Wat. Res. Vol. 22, No. 12, pp. 1503–1511, 1988
Printed in Great Britain.

0043-1354/88 $3.00 + 0.00

UPGRADING A FACULTATIVE POND BY IMPLANTING WATER HYACINTH

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(*First received February 1988; accepted in revised form August 1988*)

Abstract—Water hyacinth was implanted in one of two existing facultative ponds and both units were operated in parallel under comparable conditions. The ponds were fed with mainly domestic wastewater after pretreatment in anaerobic ponds and operated at a BOD_5-loading of about 48 kg (ha d)$^{-1}$ and a detention time of 12 days. This paper covers a period of 4 months, from the implantation of the water hyacinths until no further systematic change in the treatment efficiency of the water hyacinth pond was observed. The median effluent concentrations of the facultative pond for SS, COD, TKN and TP were 55, 95, 6.4 and 1.4 mg l^{-1}, respectively. The values for the water hyacinth pond were 12, 26, 2.5 and 0.4 mg l^{-1}, respectively. The average DO effluent concentration of the water hyacinth pond was 1.2 mg l^{-1}, but this still increased slightly as compared to the influent. The study demonstrates that the implantation of water hyacinth is an appropriate option for upgrading facultative ponds. In many cases where more stringent effluent standards are imposed the method may be a suitable alternative to technical treatment processes.

Key words—facultative pond, water hyacinth, SS, COD, nitrogen, phosphorus

INTRODUCTION

Oxidation ponds are a widely used wastewater treatment method, particularly for small communities and in hot climates. If the land area required is available at economical cost, oxidation ponds represent an attractive treatment technology option given their low construction and operating cost, and operational simplicity. A serious drawback associated with oxidation ponds, however, is the growth of algae induced by intense solar radiation. In hot climates, the solar radiation is sufficiently intense all year round to induce high algae concentrations in the effluent of aerobic and facultative ponds. This reduces treatment efficiency, particularly with respect to the suspended solids concentration, which is commonly between 40 and 100 mg l^{-1}. Whereas such values were accepted in the past as inherent to the process, increasingly stringent effluent standards now in many cases require the upgrading of pond effluents. Implanting water hyacinth appears to be an attractive alternative option to technical processes. Water hyacinths can improve the effluent quality of ponds at negligible additional cost and without sacrificing the operational simplicity of a pond system, which is one of its main advantages.

The concept of treating wastewater in water hyacinth ponds is receiving increased attention in warm climatic zones in various parts of the world. The efficiency of water hyacinth in wastewater treatment has been demonstrated by several studies (e.g. Dinges, 1978, 1979; McDonald and Wolverton, 1980; Wolverton and McDonald, 1979). A conceptual overview of aquatic treatment systems is presented by Stowell *et al.* (1981) while O'Brien (1981) and Middlebrooks *et al.* (1982) compile information on existing water hyacinth systems and develop initial design criteria. Much of the present research concentrates on the efficiency of water hyacinths for the removal of nutrients (Reddy and De Busk, 1985; Weber and Tchobanoglous, 1985) and of heavy metals (Muramoto and Oki, 1983, 1984; O'Keeffe *et al.*, 1984), as well as the re-use of the hyacinths for composting or methane gas production (Simeon *et al.*, 1984; Moorhead *et al.*, 1987). A systematic discussion of the potential use of water hyacinths for biomass production is presented by Reddy and Sutton (1984).

The objective of this study is to evaluate the possibility of upgrading existing ponds by implanting water hyacinths as the main biological treatment step. A similar objective underlies studies by Wolverton and McDonald (1979) and McDonald and Wolverton (1980). However, whereas the experiments in these studies were performed consecutively, the facilities used in the study described here allow the direct comparison of parallel systems under practically identical conditions. As the main parameters, chemical oxygen demand, suspended solids and nitrogen and phosphorus concentrations were recorded (Sapkota, 1987). This report covers a period of 4 months, beginning with the initial stocking of the water hyacinth pond and ending 2 weeks after the water hyacinth canopy covered the entire surface. No systematic change in the treatment efficiency of the water hyacinth pond was observed after this stage.

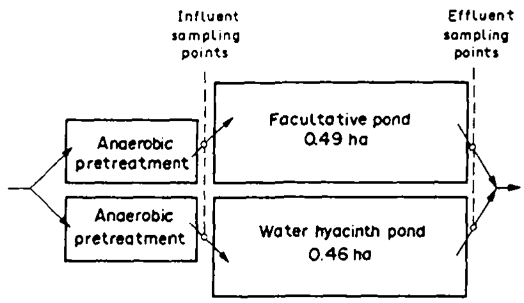

Fig. 1. Flow diagram of the experimental facilities.

