling 200 to 300 m3/ha/d or approximately 2,000 to 3,000 i.e./ha. The area used for infiltration exists of four fields with a total area of 1.3 ha or 2.1 ha, including the area needed for maintenance, influent and effluent facilities. The fields are drained with drainage pipes every 15 m, 0.55 m below the soil and planted with P. AUSTRALIS. P. AUSTRALIS was chosen for its better endurance of dry periods and provision of a better permeability compared to S. LACUSTRIS. The effluent of the system is only partly discharged on surface water, the remaining part being used for dilution of the influent. Every three to four days one of the four infiltration fields is irrigated, leaving a dry period of ten to eleven days afterwards. The periodical loading of the fields causes temporary drying up and aeration of the soil, being important for denitrification and P-immobilization. The main purification processes are: adsorption and desorption, chemical precipitation and solubilization, and (micro)biological decomposition and conversion. In Table 38 a survey is given of the performance of the plant over the period 1976 to 1980.

Table 38. Purification by infiltration fields planted with P. AUSTRALIS in the Lauwerszee area, The Netherlands. Average values of 9 samples, each a mixture of 4 drain pipes (Greiner and De Jong, 1982).

NH4-N		1976	1977	1978	1979	1980
Influent	(mg/l)	18.5	62.2	65	65	65
Effluent	(mg/l)	4.6	5.7	5.2	7	5.6
Removal	(%)	75	91	92	89	91
Kjeldahl-N		**1976**	**1977**	**1978**	**1979**	**1980**
Influent	(mg/l)	32.2	77.4	94.7	84.2	94
Effluent	(mg/l)	6.9	7.7	6.8	8.2	10.4
Removal	(%)	79	90	93	90	89
BOD		**1976**	**1977**	**1978**	**1979**	**1980**
Influent	(mg/l)	91	183	230	238	317
Effluent	(mg/l)	4.8	3.5	5.9	7	7
Removal	(%)	95	98	97	97	98
Total-P		**1976**	**1977**	**1978**	**1979**	**1980**
Influent	(mg/l)	5.5	14.8	17.8	17.8	20.7
Effluent	(mg/l)	2.3	4.7	3.7	4.5	5.1
Removal	(%)	56	68	80	75	75

The nutrient removal was excellent, but the effluent often had low oxygen levels of (5mg/l. The hydrology was studied in the summer of 1977. Seepage into the soil below the infiltration fields has been calculated by stopping the discharge of drainage water. The seepage was 3 to 3.5 l/m2/d and the evapotranspiration 4.5 l/m2/d, together equalling 60 % of the influent. Almost no nutrient enrichment of the groundwater was found, except for a higher concentration of Kjeldahl-N. In 1979/80 an extra drainage system was built, since infiltration rates decreased, resulting in an infiltration rate of 2 to 3 m/d as found in 1976.

To get more insight into the purification mechanisms several recalculations were made in this study (Table 39). An influent of 20 to 30 mm/d equals 20 to 30 l/m2; in the calculations of Table 25 l/m2/d will be further used. The total amount of effluent can be calculated:

$$\text{effluent} = \text{influent} - \text{evapotranspiration} - \text{seepage}$$

$$= 25 - 4.5 - 3.5 = 17 \text{ l/m2/d} \qquad (4.17)$$

Table 39. Calculation of the purification capacity of infiltration fields using assumed values for nutrient concentrations of influent and effluent and for hydrology, after results of Greiner and De Jong (Table 38 and (4.17)).

Nutrient	Influent		Effluent		Removal	
	conc. (mg/l)	load (g/m2/d)	conc. (mg/l)	load (g/m2/d)	conc. (%)	in (g/m2/d)
BOD	250	6.25	6	0.10	98	6.15
NH4-N	65	1.63	6	0.10	91	1.53
Kj.-N	90	2.25	8	0.14	91	2.11
tot. P	18	0.45	4.5	0.08	75	0.37

4.5.4. Wurzelraum Verfahren

In the eastern part of Western-Germany a wastewater treatment plant with emergent macrophytes is operating since 1974. The area was originally used for the purification of mining water and thus a wetland vegetation developed. At the end of the mining period, 1962, far less water was being let in, causing deterioration of the wetland. By using the area for sewage purification purposes, conditions favourable for wetlands were re-established. The active part of the system is the so-called 'Wurzelraum Verfahren' (root horizon process), consisting of a soil matrix with aerobic compartments near the roots of the macrophytes and anaerobic regions at other sites (Kickut, 1975, 1976, 1980a, 1980b; Osman, 1981; Kurpas, 1980). The sewage of 3,000 inhabitants of the village Othfresen is purified on a rather small area, being 5,400 m2 planted for years with P. AUSTRALIS. The total treatment area is 22.5 ha with a storage capacity for 265,000 m3 water. A 5 to 7 m thick clay layer, one m below the soil surface, separates the waterbody hydrologically from the surrounding area. The vegetation is predominated by P. AUSTRALIS. The influent is distributed by two dividing ditches, length 60 m and width 0.8 m, situated at the highest part of the purification area. Here occurs the presettling of bigger particles. Subsequently, the sewage is discharged on top of the soil. The solids accumulated on the soil surface, are rapidly penetrated by the macrophytic roots, providing a good infiltration capacity. The water flows aboveground, is infiltrated on an area of about 1,800 m2 and it is subsequently percolating through the root horizon by gravity. Both, soil surface and clay layer slope slightly towards the Innerste river. The hydrology is determined by precipitation (700 mm/y), evapotranspiration (up to 1800 mm/y in the reed stand) and sewage influent and effluent. The soil in the contaminated area is composed by clay (60%), some is silt and only a small part is sand (Osman, 1981). Ironoxide content of the soil is high, being 5 to 11 % (Kickut, 1980b). A vegetation of emergent macrophytes may affect the permeability of the soil considerably in the zone between 0.10 and 0.70 m below the surface, resulting in a permeability (Kf) of approximately 10 exp(-3) m/s, independent of the original permeability (Kickut, 1980a). The soil permeability and the slope of the clay layer determine the waterflow in vertical and horizontal direction along the relatively impermeable clay layer (Kf < 10 exp(-6) m/s).
At known permeability of the soil toplayer and loading of sewage per

m2, the area required for infiltration is easy to calculate. In the present case, the Kf(top) was 1.9 x 10exp(-6) m/s, and sewage loading 50 l/m2 for a total area of 5,400 m2. This resulted in a maximum loading of 1.9 x 10exp(-6) m/sec (= 0.16416 m/d = 164 l/m2/d). The actual loading was 50 l/m2/d. Thus only a small part of the total area was required, being (50/164) x 5,400 m2 or 1646 m2. Actually, only 1800 m2 water was required for the infiltration (Osman, 1981).

