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The development from kinetic coefficients of a predictive model for the growth of *Eichhornia crassipes* in the field. IV. Application of the model to the Vernon Hooper Dam — a eutrophied South African impoundment

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Keywords: *Eichhornia crassipes*, model application, harvesting, nutrient removal

ABSTRACT

A model developed for *Eichhornia crassipes* (Mart.) Solms was used to identify the limiting nutrient in the Vernon Hooper Dam and to predict population sizes, yields, growth rates and frequencies and amounts of harvest under varying conditions of nutrient loading and climate. Predicted data were used to evaluate the effectiveness of harvesting measures currently being employed for controlling both nutrient inputs and the population size in this impoundment. Predictions of the population size, before harvesting was initiated, generally compared favourably with that estimated visually. Predictions of the quantities of P that could be removed daily by a 20 ha population indicate that such a population in the impoundment could reduce P concentrations in the epilimnion during summer stratification to levels limiting for algae. This may explain the observed reduction in algal concentrations since the introduction of harvesting. Estimates of the amounts and frequencies of harvest required to contain the predicted potential yields of a 20 ha population indicate that 100 metric tonnes of fresh water hyacinths harvested daily from the impoundment, under present conditions of reduced nutrient loading, are adequate during winter, but not during summer.

INTRODUCTION

Harvesting *Eichhornia crassipes* (Mart.) Solms (water hyacinth) growing in eutrophied aquatic systems may constitute an effective means of removing nutrients and controlling excessive growth of plants (Boyd, 1970; Yount & Crossman, 1970). However, to achieve maximum nutrient removal efficiency by *E. crassipes* in a nutrient removal scheme, it is necessary to establish the size of the population required to maintain desirable nutrient concentrations in the water, under varying conditions of nutrient loading and climate, and the amounts and frequencies of harvest required to control the population size.

Musil & Breen (1985a, 1985b, 1985c) developed, tested and refined a model, incorporating culture and field derived kinetic coefficients, for predicting growth of water hyacinth in eutrophied aquatic systems. In this paper we demonstrate how this model can be used to identify the limiting nutrient and predict population sizes, yields, growth rates and frequencies and amounts of harvest, under varying conditions of nutrient loading and climate, in the Vernon Hooper Dam. Predicted data are used to evaluate the effectiveness of harvesting measures currently being employed for controlling both nutrient inputs and the population size in this impoundment.

STUDY SITE

The Vernon Hooper Dam at Ntshongweni in Natal is located in a deep, rocky gorge below the original confluence of the Mlazi, Sterkspruit and Wekeweke (Ugede) Rivers. A description of the catchment and the physicochemical and hydrological characteristics of the impoundment are presented in Archibald & Warwick (1980). For many years this impoundment has served as an important water supply for the city of Durban, but its continuation as a water resource is jeopardized by poor water quality. Effluent discharges from domestic sewage treatment works and industrial complexes in the Mlazi and Sterkspruit River catchments have resulted in a considerably enriched impoundment with little opportunity for effluent diversion. A history of the development in the catchment area, which includes a record of changes in water quality and subsequent action taken by the Durban City Engineers Department, is given by Howes (1976).

Before 1979, water hyacinth was observed occasionally in the impoundment. The populations, however, were generally small and confined to the major inlets with aggregations of plants occasionally being wind-blown across the reservoir (C. G. M. Archibald, pers. comm.†). Water quality at this time was described by Howes (1983) as consisting of three types, each requiring different chemical treatments. These were: (i) 'Normal', (ii) 'Algal laden' and (iii) 'Manganese' water. The latter results from anaerobic conditions during summer when severe stratification occurs in the impoundment (Archibald & Warwick, 1980).

During 1979, water hyacinth spread extensively and covered 70 to 80% of the reservoir by March, 1980 (Everitt, 1980). Light wind action compressed