Another important aspect in the assessment of wastewater treatment ponds is the destruction of pathogens or the possible spread of disease carriers, e.g. by mosquito breeding. Such health aspects were not part of the study period reported here. They are, however, included in a research program which is still in progress.

EXPERIMENTAL FACILITIES AND METHODS

Facilities

The experiments were performed at the treatment plant of the Asian Institute of Technology in Bangkok. The plant is designed in two parallel streets, each consisting of an anaerobic pond followed by a facultative pond (Fig. 1). The ponds have been in operation for 14 years and satisfy the regulations and specifications set for such ponds in Thailand. Maintenance is limited to the weekly grass cutting on the embankment and the removal of aquatic microphytes and other floating materials. Bottom sludge is removed from the anaerobic ponds every 5 years. No sludge has so far been removed from the facultative ponds.

The condition of anaerobic ponds, which are 2.4 m deep and provide a calculated detention time of 3.4 days, was not altered for the experiments, whereas one of the facultative ponds was stocked with water hyacinths. The second facultative pond was also left unmanipulated, to be used as a control unit. The flow rate in the facultative and water hyacinth pond was controlled by triangular weirs and adjusted so that both ponds received almost equal loading. Design and average operation data for the facultative pond and the water hyacinth pond during the experimental period are given in Table 1.

The wastewater source is the campus of the Asian Institute of Technology. The wastewater is primarily of domestic origin, with some inflow from chemical laboratories.

Climatic information

The experimental site is located at a latitude of about 14°04′ N in a tropical climate. The experimental period covered the end of the rainy season and the beginning of the dry season. Individual rainfall events show a high intensity, as indicated by the comparison between the monthly average and the daily maximum rainfall (Table 2). The rainfall, particularly in November and December, is caused by only a very few events. The values for solar radiation show only moderate variation over the experimental period. Most of the time, solar radiation intensity is sufficient to cause intensive algal growth. Temperature variations are moderate, with the temperature always within in a range conducive to water hyacinth growth. In the other seasons, temperature and solar radiation never fall much below the values presented here. Thus, both algae and water hyacinths enjoy suitable growth conditions throughout the year.

Table 1. Design and average operation data of facultative pond and water hyacinth pond

		Facultative pond	Water hyacinth pond
Surface area	ha	0.49	0.46
Depth	m	1.3	1.3
Volume	m^3	5600	5300
$L:W$ ratio	—	1:3	1:3
Flow rate	$m^3 d^{-1}$	480	460
Detention time	d	12	12
Hydr. loading rate	$m^3 (m^2 d)^{-1}$	0.10	0.10
Hydr. application rate	$m^3 (m^2 d)^{-1}$	9.8	10.3
COD-loading	kg (ha d)$^{-1}$	98	105
COD-influent	mg l^{-1}	100	105
BOD-loading	kg (ha d)$^{-1}$	48	48
BOD-influent	mg l^{-1}	49	48

Experimental program

Water hyacinths were implanted in one pond at the end of September, covering about 5% of the surface area. After 1 month, the plant canopy covered about 20% of the pond surface and the sampling program was resumed. Full coverage was reached in early January, after about 15 weeks. The sampling program was then continued for another 2 weeks. The parameters recorded were suspended solids (SS), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), total phosphorus (TP), dissolved oxygen (DO), temperature and pH-value. Grab samples were taken every third day for all parameters except temperature and pH-value. Temperature and pH-value showed only slight fluctuations and they were therefore controlled only occasionally. The samples were immediately analyzed in the Environmental Engineering laboratory of the Asian Institute of Technology. Unfiltered samples were used throughout the study. Additional data on filtered and unfiltered BOD and pH-value are available from the regular effluent monitoring program. Sampling for the monitoring program was performed twice a month using grab samples. The experimental program was accompanied by a study on the biometrics of water hyacinths. This program still continues and complete results will be reported elsewhere. However,

Table 2. Rainfall, temperature and solar radiation during the experimental period

	October	November	December	January
Rainfall				
Monthly average (mm month^{-1})	240.6	3.2	47.0	0
Daily maximum (mm d^{-1})	79.9	2.4	26.2	0
Daily minimum (mm d^{-1})	0.1	0.8	0.1	0
Daily solar radiation [MJ (m^{2}d)$^{-1}$]				
Average	17.3	18.4	17.0	18.1
Maximum	23.6	20.6	22.7	19.9
Minimum	11.4	14.3	11.8	11.2
Temperature (°C)				
Average	27.4	26.1	24.5	24.8
Maximum	32.2	31.1	30.9	32.3
Minimum	24.7	22.7	19.8	19.8

some data related to the growth of the water hyacinths are also reported in this paper.