The flow rate of the water in horizontal direction can easily be calculated using an average permeability coefficient and the slope of the impermeable clay layer. For a several years old P. AUSTRALIS stand with a high permeability coefficient (Kf = 8.5 x 10 exp(-3) m/s between 10 to 70 cm depth) and a slope of 10 % -conditions which can been found in Othfresen- this flow rate is:

$$v_{hor} = Kf \times \sin(9^{o}) = 1.33 \times 10^{-3} \text{ m/s}$$

At a distance of 60 m from the inlet no further purification occurred, resulting in a residence time of 12.5 h for the Othfresen wastewater treatment system. The nitrogen kynetics in the Othfresen wastewater treatment system were studied (Osman, 1981). Removal of N and P behaved as a first order reaction:

$$C_t = C_0 \cdot e^{-K.t} \qquad (4.18)$$

in which C = conc. at t=0 and t=t
t = time (h)
K = reaction constant

For the nitrogen removal an area of only 3,350 m2 was required (60 m width and 62.5 m length, minus the 400 m2, which do not receive sewage); all N-involving processes occurred in the upper 0.10 m of the soil. This indicates a 335 m3 reaction volume with a porosity of 50 %, and residence volume of 168 m3. Daily loading of 300 m3 sewage requires thus an average residence time of about twelve h (exactly 13.44 h). The N-conc. in the most contaminated area near the infiltration site was 2.7 %, being only 0.0768 % around the treatment plant. With equation (4.18) the reaction constant K can be calculated for control soil and a residence time of 13.44 h, as follows:

$$0.0768 \% = 2.7 \% \cdot e^{-K \times 13.44}$$

K is then 3.5598/13.44 = 0.265 (Osman's graphical solution gave K=0.256). With this K-value the N-conc. can be calculated at each time and site along the 62.5 m long underground water-trajectory. Calculating the average N-conc. of the contaminated area (which means after 13.44/ 2 h or at a distance of 31 m from the inlet) Osman determined (by graphical solution) an average N-conc. of 0.48 % N of the soil, being close to 0.45 %, as calculated from equation (4.18) with the 0.265 K-value and residence time of t = 13.44/2 h. The N-conc. of the soil increased over a period of four years with 0.403 % (= 0.48 to 0.0768), due to its use for sewage treatment.

To get insight in the contamination of the area, used for sewage treatment in Othfresen, the fate of N was determined (Osman, 1981). The total weight of the soil contaminated by N was 502.5 t (335 m3 x 1.5), containing 0.403 % N; thus 2.025 t N is soil-bound. The total sewage loading in four years was 317,759 m3, with an average N-conc. of 80.37 mg/l, resulting in a N-loading of 25.54 t for the whole area. The average N-conc. of the effluent was 3.97 mg/l, accounting for 1.262 t nitrogen, in case the effluent would contain all infiltrated sewage water without any removal.

In influent (4 years)		25.54 t N
In effluent	1.262 t	
Bound to the soil	2.025 t	
	3.287 t	3.287 t N
N eliminated in other ways		22.25 t N
		(87.13 % of the influent)

Thus the main part of the N in the sewage did not contaminate the soil in Othfresen. Since the thick clay-layer prohibits seepage, most N is removed by other means, like volatilization of NH3 and denitrification. In contrast to N, P is largely bound to the soil, or washed out with the effluent. Besides the removal of N and P, large quantities of BOD were removed (95 to 99 % of the BOD in the influent); therefore the Othfresen system is a proper method the treat wastewater (Table 40).

Table 40. Wastewater purification in the Othfresen plant based on 'Wurzelraum Verfahren', with a sewage loading of 50 l/m2 (Kurpas, 1980).

Nutrient	Influent (mg/l)	Effluent (mg/l)	Removal (%)
BOD	400-550	7 - 17	95.8 - 98.7
tot.-N	75-115	3 - 14	81.3 - 97.4
tot-P	16-22	0.08 - 1.1	93.1 - 99.6

4.5.5. Comparison of three small commercial treatment systems

Comparing the data of the purification ditches with the aboveground water-flow (Table 34a,b,c), with those of the infiltration fields (Table 39), and with those of the Othfresen plant (Table 40), it becomes evident that the BOD-removal in all systems is high; on the other hand, the Kjeldahl-N- and P-removal are better in the infiltration fields than in the purification ditches, but N and P-removal are best in the Othfresen plant, even with heavier loading (Table 41).

Table 41. Comparison of wastewater treatment by purification ditches, infiltration fields and the Othfresen plant (see also Tables 34a,b,c, 39 and 40).

Nutrient	Purification ditches		Infiltration fields		Othfresen plant	
	Loading (g/m2)	Removal (%)	Loading (g/m2)	Removal (%)	Loading (g/m2)	Removal (%)
BOD	4.1	96	6.25	98	20-27.5	96-99
Kj.-N	2.0	59	2.25	91	3.8-5.8	81-97
tot-P	0.295	35	0.45	75	0.8-1.1	93-99

5. CALCULATIONS

5.1. Purpose

In order to give fairly detailed information on wastewater purification in general, all processes involved in the sewage treatment in the Othfresen plant are desribed, the system being considered as representative. All processes are calculated on basis of one m3 soil, although in reality total purification requires a 12 h trajectory of the sewage through a root horizon with a length of 90 m.

5.2. Oxygen surplus

Four different estimates are presented for the production of oxygen and its availability in the rhizosphere of P. AUSTRALIS.