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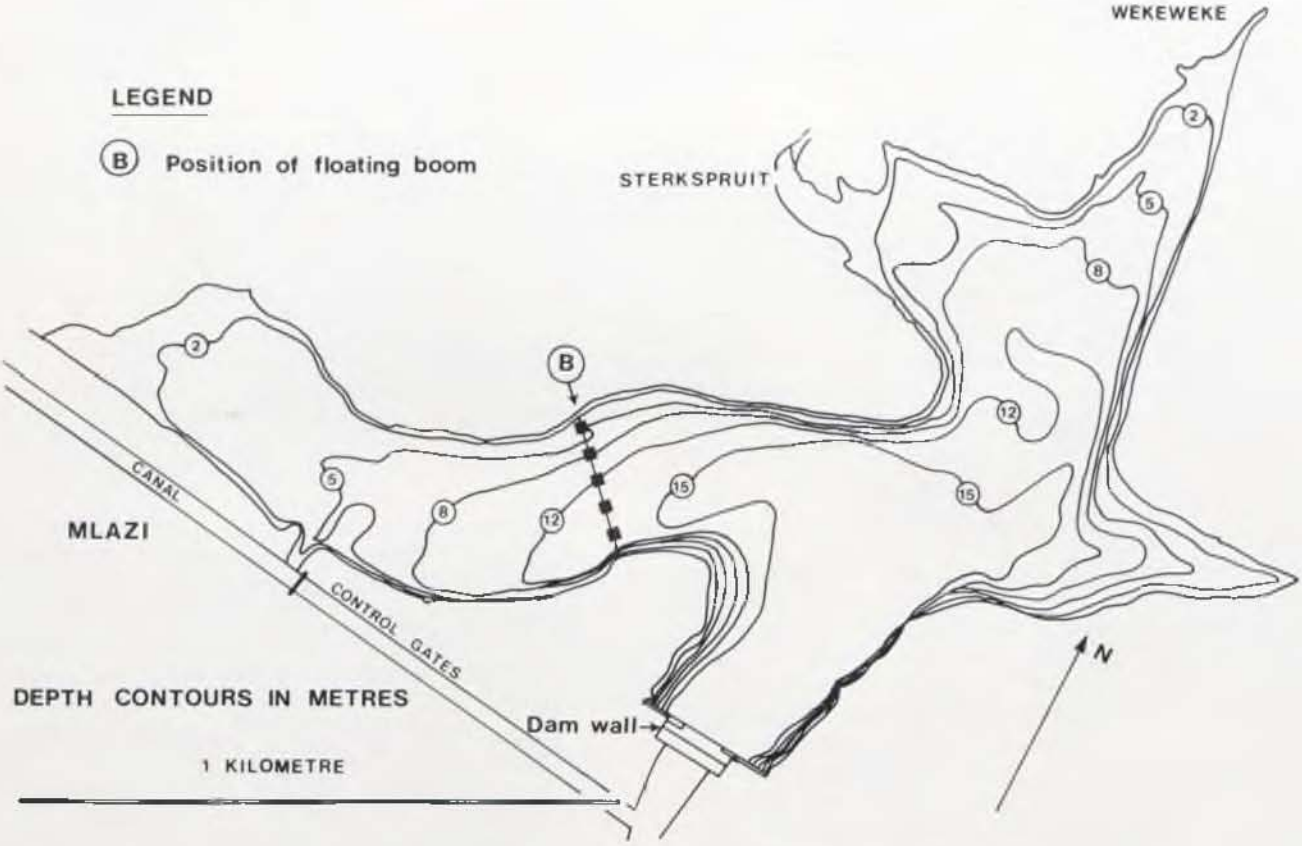

FIG. 1. — Map of Vernon Hooper Dam showing position of floating boom.

this population to ca 50% of the water surface area. A marked improvement in the quality of the 'Algal laden' water, noted by the Chemical Branch of the Durban City Engineers Department, was attributed to P removal by the water hyacinth population (A. M. Howes, pers. comm.*). In view of this, the **Durban City Engineers Department decided against eradicating the water hyacinth population in the impoundment by chemical control measures. Instead, ca 20 ha of water hyacinths were retained behind a floating boom in the Mlazi leg of the reservoir (Fig. 1) at the end of 1981 (Howes, 1983), and the populations harvested regularly with the aid of a mobile crane. Up to 100 metric tonnes of fresh water hyacinths are harvested daily from the impoundment (P. A. Larkan, pers. comm.†) which has resulted in reduced water treatment costs (Howes, 1983).

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** The Vernon Hooper Dam presently falls under the jurisdiction of the Umgeni Water Board, P.O. Box 9, Pietermaritzburg, 3200.

† P. A. Larkan, Umgeni Water Board, P.O. Box 9, Pietermaritzburg, 3200.

METHODS

Physicochemical measurements

Flow

Mean daily inflow rates ($m^3 s^{-1}$) for the impoundment were derived from flow-measuring weirs located on the Mlazi, Sterkspruit and Wekeweke Rivers, whereas outflow rates were derived from the spillway, scour and dam outlet (draw). These rates, measured fortnightly, were supplied by the National Institute for Water Research (NIWR), Council for Scientific and Industrial Research (CSIR), Durban, and converted to monthly flows using the following formula:

Monthly flow (Mℓ) = mean daily flow rate per month ($m^3 s^{-1}$) × number of days in month × 0,0864 × 10^3.