Analytical methods

SS, BOD, COD (dichromate reflux m.), TKN (macro-Kjeldahl m., titration) and TP (stannous chloride m.) were analyzed according to standard methods (APHA *et al.*, 1981). Standard instruments were used for the measurement of DO, temperature and the pH-value. Wind influence meant that the water hyacinth canopy developed from one side of the pond in mats. This allowed satisfactorily accurate measurement of the growth of the water hyacinth canopy from the shore.

Statistical evaluation

The concentrations of SS, COD, TKN and TP fluctuated over a wide range. The normal distribution and the log-normal distribution were therefore tested for the description of parameter fluctuations. The log-normal distribution gave better results and is used here in the presentation of parameter fluctuations. Estimates for median value m and factor S are given to define the distribution functions. For example, concentration at the 84.13 percentile is given by the product $m\,S$.

RESULTS AND DISCUSSION

Plant growth

The initial water hyacinth stocking covered about 5% of the pond surface. The extension of the canopy increased at an exponential rate until about 70% of the pond surface was covered (Fig. 2). The extension of the canopy was then increasingly restricted by the pond boundaries. During this phase plant growth results in the densification of the canopy even as the rate of the areal expansion of the canopy slows down. During the initial phase of growth, the area covered by water hyacinth doubled about every 15 days. The density of water hyacinths at the end of the measurement period was 23 kg m^{-2} at the influent and 18 kg m^{-2} (wet wt) at the effluent with an average root length of 5 and 9 cm at influent and effluent, respectively. The decrease in density and increase in root length towards the effluent is explained by the decreasing nutrient concentration. The canopy eventually reached a height of 1 m.

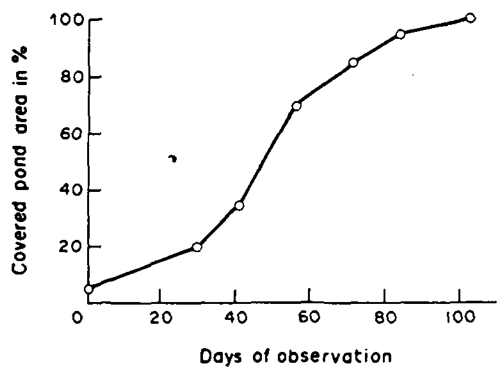

Fig. 2. Development of the water hyacinth canopy.

Effluent quality

Comparing the effluents of the facultative and water hyacinth ponds, the difference was visually very significant. The effluent of the facultative pond was slightly turbid and green, indicating high algae content. In contrast, the effluent of the water hyacinth pond was unexpectedly clear, distinguishable from tapwater only by the presence of some small flocks. The visual impression was confirmed by the effluent concentrations as shown in Table 3 and Fig. 3. The median SS concentration increased from 47 to 55 mg l^{-1} in the facultative pond, whereas in the water hyacinth pond it fell from 50 to 12 mg l^{-1}. COD-concentrations show a similar trend. The COD decreases only insignificantly in the facultative pond whereas the median concentration in the water hyacinth pond is reduced from 101 to 26 mg l^{-1}. The

Table 3. Summary of influent and effluent concentrations (median and S-factor based on a log-normal distribution)

	Facultative pond		Water hyacinth pond	
	Influent	Effluent	Influent	Effluent
SS (mg l^{-1})				
Median	47	55	50	12
S-factor	1.46	1.47	1.38	2.05
Range	20–84	22–134	30–90	5–40
COD (mg l^{-1})				
Median	97	95	101	26
S-factor	1.22	1.30	1.26	1.64
Range	63–133	65–209	65–162	14–53
TKN (mg l^{-1})				
Median	9.3	6.4	9.5	2.5
S-factor	1.49	1.57	1.50	1.97
Range	5.6–16.4	3.4–18.9	4.0–16.5	1.2–6.7
TP (mg l^{-1})				
Median	1.3	1.4	1.4	0.4
S-factor	1.59	1.44	1.40	1.75
Range	0.5–2.7	0.7–3.5	0.7–2.3	0.1–1.0
DO (mg l^{-1})				
Average	0.4	3.3	0.7	1.2
Range	0.1–1.4	1.2–6.2	0.2–2.5	0.3–2.1
pH-value				
Average	7.6	8.4	7.7	7.3
Range	7.4–7.9	8.1–8.9	7.4–8.2	7.0–7.7