1.Estimate for Othfresen, occupied by a P. AUSTRALIS vegetation (Werkblatt Wurzelraumverfahren Othfresen, cf. H.J. Grommelt):

Parameters		Minimum	Maximum
Shoot biomass	(g DW/m2)	600	1500
Net. assimilation	(g CO2/m2/h)	18	45
Net. assimilation	(g CO2/m2/d)	43.2	108
Net. assimilation	(g O2/m2/d)	31	78.5
Underground biomass	(g DW/m2)	500	2500
Oxygen consumption	(g O2/m2/d)	5.1	18
Surplus oxygen (1)	(g O2/m2/d)	0	29

(1) Not used by the underground plant parts

2.Estimate of the oxygen production of a well-growing crop from literature. The values for aboveground production refer to C3-plants with a closed canopy (J. Goudriaan, pers. comm., 1983), whereas those for the underground oxygen consumption come from tundragrasses (Shaver and Billings, 1975):

Parameters		Average	Maximum
Shoot biomass	(g DW/m2)	-	-
Net. assimilation	(g CO2/m2/d)	30	43
Net. assimilation	(g O2/m2/d)	21.8	31.3
Underground biomass	(g DW/m2)	-	-
Oxygen consumption	(g O2/m2/d)	2.6 (1)	-
Surplus oxygen	(g O2/m2/d)	19.2	28.7

(1) 120 to 190 mg CO2/m2/h, here is used for the calculation
150 mg CO2/m2/h = 3.6 g CO2/m2/d = 2.6 g O2/m2/d

3.Estimate of the oxygen production using data derived from the calculation model for photosynthesis of reed (Ondok, 1978), whereas those for the underground oxygen consumption come from tundragrasses (Shaver and Billings, 1975):

Parameters		September	June (1)
Shoot biomass	(g DW/m2)	-	-
Net. assimilation	(g CO_2/m2/d)	24.2	37.6
Net. assimilation	(g O_2/m2/d)	17.6	27.4
Underground biomass	(g DW/m2)	-	-
Oxygen consumption	(g O_2/m2/d)	2.6 (2)	2.6 (2)
Surplus oxygen	(g O_2/m2/d)	15.0	24.8

(1) Values for June are calculated, using an average CO_2-uptake of a C3 crop in The Netherlands on 15 Sept. of 499 kg CO_2/ha/d and on 15 June of 776 kg CO_2/ha/d, resulting in a conversion factor of 776/499 = 1.6

(2) 120 to 190 mg CO_2/m2/h; here is used for the calculation 150 mg CO_2/m2/h = 3.6 g CO_2/m2/d = 2.6 g O_2/m2/d

4.Estimate based on the Radial Oxygen Loss (see section 2.4.6.). Since there are no data available on the ROL of reed, the calculations are carried out with a value in the range of those on JUNCUS EFFUSUS (ROL = 71 ng/cm2/min, root apex) and waterlogged rice cv NORIN37 (183 ng/cm2/min). Assuming a ROL for reed of about 100 ng/cm2/min, a light period of 12 h and an active root surface of 400,000 cm2/m2 soil area, the ROL for a reed stand would be:

$$ROL = 400{,}000 \times 100 \times 60 \times 12 \text{ ng/m2/d} = \underline{28.8 \text{ g } O_2/m2}$$

Several remarks have to be made on the mentioned estimates. In the estimates one to three the oxygen production was rather high compared to data of other authors; moreover, not all oxygen produced is transported to the underground plant parts, since part of it is lost to the air. For the fourth estimate ROL-data of the top cm of a root are used, which are certainly not representative for the whole root. It is difficult to determine the total surface area of reed roots per m3, since it depends on factors as soil type and water availability. However, although oxygen loss by reed roots is hard to estimate, it is feasible that roots of waterlogged reed plants transport more oxygen to the underground parts than the amount needed for respiration.
Taking the four estimates and the critical remarks referring to them into consideration, it is still feasible that the required extra 28 g O_2/m2/d is available for the oxidation processes in the soil.

5.3. Hydrology and loading

The water input in the Othfresen plant is determined by rain and the influent of sewage. An average rainfall of 700 mm/y equals about 2 l/m2/d, and the influent fluctuates around 50 l/m2. The output is composed by evapotranspiration (soil + vegetation), being 4 to 5 l/m2 (similar to 5.01 to 7.57 kg H_2O/m2/d for reed under eutrophic conditions, found by Rychnovska, 1978), and an average effluent of 46 l/m2/d.

> For the following calculations it will be assumed, that per m2 50 l/d sewage is purified, representing about half an i.e., or 27 g BOD, 5 g N and 1.75 g P.

5.4. Processes

The (bio)chemical processes involved in the purification process are described in terms of chemical equations and in terms of nutrient budgets. This gives an overall view of this type of wastewater purification, although it does not account for the time dependency of the processes involved.

Aerobic decomposition of organic matter by bacteria can be described by:

$$(-CH_2O)_n + n\,O_2 \longrightarrow n\,CO_2 + n\,H_2O \qquad (5.1)$$

(org.matter)

Decomposition of organic nitrogen does not require oxygen (see also (2.10)):

$$\text{org.-N} \longrightarrow NH_3 + \ldots\ldots \qquad (5.2)$$

Nitrification, actually a two step process (see (2.7) and (2.8)), involves:

$$NH_3 + 2\,O_2 \longrightarrow NO_3^- + H_2O + H^+ \qquad (5.3)$$

Denitrification (see (2.4):

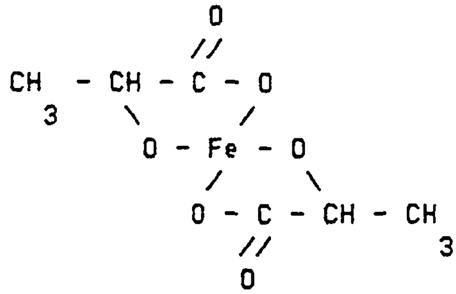
$$5\,(-CH_2O)_n + 6n\,NO_3^- + 6n\,H^+ \longrightarrow 5n\,CO_2 + 8n\,H_2O + 3n\,N_2 \qquad (5.4)$$