Total monthly inflow was calculated as the sum of monthly flows of the Mlazi, Sterkspruit and Wekeweke Rivers, whereas total monthly outflow was calculated as the sum of monthly flows of the spillway, scour and dam outlet.

Chemical analysis of water

Chemical analyses of water samples, collected fortnightly from the Mlazi, Sterkspruit and Wekeweke Rivers and from the outflowing water, were carried out by the NIWR, CSIR, Durban. These analyses were automated and derived from published methods (Environmental Protection Agency, 1974; American Public Health Ass.: *Standard Methods*, 1975).

The following N and P fractions were analysed in the water samples:

a) in filtered samples, nitrate-nitrogen (NO_3–N) by colorimetry after reduction to nitrite and soluble reactive phosphorus (SRP) (Twinch & Breen, 1980) by colorimetry using the molybdenum blue method.

b) in unfiltered samples, Kjeldahl nitrogen as ammonium (NH_4–N) after digestion of the samples with conc. H_2SO_4 in the presence of a mercury catalyst and total phosphorus (total P) as SRP after digestion of the samples with H_2SO_4 and persulphate. Total nitrogen (total N) was calculated as the sum of Kjeldahl nitrogen and nitrate plus nitrite (NH_4–N + NO_3–N + NO_2–N).

Nutrient loading and release

Monthly flows of the Mlazi, Sterkspruit and Wekeweke Rivers were multiplied by the average monthly total N and total P concentrations in the water of each river and summed to give monthly total N and total P inflow loads (inputs) for the impoundment. Total monthly outflows via the spillway, scour and dam outlet were multiplied by the average monthly total N and total P concentrations in the outflowing water to give monthly total N and total P outflow loads (release).

Environment

Mean daily air temperature data for the Vernon Hooper Dam, derived from monthly averages over the period 1932 to 1946 (Climate of South Africa, 1954), were supplied by the Weather Bureau, Department of Transport. No measurements of radiant flux density or relative humidity were available for the impoundment.

RESULTS AND DISCUSSION

Retention estimates for the impoundment

Chemical and biological transformations

Estimates of the proportions of N and P inflow loads retained or lost by chemical and biological transformations in the impoundment, i.e. through sediment adsorption and denitrification, were based on monthly inflow and outflow data and N and P balances for the impoundment for the period January to December, 1976 (Table 1). Water hyacinth was either absent, or present as small populations in the reservoir during this period (C.G.M. Archibald, pers. comm.). The differences between total N and total P inflow and outflow loads, expressed as percentages of inflow loads, estimated the percentages of N and P inflow loads retained or lost by chemical

TABLE 1. — Inflow and outflow data and total N and total P balances for the Vernon Hooper Dam (monthly averages: January to December, 1976)

Month	Inflow	Outflow	Inflow load N	Inflow load P	Outflow load N	Outflow load P	Difference N	Difference P
	Mℓ	Mℓ	kg	kg	kg	kg	% inflow load	% inflow load
Jan.	19421	10178	24492	2410	15725	1231	35,8	48,9
Feb.	22530	12097	27882	3292	15049	835	46,0	74,6
Mar.	32007	3622	41302	4097	5451	275	86,8	93,3
Apr.	23103	4051	46569	3269	10034	417	78,4	87,2
May	5844	4028	12309	687	9486	238	22,9	65,4
Jun.	2909	2370	6480	428	5304	137	18,1	68,0
Jul.	2360	2666	8053	551	6225	141	22,7	74,4
Aug.	2921	2666	9719	822	7161	173	26,3	78,9
Sep.	2484	2423	6215	890	6620	182	*-6,5	79,5
Oct.	22191	12703	48590	3259	30271	1258	37,7	61,4
Nov.	5337	3512	10197	864	6922	284	32,1	67,1
Dec.	3291	3043	7473	692	4683	237	37,3	65,7

* A negative value indicates export.