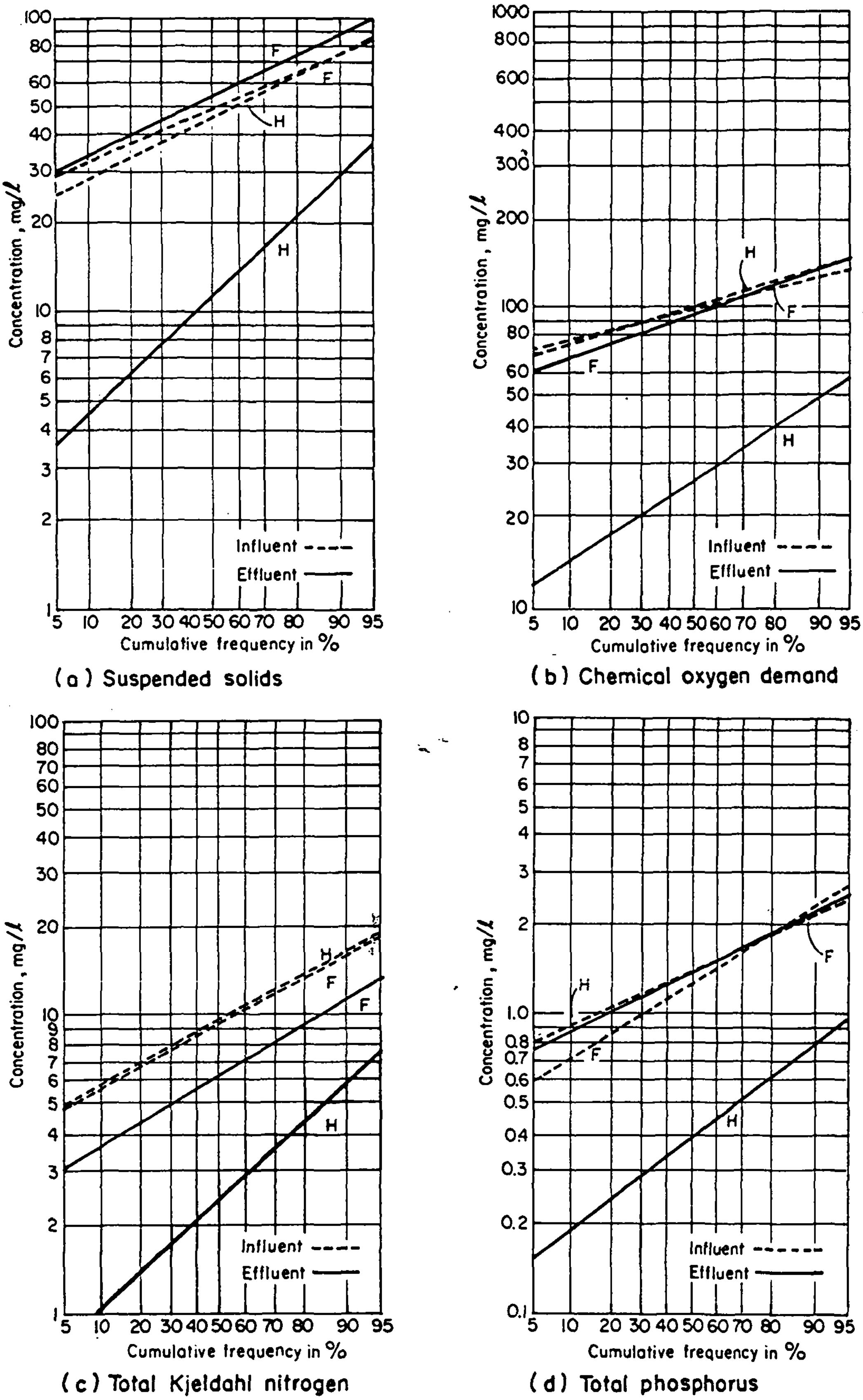

Fig. 3. Cumulative frequency of influent and effluent concentrations (F = facultative pond, H = water hyacinth pond).

inefficiency of the facultative pond with respect to COD removal does not correspond to the BOD_5 removal as recorded by the BOD_5 measurements of the regular monitoring program. The seven BOD_5 samples taken during the experimental period showed an average influent and effluent concentration of 47 and 19 mg l^{-1}, respectively for the facultative pond. The inefficiency of the facultative pond with respect to COD and the simultaneous decrease of BOD_5 will be the subject of further investigations.