In the absence of oxygen a variety of organic acids is formed (see also (2.5):

$$(-CH_2O) \longrightarrow CH_3.CH_2.COOH + CH_3.COOH + H.COOH +$$

$$+ \; 2\,CH_3.CHOH.COOH \;\; \text{(lactic acid)} \qquad (5.5)$$

These organic acids, like lactic acid, enhance the solubility of metals. In the Othfresen plant this concerns mainly iron, which can be transported in this way to aerobic sites in the soil matrix:

$$2\ CH_3CHOH.COOH\ +\ Fe^{2+}\ \text{------>}$$  (5.6)

In the presence of oxygen the Fe2+-organic-acid-complex, which is unstable, decomposes, followed by oxidation of Fe2+ to Fe3+:

$$4\ Fe^{2+}\ +\ O_2\ +\ 4\ H^{+}\ \text{------->}\ 4\ Fe^{3+}\ +\ 2\ H_2O \qquad (5.7)$$

These Fe3+-ions can precipitate phosphate easily, forming a rather stable compound:

$$Fe^{3+}\ +\ PO_4^{3-}\ +\ 2\ H_2O\ \text{----->}\ FePO_4.2\ H_2O\ \text{(strengite)} \qquad (5.8)$$

In the absence of oxygen lactate is fermented, for instance by reduction of sulphate in strongly reducing soil layers (Cappenberg, 1975):

$$SO_4^{2-}\ +\ 2\ CH_3.CHOH.COOH\ \text{------>}\ H_2S\ +\ 2\ CH_3.COOH\ +\ 2\ CO_2\ +\ 2\ OH^{-} \qquad (5.9)$$

The thus formed acetic acid may generate methane in the absence of oxygen, in conditions even more reducing than (5.9). The growth of the methanobacteria, involved in this methane production is inhibited by sulfide-ions, so (5.9) and (5.10) will not occur simultaneously (Cappenberg, 1975):

$$CH_3.COOH\ \text{------>}\ CO_2\ +\ CH_4 \qquad \text{(Methanobacterium)} \qquad (5.10)$$

Organic matter, like glucose, can also be decomposed to acetic acid, consuming less oxygen than aerobic decomposition (5.1). This process occurs actually in the Othfresen plant (Kickut, 1980a):

$$C_6H_{12}O_6\ +\ 2\ O_2\ \text{----->}\ 3\ CH_3.COOH \qquad (5.11)$$

5.5. Nitrogen budget

The N in the influent is mainly in the form of organic- and NH3-N. All organic-N will be decomposed to NH3 (see (5.2)). N in the effluent consists of nitrate and nitrite, which is formed by nitrification. Reed normally prefers NH4-N, but here the uptake of N by reed is supposed to be in the form of nitrate. However, a large part of the N of the influent will be incorporated in living or dead biomass, like micro-organisms, which is not taken into account in the N budget (except the N in the reed plants). It is to be expected that the decomposition of this biomass releases an amount of N equal to that incorporated in the biomass in that year. In this case the biomass acts as temporary storage of N, and the overall effect on the N-budget is zero.

INPUT (1):		
Influent (2)	= 5.000	g N/m2/d
N-fixation from the atmosphere by micro-organisms of a rice field 72 kg/ha/y	= 0.020	g N/m2/d
total	= 5.020	g N/m2/d
OUTPUT:		
Effluent (2)	= 0.400	g N/m2/d
NH4-fixation to the soil (3)	= 0.048	g N/m2/d
Volatilization of NH3 (4)	= 0.500	g N/m2/d
Incorporated in the harvestable part of the reed (5)	= 0.055	g N/m2/d
total	= 1.003	g N/m2/d
Fraction disappeared by denitrification ...	= 4.017	g N/m2/d
	(or 4.878 g NH3/m2/d)	

(1) Rain accounts for 20 mg NH3-N/m2/y and 3 mg (NO3 + NO2)-N/m2/y, giving a total extra N-supply of 23 mg N/m2/y or 0.063 mg/m2/d. Being small, this input is neglected here.
(2) Measured.
(3) An increase of 0.057 mg NH4/g soil/4 y = 0.0143 mg NH4/g soil/y = 0.059 g NH4/m2/d was measured (Osman, 1981).
(4) 10 % of the influent-N (Lance, 1972).
(5) Biomass-N is 200 kg/ha/y (De Jong, 1976); in the Othfresen plant no reed plants are harvested.

About 80 % of the N in the influent will be removed by denitrification. Nitrification is needed for all N in the effluent, N-uptake by the reed, and N, removed by denitrification afterwards; thus 4.472 g N/m2/d (or 5.430 g NH3/m2/d) is to be nitrified:

1	mol	NH3	+	2	mol	O2	---->	1	mol	NO_3^-		
17	g	NH3	+	64	g	O2	---->	62	g	NO_3^-		
5.43	g	NH3	+	20.44	g	O2	---->	19.80	g	NO3		
4.47	g	NH3-N	+	20.44	g	O2	---->	4.47	g	NO3-N		(5.12)

For nitrification 20.44 g O2/m2/d is needed and of the thus-formed 19.80 g NO3/m2/d, 17.79 g NO3/m2/d (=(4.878/5.430)x 19.80 g NO3/m2/d) will be denitrified, concomitant with oxidation of a considerable amount of organic matter:

$$1 \text{ mol } NO_3^- + 5/6 \text{ mol } (-CH_2O) \longrightarrow 1/2 \text{ mol } N_2 \quad \text{(see (5.4))}$$
$$62 \text{ g } NO_3^- + 25 \text{ g } (-CH_2O) \longrightarrow 14 \text{ g } N_2$$
$$17.79 \text{ g } NO_3 + 7.17 \text{ g } (-CH_2O) \longrightarrow 4.02 \text{ g } N_2$$
$$4.02 \text{ g } NO_3\text{-}N + 7.17 \text{ g } (-CH_2O) \longrightarrow 4.02 \text{ g } N_2 \quad (5.13)$$

For the denitrification of every g NO_3-N, 1.78 g organic matter is used. This leads to a BOD-reduction of 1.78 g BOD/g NO_3-N (see (5.13) and (5.1)). For the Othfresen project originally a BOD-reduction of 1.85 g BOD/g NO_3-N was calculated (Osman, 1981).