TABLE 2. — Inflow and outflow data and total N and total P balances for the Vernon Hooper Dam (monthly averages: August, 1979 to July, 1980)

Month	Inflow	Outflow	Inflow load N	Inflow load P	Outflow load N	Outflow load P	Difference N	Difference P
	Mℓ	Mℓ	kg	kg	kg	kg	% inflow load	% inflow load
Aug.	6509	1607	20218	1598	1605	72	92,1	95,5
Sep.	6104	1672	25589	1484	1324	79	94,8	94,7
Oct.	6034	1366	22157	1275	2422	158	89,1	87,6
Nov.	3045	1361	7139	785	3373	408	52,7	48,0
Dec.	3857	964	12370	-	2795	-	77,4	-
Jan.	2718	978	29605	224	3465	479	88,3	*-113,8
Feb.	2921	1065	10718	578	3595	476	66,4	17,6
Mar.	954	857	2642	187	2448	392	7,3	*-109,6
Apr.	1006	848	2985	221	1302	199	56,4	9,9
May	833	884	4104	306	830	159	79,8	48,0
Jun.	519	609	4108	128	597	59	85,5	53,9
Jul.	-	723	-	-	750	42	-	-

* A negative value indicates export.
- data incomplete or unavailable.

and biological transformations in the impoundment monthly and, although potentially available, were assumed not to be readily available to water hyacinths for growth. A net export of N from the system was evident during September, 1976. However, this could not be attributed to a net loss of water from the reservoir during this month since the recorded inflow was larger than the recorded outflow (Table 1).

Chemical and biological transformations and water hyacinth uptake

Monthly inflow and outflow data and N and P balances for the impoundment for the period August, 1979 to July, 1980, when an extensive cover of water hyacinth was present (Everitt, 1980), are given in Table 2. The differences between total N and total P inflow and outflow loads, expressed as percentages of inflow loads, estimated the percentages of N and P inflow loads removed by water hyacinth plus those retained or lost by chemical and biological transformations in the impoundment monthly. Net exports of P from the system were evident during January and March, 1980. Again, these could not be attributed to net losses of water from the reservoir during these two months since recorded inflows were larger than recorded outflows (Table 2).

Water hyacinth uptake

Subtracting the percentages of N and P inflow loads estimated to have been retained, lost or removed monthly in Table 1 from those in Table 2 and multiplying these by the recorded monthly N and P inflow loads for the period August, 1979 to July, 1980, gave estimates of the quantities of N and P removed monthly by the water hyacinth population in the reservoir. The results (Table 3) suggest that during the periods March to April, 1980 and November, 1979 to June, 1980, N and P respectively were exported from the system. The estimated percentages of N and P inflow loads removed by water hyacinth plus those retained or lost by chemical and biological transformations in the reservoir during these periods being considerably lower than those estimated to have been retained or lost by chemical and biological transformations only. These apparent net exports of N and P from the system, however, could not be attributed to any large net losses of water from the reservoir during these periods since recorded inflows, with the exception of May and June, 1980, were generally considerably higher than recorded outflows (Table 2).

The apparent net exports of P from the system may be explained by a release of sediment-bound PO_4–P during anoxic conditions produced in the impoundment by the extensive water hyacinth cover (Everitt, 1980) and accentuated by summer stratification in the reservoir (Archibald & Warwick, 1980). In fact, Everitt (1980) reported a dissolved oxygen concentration of less than 0,5 mg ℓ^{-1}(ppm) in the water at the dam wall during March, 1980 which indicated anaerobiosis below the thermocline. This suggestion is supported by the large (up to 1 100%) increase in the total P concentration in the water during the period November, 1979 to June, 1980, even though P inflow loads during this period were 25 to 50% lower than those during the preceding period, i.e. August to October, 1979 (Table 3). An increased P release from sediments under anoxic conditions is well documented (Mortimer, 1941) and Vollenweider (1972) has shown that oxygen depletion is accompanied by a breakdown in the ability of sediments to adsorb PO_4–P so that sediments act as a source rather than a sink for P.

The apparent net exports of N from the system could not be readily explained, since total N concentrations in the water relative to N inflow loads did not show any significant differences during March and April, 1980 compared with other months (Table 3). These apparent net exports of N from the system, however, could have been due to increased rates of NO_3–N loss via denitrification (Keeny, 1973; Chon & Knowles, 1979), accentuated by anoxic conditions produced in the reservoir by the extensive water hyacinth cover (Everitt, 1980).