TKN was reduced in both systems but at a considerably higher rate in the water hyacinth pond. The median concentration in the facultative and in the water hyacinth ponds fell from 9.3 to 6.4 mg l^{-1} and from 9.5 to 2.5 mg l^{-1}, respectively. No TP reduction occurred in the facultative pond whereas the median TP-concentration in the water hyacinth pond was reduced from 1.4 to 0.4 mg l^{-1}.

The pH-values for both systems show only moderate fluctuations and remained in an uncritical range throughout the experimental period. The pH-value increased slightly in the facultative pond and decreased in the water hyacinth pond. The DO-concentration increased in both ponds but at a much higher rate, of course, in the facultative pond. A maximum value of 6.2 mg l^{-1} was observed in the facultative pond, compared with 2.1 mg l^{-1} in the water hyacinth pond. Higher oxygen levels are frequently recommended as they allow the use of the mosquitofish (Gambusia) for mosquito control. However, the malaria-carrying mosquitos prevailing in the study area do not anyway find living conditions favorable in wastewater ponds (Herbert, 1985).

It can be concluded that the water hyacinth pond showed in all measured parameters a much higher effluent quality than the facultative pond, the only exception being DO-concentration. The improvement in SS-concentrations is particularly important, as common effluent standards for SS cannot usually be maintained in areas where algal growth is prolific. The significance of the improvement achieved is apparent from the frequency distribution in Fig. 3(a). An assumed effluent standard for suspended solids of 30 mg l^{-1} is expected to be maintained in the case of the water hyacinth pond for 90% of the time; in the case of the facultative pond the figure is only 6%.

The higher values for effluent concentrations of SS, COD, TKN and TP are caused by particular events, as indicated by a comparison of the median and the range of individual parameters. Exceptionally high values can all be traced back to pond disturbance due to maintenance work or the uncontrolled activities of nearby dwellers. These are not eliminated from the analysis since they reflect practical operational conditions.

The effluent quality described was achieved with a BOD_5-loading in the order of 50 kg (ha d)$^{-1}$ and a detention time of 12 days. The result is in agreement with earlier studies in the same area and for mixed domestic and industrial wastewater (Orth *et al.*, 1987). The values may thus be taken as preliminary design values for the area until more data are available. Hydraulic loading and application rates were 0.10 and 10.3 m^3 (m^2 d)$^{-1}$, respectively in this study, compared with 0.05 and 30 m^3 (m^2 d)$^{-1}$, respectively, in the previous study.

Removal efficiency

Table 4 shows removal efficiencies for the facultative and the water hyacinth ponds in terms of mass flux. The calculations are based on median concentrations and, since the flow rate fluctuates only insignificantly, on the average flow rate. The water loss was 22% in the facultative pond, 20% in the water hyacinth pond and losses were taken into account in calculating percentage removal. The improvement in removal efficiency resulting from water hyacinths implantation is clearly demonstrated in Table 4. The facultative pond in its present state is particularly ineffective in the removal of SS, COD and TP.

Data by Reddy and Sutton (1984) on the N- and P-concentrations in water hyacinths cultured in raw sewage may be used for a rough estimate of plant uptake; with an average plant density of 20 kg m^{-2} (wet wt) and with an assumed wet-to-dry weight ratio of 20, the biomass produced was in the order of 30 t (ha yr)$^{-1}$ (dry wt). With N- and P-concentrations of 37 and 9.4 g kg^{-1}, respectively, the estimated plant uptake rates are 1110 kg (ha yr)$^{-1}$ for N and 282 kg (ha yr)$^{-1}$ for P. A comparison with the removal rates in Table 4 shows that the increase of P-removal in the water hyacinth pond exceeds the estimated plant uptake by about 34%. P-uptake by water hyacinth alone can therefore not explain the increased efficiency of the water hyacinth pond. The same conclusion may be drawn in the case of N-removal, although the increase of N-removal in the water hyacinth pond is almost equal to the uptake by water hyacinth. Additional processes are required in the water hyacinth pond to compensate for N-removal processes in the facultative pond which do not occur or are reduced in the water hyacinth pond, e.g. N-uptake by algae.

The removal rates are presented on an annual basis for easy comparison, although the basic data cover only a period of 4 months after water hyacinth implantation. It should be mentioned that the actual rates for long-term operation may be different, depending largely on harvesting policy.