5.6. Phosphorus budget

The P-input in the soil matrix occurs merely with the influent. P can only be bound to the soil, or incorporated into biomass.

INPUT:			
Influent 16-22 mg/l (1)	=	1.000	g P/m2/d
OUTPUT:			
Effluent 0.2 mg P/l (2)	=	0.010	g P/m2/d
Incorporated in harvestable part of the reed (3)	=	0.011	g P/m2/d
Stored in soil matrix (mainly bound to Fe-III-ions forming strengite)	=	0.979	g P/m2/d
		(or 3.00 g PO4/m2/d)	

(1) The influent of the Othfresen plant is relatively poor in P, (Kurpas, 1980); sewage contains usually 1.50 to 1.75 g P per 50 l.
(2) The P-conc. in the effluent varies from 0.08 to 1.1 mg P/l (Kurpas, 1980).
(3) Biomass-P is 40 kg P/ha/y (De Jong, 1976).

If all P would be bound to Fe-III-irons, this would use the following oxygen quantity oxygen (see (5.7) and (5.8)):

$$1 \text{ mol } PO_4^- + 1 \text{ mol Fe-II-ions} + 1/4 \text{ mol } O_2 \longrightarrow 1 \text{ mol Fe-III-}PO_4$$
$$95 \text{ g } PO_4^- + 56 \text{ g Fe-II-ions} + 8 \text{ g } O_2 \longrightarrow 151 \text{ g Fe-III-}PO_4$$
$$3.00 \text{ g } PO_4 + 1.77 \text{ g Fe-II-ions} + 0.25 \text{ g } O_2 \longrightarrow 4.77 \text{ g Fe-III-}PO_4 \quad (5.14)$$

The soil in Othfresen contains up to 11 % ironoxide (Fe_2O_3) or 7.7 % Fe. Every m3 soil weighs 1,500 kg (see 4.5.4.) and contains 2,062 mol Fe (1,500,000 g x 0.077)/56. Therefore at the highest 2,062 mol PO_4 can be bound in 1 m3 soil or 66 kg P. With a daily load of 1 to 1.75 g P/m2 phosphate can be bound for 100 to 180 years.

5.7. BOD removal

The loading of 50 l sewage in Othfresen represents about 0.5 i.e. or 27 g BOD. The amount of BOD in the effluent can be measured and the BOD-reduction due to denitrification is also known (5.13). Small part of the organic matter (and thus of the BOD) will be decomposed during sulfate reduction under strictly anaerobic conditions. The actual amount of the latter process is not known.

INPUT:			
Influent	=	27	g BOD/m2/d
OUTPUT:			
Effluent (1)	=	0.55	g BOD/m2/d
Decomposed during denitrification (2)....	=	7.17	g BOD/m2/d
total	=	7.72	g BOD/m2/d
Remaining for decomposition under aerobic (5.1) or anaerobic (5.5), (5.9) and (5.10) conditions or according to (5.11)	=	19.28	g BOD/m2/d

(1) An average of 12 mg BOD/l/d is taken.
(2) See (5.12).

5.8. Oxygen budget

The oxygen input is estimated as 28 g O_2/m2/d; this amount is expected to be transported to the soil by the aerenchymatous tissue of P. AUSTRALIS. It is assumed that there occurs no other O_2 input. Oxygen is needed for several processes. Which process will occur depends on several conditions and the succession is not necessarily the same as given below. This will be discussed later.

INPUT:			
Influent	=	0	g O2/m2/d
By PHRAGMITES AUSTRALIS	=	28	g O2/m2/d
OUTPUT:			
Nitrification (1)	=	20.44	g O2/m2/d
Effluent (2)	=	0.23	g O2/m2/d
Oxidation of Fe-II (see (5.14))	=	0.25	g O2/m2/d
total	=	20.92	g O2/m2/d
Oxygen remaining for aerobic decomposition of BOD	=	7.08	g O2/m2/d

(1) At the highest; lower values occur, if NH_3 is nitrified to NO_2, the latter being transported to an anaerobic spot, where it can be denitrified directly. In this case an extra 5.11 g O2/m2/d would not be required for the nitrification of NO_2 to NO_3, thus it can then be used for other oxidations.
(2) Measured (Kickut, 1980a).

The quantity of 7.08 g O2/m2/d is not sufficient for aerobic decomposition of all organic matter (19.28 g BOD/m2/d); the latter will partly be decomposed otherwise as stated above (section 5.7.).

5.9. Succession of the processes

A prediction of the order in which the described processes occur can be made, taking into account the chemical properties of sewage and treatment plant. In case the soil is contaminated by sewage, usually organic matter will be oxidized by oxygen reduction at first. When oxygen is depleted, nitrate will serve furtheron as electron acceptor, oxidizing the organic matter. Sulphate-reduction and methane-production start, when conditions are even more reducing. If, on the other hand all organic matter is oxidized, different oxidation-products will be generated like ethanol, methane, sulfide and NH4-nitrogen (in the given order). All processes mentioned are biologically mediated (Stumm and Morgan, 1981).

In the Othfresen project aerobic decomposition of the organic matter is to be expected as long as oxygen is available, whereas nitrification occurs only, when all organic matter is decomposed. In this way NH4-N would not be oxidized completely at first and the rest of the available oxygen will be used for aerobic decomposition of organic matter, as is supposed in section 5.7. and 5.8. A smooth biochemical explanation can not be given for a complete oxidation of all NH4-N to NO3-N. However, hardly any NH4-N has been found in the Othfresen effluent. The explanation may be, that a certain small amount of sewage passes through different conditions, in which sometimes oxygen is available in the presence of organic matter (giving rise to aerobic decomposition), and on other moments, at another site, in the presence of NH4-N (giving rise to nitrification).