—Estimated quantities of N and P removed by the water hyacinth population in the Vernon Hooper Dam (monthly averages: August, 1979 to July, 1980)

	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.
load kg N	20218	25589	22157	7139	12370	~29605	10718	2642	2985	4104	4108	-
f N inflow load removed by water hyacinth plus that st by chemical and biological transformations	92,1	94,8	89,1	52,7	77,4	88,3	66,4	7,3	56,4	79,8	85,5	-
f N inflow load retained or lost by chemical and nsformations	26,3	*-6,5	37,7	32,1	37,3	35,8	46,0	86,8	78,4	22,9	18,1	22,7
	65,8	?	51,4	20,6	40,1	52,5	20,4	?	?	56,9	67,4	-
ntity of N removed by water hyacinth kg N	13303	?	11389	1470	4960	15543	2186	?	?	2335	2769	-
ntration in water ug N ℓ^{-1}	999	792	1773	2478	2899	3543	3376	2856	1536	939	980	1038
load kg P	1598	1484	1275	785	-	224	578	187	221	306	128	-
f P inflow load removed by water hyacinth plus that st by chemical and biological transformations	95,5	94,7	87,6	48,0	-	*-113,8	17,6	*-109,6	9,9	48,0	53,9	-
f P inflow load retained or lost by chemical and nsformations	78,9	79,5	61,4	67,1	65,7	48,9	74,6	93,3	87,2	65,4	68,0	74,4
	16,6	15,2	26,2	?	-	?	?	?	?	?	?	-
ntity of P removed by water hyacinth kg P	265	225	334	?	-	?	?	?	?	?	?	-
ntration in water ug P ℓ^{-1}	45	47	116	300	-	490	447	458	235	180	97	58

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The possibility of P inputs from internal sources (sediments) and possible increases in rates of N loss via denitrification, during those months when net exports of N and P from the system were not apparent, introduce constraints to modelling the growth of water hyacinth in the impoundment. This is because it is not feasible to accurately estimate the proportions of N and P inflow loads removed by the water hyacinth population. However, during those months where net exports of N and P from the system were not apparent, the model was applied using estimates made of the proportions of N and P inflow loads removed by the water hyacinth population.

Predictions based on water nutrient concentrations

Limiting nutrient

The nutrient (N or P) *limiting water hyacinth growth rate in the impoundment was predicted from total N and total P concentrations in the water (monthly averages) using the half saturation (Ks) concentrations of 976 μg N ℓ^{-1} and 94,1 μg P ℓ^{-1}, derived for *E. crassipes* in culture (Musil & Breen, 1985a), in the Monod model. It can be assumed (Musil & Breen, 1985b) that the specific growth rate of *E. crassipes* is limited not in a multiplicative or additive manner, but in a threshold mode by the single nutrient (N or P) in shorter supply. Estimates were based on total N and total P concentrations, rather than on soluble N and P fractions, in the water since specific growth rates of *E. crassipes* in the field are more accurately predicted from these concentrations (Musil & Breen, 1985b). For example, the average total N and total P concentrations in the water of the impoundment during August, 1979 (Table 4) were 999 μg N ℓ^{-1} and 45 μg P ℓ^{-1} respectively. The percentages of the maximum specific growth rate (Umax) that *E. crassipes* would achieve at (i) this average total N and (ii) this average total P concentration in the water were estimated using the Monod model as follows:

$$U = Umax \frac{999}{976 + 999} \times 100 \text{ ....(i)}$$

$$= 50{,}6\% \ Umax$$

$$U = Umax \frac{45}{94{,}1 + 45} \times 100 \text{.............(ii)}$$

$$= 32{,}3\% \ Umax$$

The results show that during August, 1979, *E. crassipes* would achieve a lower percentage of the Umax at the average total P than at the average total N concentrations in the water, indicating that P was the limiting nutrient.

Estimates of the limiting nutrient in the impoundment for the period August, 1979 to July, 1980, are given in Table 4. The results show that during July, 1980 and for the period August to October, 1979, P was limiting for water hyacinth, whereas for the period November, 1979 to June, 1980, N was limiting. The change from P to N limitation after October, 1979 was reflected in the considerable increase in the total P concentration in the water (Table 4).

Specific growth rate

Specific growth rates of water hyacinth occurring in loosely crowded populations in the impoundment were predicted from mean daily air temperatures (monthly averages) and limiting total N or total P concentrations in the water (monthly averages) using the following mathematical expression (Musil & Breen, 1985b):

$$U = 5{,}2631 \times 10^{8} e^{-6540/T} \times \frac{S}{Ks + S}$$

where U = specific growth rate g fresh mass g^{-1} d^{-1}; T = absolute mean daily air temperature °K; S = limiting nutrient concentration μg ℓ^{-1}; Ks = half saturation concentration μg ℓ^{-1}.