Table 4. Comparisons of removal of SS, COD, TKN and TP based on mass flux

	Facultative pond		Water hyacinth pond	
	kg (ha yr)$^{-1}$	%	kg (ha yr)$^{-1}$	%
SS	1533	9	14,762	81
COD	8304	24	29,308	80
TKN	1548	47	2741	79
TP	76	16	453	89

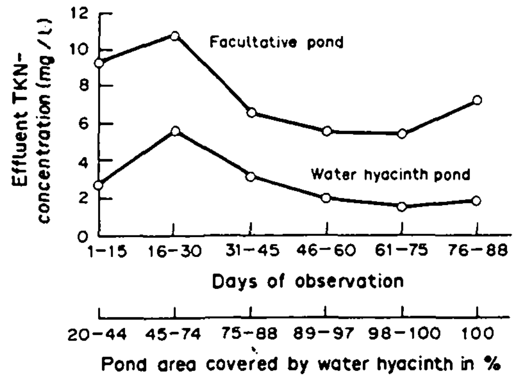

Fig. 4. Effluent TKN-concentration (15-day average).

Development of treatment efficiency

Measurements were resumed when the water hyacinth canopy covered about 20% of the pond surface. This allows an assessment of the treatment efficiency of the water hyacinth pond in relation to the extension of the canopy. However, this assessment encounters difficulties which become apparent when the TKN-concentrations (Fig. 4) and the suspended solids removal [Fig. 5(a)] of the facultative pond and the water hyacinth pond are compared. The curves for the facultative and water hyacinth ponds show a fairly parallel development, some correlation between influent concentrations and treatment efficiency being observed. Another possible factor is the weather; an increase of effluent concentrations was observed after some rainfall events. However, in both cases the correlations were not sufficiently systematic to explain the developments in treatment efficiencies. Apparently, the treatment efficiency is additionally influenced by some external, uncontrollable and time-variant factors. The influence of time-variant external factors confirms that, if possible, comparisons between facultative ponds and water hyacinth ponds should be based on simultaneous operation rather than on ante/post experiments in the same unit.

However, in spite of these difficulties, some conclusions seem possible. A first and rather unexpected result is that the removal efficiency of the water hyacinth pond was, as early as the first 2 weeks of the measurement, much higher than that of the facul-