6. DISCUSSION AND CONCLUSIONS

The use of macrophytes in wastewater purification gives usually better results than is to be expected from harvesting as means to remove N and P. Macrophytes play an important role in the removal of biodegradable organic matter (or BOD), but the organic matter is not actually decomposed by the plants themselves. Macrophytes act as substrate for micro-organisms and change the chemical conditions in water and soil. Usually, nutrient uptake by the plants removes only small amounts of N and P.

For the purification of N and P representing 1 i.e., only 7 to 18 m2 are required in case of the use of the fastgrowing EICHHORNIA CRASSIPES under optimum conditions; all other species give worse results. The removal of N and P in wastewater ponds planted with free-floating macrophytes depends on pond area and the amount of wastewater entering the pond. Equations describing the relationship between N- and P-removal percentages and the surface area required for a certain influent-flow, under laboratory conditions, give little information on purification mechanisms, and are only valid under exactly similar (experimental) conditions. However, it was experimentally demonstrated, that P was limiting, when E. CRASSIPES was used for the final treatment of secondary effluent. The N- and P-absorption by E. CRASSIPES were correlated with the N- and P-conc. in the water, the highest P accumulation occurring at a concentration of 26.1 mg P/l and 36 mg N/l.

Duckweeds, like LEMNA MINOR grew well on secondary treated wastewater, decreasing the N- and P- concentrations considerably within ten days. SPIRODELA OLIGORHIZA was used to treat wastewater of a swine lagoon. N- and P-removal rates of 168 kg N/ha/month and 56 kg P/ha/month were reached (or 84 g N/m2/y and 28 g P/m2/y, with a growth season of five months). A curvilinear relationship was found between P-conc. in water (static secondary effluent) and duckweed tissue (a mixture of LEMNA MINOR and L. GIBBA). The highest P-conc. in duckweed tissue was reported as 9.7 mg P/g DW, at a P-conc. in water of 2.1 g ortho-P/l water. SPIRODELA POLYRHIZA behaved similarly. However, still higher nutrient conc. were reported for LEMNA indicating a maximum of 17 mg P/g DW at a P-conc. up to 30 mg P/l water, and 60 mg N/g DW at a N-conc. up to 40 mg N/l water.

By calculating N- and P-budgets for the performance of floating macrophytes as wastewater treatment agent, it became clear that far more N and P are removed from the wastewater than the quantities in the harvestable plant biomass. This may indicate that the main part of the N is removed by denitrification under the thick layers of duckweeds, whereas P has been precipitated.

Also emergent plants were used for wastewater treatment experiments, their impact varying greatly with species, soil and flow conditions. For TYPHA LATIFOLIA, growing on nutrient solution, a maximum biomass of 8,231 g DW/m2 was reached, containing 156.2 g N/m2 and 37.5 g P/m2. Harvesting the aboveground biomass would remove 565 kg N/ha and 112 kg P/ha.

In using SCIRPUS VALIDUS and TYPHA LATIFOLIA for treatment of raw sewage, Lakshman found exponential equations describing nutrient removal rates by the plant/gravel/bacteria system, depending on time and the nutrient quantity in the influent.

For P: Mefl1 = Mi exp(-0.18t + 0.663)

For N: Meffl = Mi exp(-0.125t + 0.372)

In which Meffl = the quantity of nutrient in effluent (g)
Mi = the quantity of nutrient in influent (g)
t = time (d)

A similar equation was derived for N-removal using P. AUSTRALIS in the Othfresen project by Osman. In both cases the nutrient removal rates are first order reactions; however, in the former case total amounts of nutrients in in- and effluent were used, whereas in the latter N-conc. was taken. Osmans system was far more efficient than that of Lakshman, the latter at first acting as nutrient source: for P at t < 3.68 days, and for N at t < 2.98 days.

The impact of P. AUSTRALIS, SCIRPUS VALIDUS and a mixture of TYPHA ORIENTALIS and TYPHA DOMINGENSIS together withrespect to the nutrient removal from sewage differed in the experimental system of Finlayson and Chick. Since in this particular case the water flowed through long trenches during purification, better nutrient exchange between soil and water was provided with the risk that the soil acted as P-source. Climatological circumstances favouring high evaporation affected their system also considerably.

The performance of different macrophytic groups in pilot plants was measured.

A combination of EICHHORNIA CRASSIPES and LEMNA MINOR/L. GIBBA was used in Northern Italy by Ghetti c.s.. In spring and autumn only duckweeds were involved in the purification process, whereas in summer E. CRASSIPES was compared with the duckweeds. The seasonal biomass production of duckweeds, of E. CRASSIPES and of a combined culture (duckweeds in spring and autumn and waterhyacinth in summer) was 1,500, 1,900 and 2,700 g/m2, respectively. In case duckweeds were allowed to continue growing the whole season, the N- and P-yields were 70.5 and 16.5 g/m2/218 d, respectively. Treatment in ponds with E. CRASSIPES removed considerable amounts of COD, NH4-N, and PO4-P. About 30 % of the N and 50 % of the P removed was estimated to be due to the direct activity of the macrophytes.

Removal of nutrients and BOD in Spangler's pilot plant with SCIRPUS VALIDUS was insignificant, although oxygen concentrations were higher in the latter case. Repeated harvesting enhanced the P-removal, resulting in a higher P-yield for S. VALIDUS (3.51-3.83 g P/m2) than for S. FLUVIATILIS (1.13 g P/m2). The fraction of total-P in the biomass compartment varied with season, being in June only 34 % and in September 54 %, whereas in December most P was washed out from the plant/water/soil system.

Seidel's ideas have been used to develop several small sewage plants. Especially BOD reduction was quite good.

In Viville, Belgium, a pilot plant is in operation already for several years. Several macrophytic species were used in succession, the basic principle being nutrient uptake by the macrophytes without any influence of the quartz substrate and without stimulating denitrification. Systems with macrophytes and an underground waterflow (percolation) had a better N-removal capacity than systems with an aboveground waterflow, or systems without macrophytes. Almost all N removed from the system was in the plant biomass. In contrast TYPHA LATIFOLIA performed worse with percolation than without, probably due to its possesion of aboveground roots. P-removal was not as efficient as that of N, the presence of the macrophytes not making a large difference. Total loadings were not very high in this pilot plant and it operated only during growth season.

For several years macrophytes have been used for sewage treatment on small commercial scale. In The Netherlands two types with reed are present. In one of them most degradation of organic matter and removal of N and P occurs in water flowing through long ditches. In the other one, the wastewater is infiltrated into the soil and percolates towards drainage pipes. The results of both systems are good, but the N- and P-removal in the infiltration fields are better. The Othfresen project of Kickut,in West Germany, performs even better. Here the sewage is infiltrated into the soil and forced to flow through the root horizon under a PHRAGMITETUM. The transport of oxygen from the air to the soil by the macrophytes generates aerobic and anaerobic gradients, providing suitable conditions for processes like nitrification and denitrification. In the Othfresen project higher loadings are possible, due to the longer course of the sewage in the system compared to other ones.

As example for mass balances for N, P, oxygen and BOD data of the Othfresen project were taken. Several assumptions had to be made because no data were available. The N in the influent was bound only to small extent to the soil; however, exact rates of nitrification, denitrification and volatilization of ammonia could not be made. More research is needed on this topic, as is for the rate of oxygen-transport into and through the soil. Also unknown is the rate of oxygen transport from air into the soil under these conditions. More accurate estimations have to be made to the extent of BOD-removal under aerobic and anaerobic conditions. The role of iron in immobilizing P in iron-oxide-P-complexes, the extent in which hydroxyl-apatite is formed and P is adsorbed to clay have to be studied.

Unique in the Othfresen concept and the infiltration fields is the way in which the sewage is infiltrated in a large soil body, where biodegradation occurs and P is bound in a more or less stable way. Risks of N and P wash-out are minimized by using a subsoil consisting of impermeable clay, although regular checks of the effluent are advisable.

In conclusion, using macrophytes for the purification of wastewater requires no high level of technology and is always cheaper than other treatment systems with comparable purification results. Therefore the macrophyte system is appropriate for the treatment of domestic sewage, which is not contaminated by chemical waste like pesticides, detergents, and heavy metals, in cases, when otherwise no purification would occur. Most of the systems can handle large fluctuations in loading, which are unsuitable for conventional sewage treatment systems.

7. SUMMARY

Aquatic macrophytes have been used for wastewater purification for more than fifteen years. The present literature study summarizes the complex role of the macrophytes in this type of wastewater purification. By harvesting the plants organic matter, N and P are withdrawn from the system. Macrophytic species with high growth rates, like EICHHORNIA CRASSIPES and PHRAGMITES AUSTRALIS produce substantial biomass under optimum conditions of 15,400 and 5,700 g DW/m2/y, respectively. In the case of the (sub)tropical free-floating, E. CRASSIPES, this biomass harvest represents 200 to 508 g N/m2/y and 88 to 123 g P/m2/y, while for P. AUSTRALIS it is 114 g N/m2/y and 11 g P/m2.

All studies on this type of wastewater treatment showed higher removal rates of N and P than expected, when biomass harvesting was the only nutrient removal mechanism. All processes involved in usual wastewater treatment systems occur also in this purification type. The main mechanisms of N-removal are volatilization of NH_3 to the air, nitrification to NO_3, and subsequent denitrification to N_2, while NH_4-fixation to the soil and incorporation of N in harvestable plant parts play a minor role. P-removal occurs mainly by precipitation in the water column or fixation to Fe-III-complexes in the soil matrix, whereas P-absorption by macrophytes contributes only slightly to this process.

Although nutrient uptake by the plants explains purification to a small extent only, their N- and P-absorption are widely investigated. It varies mainly with plant species, nutrient concentration in the water column and/or soil, depending on the root system and biomass of the plants.

Several pilot plants have been used to investigate N-, P-removal, and decrease in Biological Oxygen Demand (BOD), depending on frequency and timing of harvesting, loading and wastewater composition, dividing the treatment system into separate ponds - each planted with different species - water flow (above- as well as underground), and the use of two different plant species in succession.

Some authors suggest the use of natural marshes for wastewater purification, which have been exploited for this purpose in several countries for many years; others emphasize the risks of such a use.

In this review three systems for wastewater purification by aquatic macrophytes are compared, which are being used for several years in a temperate climate. Two systems are located in The Netherlands, and the third one in Western Germany. The first one in The Netherlands uses ponds and ditches, planted with P. AUSTRALIS or SCHOENOPLECTUS LACUSTRIS. The sewage from a campsite flows through the ponds and ditches, and substantial reduction in BOD, N and P occurs. The second Dutch system uses infiltration fields, planted with P. AUSTRALIS. The raw sewage infiltrates the soil after presettling of the large particles, and percolates towards drainage pipes placed at distances of 15 m. In the third, German, system sewage infiltrates the soil also to a depth of 1 m, where a clay layer of 5 to 7 m thickness inhibits seepage of sewage to the groundwater. Soil surface and clay layer slope slightly, resulting in a sewage flow through the root horizon of the P. AUSTRALIS plants.

The role of the macrophytes in the first system, with the aboveground waterflow, acting as attachment sites for micro-organisms, and causing a better precipitation of P by regulating the waterflow; harvesting the reed plants represents in the present case a notable amount N and P. In the second and third systems the reed plants facilitate infiltration of sewage, and provide alternating aerobic and

anaerobic micro-areas by transportof oxygen into the soil. In the more or less horizontally flowing sewage, both nitrification and, subsequently, denitrification occur within the root horizon. High iron concentrations in the soil form complexes with P in the sewage.

In all three systems, BOD-reduction is high (96 to 99 %). Kjeldahl-N removal is lowest (59 %) in the first system, with the aboveground water flow, while in the second and third it is 91 and 81 - 97 %, respectively. P-removal in the first, second and third systems are 35, 75, and 93 - 99 %, respectively. The third, German, treatment system evidently removes BOD, N and P most efficiently, even at higher loading than used in both other systems. The loadings were: 4.1, 6.25, and 20 - 27.5 g BOD/m2/d in the first, second and third system, respectively; 2.0, 2.25, and 3.75 - 5.75 g Kjeldahl-N/m2/d; 0.295, 0.45, 0.8 - 1.1 g P/m2/d.