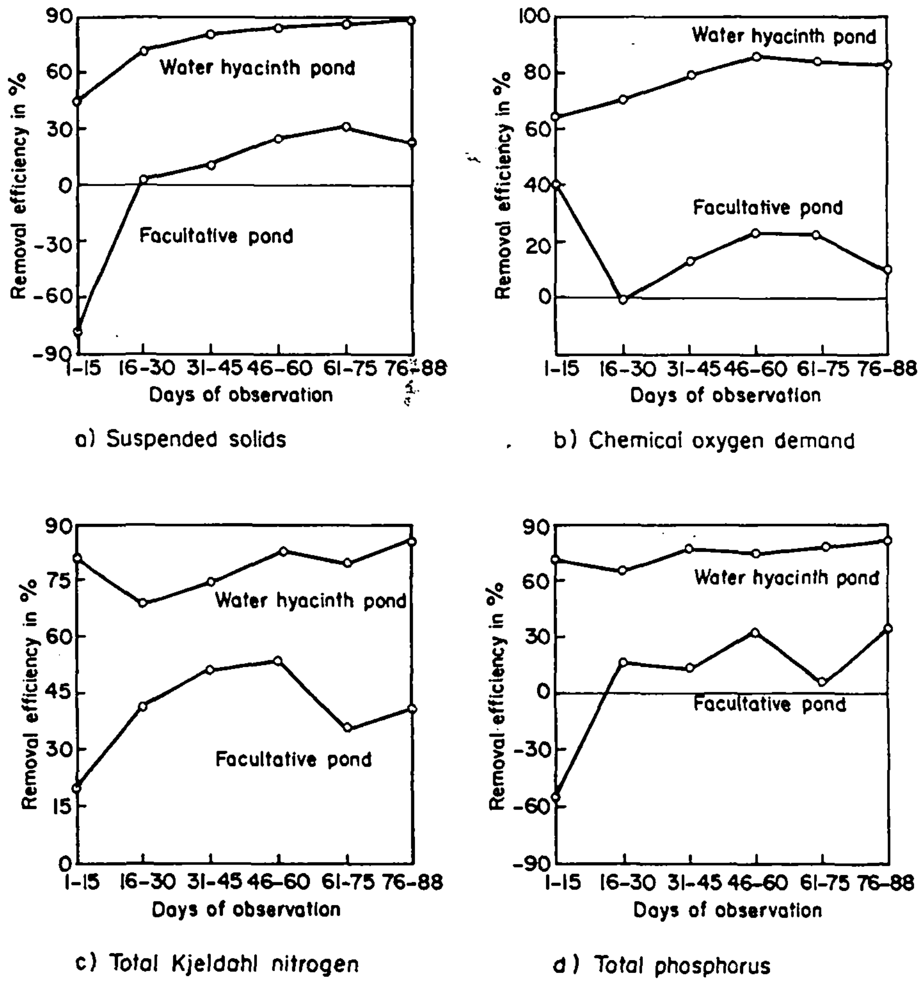

Fig. 5. Removal efficiencies based on mass flux (15-day average).

Table 5. Standard deviations of effluent concentrations for two experimental periods in mg l^{-1} (water hyacinth coverage below and above 80%)

	Facultative pond			Water hyacinth pond		
	Week 1–5	Week 6–13	Δ in%	Week 1–5	Week 6–13	Δ in%
Coverage %	—	—	—	20–80	80–100	—
SS	24	14	−42	12	4	−67
COD	39	26	−33	9	6	−33
TKN	4.8	2.0	−58	2.0	0.4	−80
TP	0.6	0.7	17	0.3	0.2	−33

tative pond. At this stage, the plant canopy covered only 20–30% of the pond surface. Removal efficiency increased from the beginning of the measurements until 100% plant coverage was reached, in the case of SS from about 45–85% and in the case of COD from about 65–85%. The removal efficiency for TKN and TP at 20–30% coverage was already about 80 and 70%, respectively, and increased only slightly for both parameters until 100% pond coverage.

The extension of the plant canopy shows a significant influence on the fluctuations of the effluent concentrations. The standard deviations of the effluent concentrations and the variations of COD-effluent concentrations are presented in Table 5 and Fig. 6, respectively, to demonstrate this effect. The standard deviations are presented separately for the first 5 weeks and the remaining experimental period. At the end of the first period the water hyacinths covered about 80% of the pond area. All standard deviations for the water hyacinth pond are considerably lower than those for the facultative pond. The standard deviations are lower in the second period compared to the first, but this effect appears for both the water hyacinth pond and the facultative pond, indicating again the influence of uncontrollable external factors. The percentage reduction from the first to the second period is nevertheless considerably higher for the water hyacinth pond, COD being the only exception.

Water loss, temperature

Average water losses of 22 and 20% from the facultative and the water hyacinth ponds, respectively, cannot be explained by evaporation/evapotranspiration only. The loss is much higher than the evaporation from an open water surface in the area. Seepage is the most likely explanation in spite of the length of operation of the ponds, which should make them more impervious. The pond surface is about 2.2 m above the receiving drain, as measured during the rainy season.

However, the interesting point is that the losses from the two ponds differ only insignificantly and that they are rather lower in the water hyacinth pond. This indicates that evapotranspiration in the water hyacinth pond is no higher than the evaporation from an open water surface. Water hyacinth evapotranspiration rates from different sources are summarized by Reddy and Sutton (1984), with reported evapotranspiration rates 3.2–6 times the evaporation rate. In contrast, Doorenbos and Pruitt (1984) report that the water loss from a water surface covered by aquatic weed is similar to the loss from an open water surface. Reported coefficients relating the

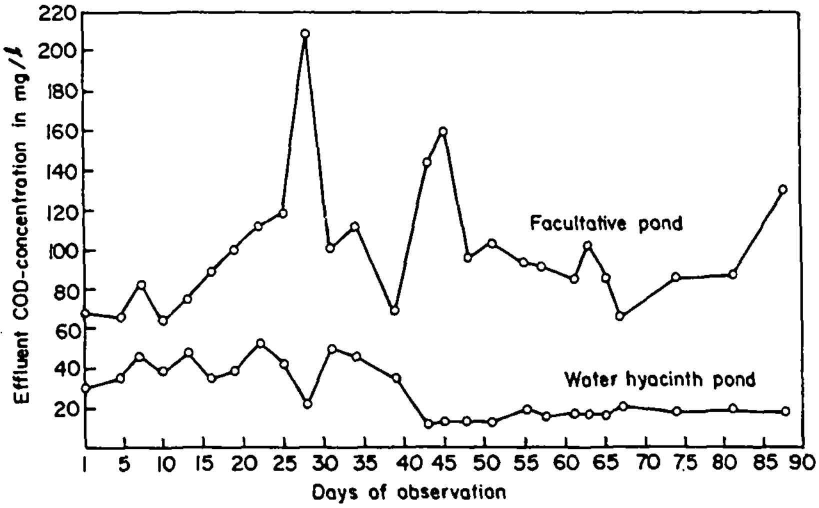

Fig. 6. Variation of effluent COD-concentrations.