8. SAMENVATTING

Hogere waterplanten worden al langer dan vijftien jaar gebruikt bij de zuivering van afvalwater. In deze literatuurstudie wordt aangetoond, dat de rol van deze planten bij een dergelijke zuivering complex is. Het oogsten van plantaardig materiaal onttrekt organische stoffen, N en P aan het water. Snelgroeiende planten, zoals EICHHORNIA CRASSIPES en PHRAGMITES AUSTRALIS, vormen onder optimale condities veel biomassa tot maxima van respectievelijk 15.400 en 5.700 g DW/m2/j. Wat betreft E. CRASSIPES, komt dit overeen met 200 tot 508 g N/m2/j en 88 tot 123 g P/m2/j, terwijl dit voor P. AUSTRALIS 114 g N/m2/j en 11 g P/m2/j oplevert.

Uit de literatuur over dit type afvalwaterzuivering blijkt, dat afname in N en P hoger is dan op grond van alleen oogsten verwacht mag worden. Alle processen van een conventionele afvalwaterzuiveringsinrichting treden ook in het onderhavige geval op. Bij verwijdering van N ontsnapt ammoniakgas naar de atmosfeer, en vinden nitrificatie tot NO_3 en denitrificatie tot N_2 plaats, terwijl NH_4-fixatie aan de bodem en opname van N door de planten slechts een ondergeschikte rol spelen. De verwijdering van P komt vooral tot stand door het neerslaan van fosfaat in de waterkolom of fixatie aan ijzer-III-complexen in de bodem; P-opname door planten levert hieraan slechts een geringe bijdrage.

Hoewel de opname van nutrienten door de plant slechts een klein deel van de zuivering verklaart, heeft er veel onderzoek plaatsgevonden over de opname van N en P. Deze opname is afhankelijk van de plantesoort, de nutrientconcentraties in water en/of bodem (afhankelijk van de beworteling) en van de plantebiomassa.

In verschillende proefvelden zijn de volgende aspecten van deze vorm van afvalwaterzuivering onderzocht: de verwijdering van N en P, de afname in BOD, de oogstfrekwentie en het tijdstip van oogsten, in relatie tot de belasting en samenstelling van het afvalwater, het opsplitsen in een zogenaamd meertrapssytseem -elk met een andere plantesoort-, de waterstroom (boven- of ondergronds), en het afwisselend gebruik van twee verschillende plantesoorten.

Sommige auteurs stellen voor om natuurlijke moerassen te gebruiken bij het zuiveren van afvalwater, terwijl anderen de risico's hiervan juist benadrukken.

In deze literatuurstudie worden drie systemen met elkaar vergeleken, die gebruik maken van waterplanten bij de zuivering van afvalwater. Elk zijn ze al een aantal jaren in een gematigd klimaat in gebruik. Twee systemen bevinden zich in Nederland en het derde in West-Duitsland. De eerste, in Nederland, bestaat uit vijvers en sloten, waarin P. AUSTRALIS en SCHOENOPLECTUS LACUSTRIS zijn aangeplant. Rioolwater, afkomstig van een camping, stroomt door de vijvers en sloten, waar een aanzienlijke verwijdering van BOD, N en P plaatsvindt. Het tweede Nederlandse systeem gebruikt infiltratievelden, en is, evenals het Duitse, beplant met P. AUSTRALIS. Na bezinking van de grotere deeltjes, infiltreert het ongezuiverde rioolwater de bodem, en stroomt vervolgens in min of meer horizontale richting (percolatie) naar drainagebuizen, die op een onderlinge afstand van 15 m zijn aangebracht. In het derde, Duitse, systeem infiltreert het rioolwater ook de bodem tot een diepte van 1 m, waar een 5 tot 7 m dikke kleilaag vermenging met grondwater voorkomt. Bodemoppervlak en kleilaag lopen enigszins af, waardoor het rioolwater door de wortellaag van de planten stroomt.

De waterplanten in het eerste systeem, met de bovengrondse waterstroom, functioneren als aanhechtingsplaatsen voor micro-organismen, en veroorzaken een betere neerslag van P door remming van de waterstroom; het oogsten van de rietplanten vertegenwoordigt in dit geval een aanzienlijke hoeveelheid N en P. In het tweede en derde systeem vergemakkelijken de rietplanten de infiltratie van het rioolwater en zorgen voor afwisselend aerobe en anaerobe zones door zuurstof naar de bodem te transporteren. In het min of meer horizontaal door de wortellaag stromende rioolwater vindt achtereenvolgens zowel nitrificatie als denitrificatie plaats. Hoge ijzerconcentraties in de bodem zorgen voor complexvorming met P in het rioolwater.

In alle drie systemen neemt de BOD sterk af, nl. voor 96 to 99 %. In het eerste systeem, met de bovengrondse waterstroom, wordt de Kjeldahl-N het minst verwijderd, nl. voor 59 %, terwijl dit in het tweede en derde systeem 91 en 81 - 97 % is. De P wordt in het eerste, tweede en derde systeem verwijderd voor respectievelijk 35, 75 en 93 - 99 %. Het derde, Duitse, systeem verwijdert BOD, N en P het meest efficient, zelfs bij een hogere belasting dan gebruikt in beide andere systemen. Deze belastingen waren in respectievelijk het eerste, tweede en derde systeem: 4.1, 6.25 en 20 - 27.5 g BOD/m2/d; 2.0, 2.25 en 3.75 - 5.75 g Kjeldahl-N/m2/d; 0.295, 0.45 en 0.8 - 1.1 g P/m2/d.

9. ACKNOWLEDGEMENTS

I would like to thank in particular Dr. E.P.H. Best for her valuable, detailed and stimulating suggestions, and reading of the English text. Dr.R.D. Gulati is acknowledged for his hospitality in his workgroup of the Limnological Institute. Further Dr.R.W. Greiner, Federal Commission of the IJsselmeerpolders, is thanked for showing the wastewater treatment ditches in Flevoland and Dr. H.J. Grommelt for providing information on the Othfresen project in West Germany.

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