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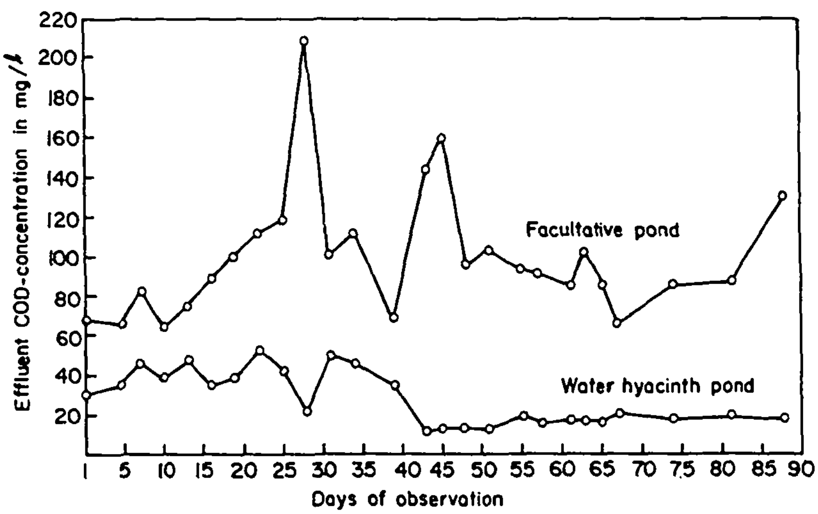

Fig. 6. Variation of effluent COD-concentrations.

evaporation/evapotranspiration to a common reference level, show the same values for water hyacinth as for open water. The results in this study are in accordance with the findings of Doorenbos and Pruitt (1984), who mention, as a possible explanation for the conflicting data found in the literature, small lysimeter and pan experiments which are not representative of natural conditions. The same opinion was expressed earlier by Idso (1979).

The inlet temperature to both ponds varied only slightly and was about 29°C, measured at noon. The temperature fell slightly to an average effluent temperature of 28°C at the facultative pond. The average effluent temperature at the water hyacinth pond was 24°C, showing a temperature loss of 5°C in the pond. All measured values were above 23°C and throughout the study remained within a range very conducive to water hyacinth growth.

CONCLUSIONS

The most critical effluent parameter for facultative ponds with respect to common effluent standards is the SS-concentration. The frequently required value of $30\,mg\,l^{-1}$, hardly ever achieved in areas with intense solar radiation, is expected to be maintained in water hyacinth ponds with high reliability. The median SS-concentrations of the effluent in the present study, were 55 and $12\,mg\,l^{-1}$ at the facultative and the water hyacinth ponds, respectively. At the same time, the water hyacinth pond was considerably more effective in the removal of COD, TKN, TP, with median effluent concentrations of 26, 2.5 and $0.4\,mg\,l^{-1}$, respectively. Fluctuations in effluent concentrations were, furthermore, considerably lower in the water hyacinth pond and lowest when the pond was completely covered by water hyacinths. The average DO-concentration in the water hyacinth pond effluent was $1.2\,mg\,l^{-1}$, with a slight increase towards the effluent.

The water hyacinth pond was operated at an average BOD-loading of $48\,kg\,(ha\,d)^{-1}$ with 12 days detention time. The pond was fed with mainly domestic wastewater after pretreatment in an anaerobic pond. These data may be used as preliminary design criteria for the study area until further data are available.

No indication was found that evapotranspiration from the water hyacinth pond exceeds the evaporation from the facultative pond, which contradicts several measurements reported in the literature. The result is however, in accordance with other studies carried out under natural conditions.

It was the objective of this study to demonstrate the possibility of upgrading facultative wastewater ponds by implanting water hyacinth. The study, operating a water hyacinth pond and a facultative control pond in parallel, fully confirmed the efficiency of this approach. Implanting water hyacinth will in many cases, particularly in developing countries, help to avoid the transition to technical treatment plants when more stringent effluent standards are imposed.

Acknowledgements—The data on rainfall and temperature were provided by J. Jensen, Division of Food and Agricultural Engineering, the data on solar radiation by the Division of Energy Technology, both sources at AIT. The root lengths were measured as part of a study on the biometrics of water hyacinth by D. Benden, AIT/University of Giessen, Germany.

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