This expression, essentially a combination of the Arrhenius and Monod equations, incorporates the Ks concentrations of 976 μg N ℓ^{-1} and 94,1 μg P ℓ^{-1}. Specific growth rates of water hyacinth occurring in densely crowded populations in the impoundment were estimated using a correction factor of 0,2236. This correction factor (Table 5) was derived from a mean value of ratios calculated between specific growth rates (estimated maximum specific growth rates) measured for water hyacinths growing in loosely and densely crowded field populations at a nearby sewage maturation pond (Musil, 1982). For example, during August, 1979 the mean daily air temperature at the impoundment and the limiting total P concentration in the water were 16,5°C and 45 μg P ℓ^{-1} respectively (Table 4). Specific growth rates (U) of water hyacinth occurring in (i) loosely and (ii) densely crowded populations in the impoundment during this month were predicted as follows:

$$U = 5{,}2631 \times 10^{8} e^{-6540/273{,}2 + 16{,}5} \times \frac{45}{94{,}1 + 45} \text{ ....(i)}$$

$$= 0{,}0267 \text{ g fresh mass } g^{-1} d^{-1} \ (2{,}67\% \ d^{-1})$$

$$U = 5{,}2631 \times 10^{8} e^{-6540/273{,}2 + 16{,}5} \times \frac{45}{94{,}1 + 45} \text{ ... (ii)}$$

$$= 0{,}0060 \text{ g fresh mass } g^{-1} d^{-1} \ (0{,}60\% \ d^{-1})$$

Predictions of specific growth rates of water hyacinth in the impoundment for the period August, 1979 to July, 1980 are given in Table 4. These ranged from 0,0267 to 0,1024 g fresh mass g^{-1} d^{-1} (2,67 to 10,24% d^{-1}) and from 0,0060 to 0,0229 g fresh mass g^{-1} d^{-1} (0,60 to 2,29% d^{-1}) for loosely and densely crowded populations respectively.

Predictions based on the proportions of N and P inflow loads removed by water hyacinth

Potential yield

The potential yields of water hyacinth in the impoundment were predicted from those proportions of limiting N or P inflow loads estimated to have

* Nutrient present at concentrations below that required for maximum plant growth and hence restricting the growth rate.

TABLE 4.—Predicted growth rates, potential yields and population sizes of water hyacinth in the Vernon Hooper Dam (August, 1979 to July, 1980)

	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Ju
al N concentration in water ug N ℓ^{-1}	999	792	1773	2478	2899	3543	3376	2856	1536	939	980	10
mated specific growth rate as % of maximum specific growth rate	50,6	44,8	64,5	71,7	74,8	78,4	77,6	74,5	61,1	49,0	50,1	51
al P concentration in water ug P ℓ^{-1}	45	47	116	300	-	490	447	458	235	180	97	5
mated specific growth rate as % of maximum specific growth rate	32,3	33,3	55,2	76,1	-	83,9	82,6	82,9	71,4	65,7	50,8	38
iting nutrient	P	P	P	N	N?	N	N	N	N	N	N	P
n daily air temperature °C	16,5	18,1	19,7	21,1	22,0	22,5	22,6	22,2	20,8	18,4	16,0	15
dicted specific growth rate g fresh mass $g^{-1} d^{-1}$ (× 100 = % d^{-1})												
Loosely crowded population	0,0267	0,0311	0,0583	0,0843	0,0941	0,1024	0,1021	0,0951	0,0702	0,0469	0,0398	0,0
Densely crowded population (× 0,2236)	0,0060	0,0070	0,0130	0,0188	0,0210	0,0229	0,0228	0,0213	0,0157	0,0105	0,0089	0,0
mated quantity of N removed by water hyacinth kg N	13303	?	11389	1470	4960	15543	2186	?	?	2335	2769	-
mated quantity of P removed by water hyacinth kg P	265	225	334	?	-	?	?	?	?	?	?	-
dicted potential yield metric tonnes of fresh water hyacinths d^{-1}	147,4	129,7	185,8	86,7	283,0	886,7	133,3	?	?	133,2	163,2	-
mated population size required to produce the predicted potential eld × 10^3 metric tonnes of fresh water hyacinths												
Loosely crowded population	5,4	4,1	3,1	1,0	2,9	8,2	1,2	?	?	2,8	4,0	?
Densely crowded population	24,5	18,5	14,2	4,6	13,3	38,3	5,8	?	?	12,6	18,2	?
mated area of population ha												
Loosely crowded population	128,3	97,4	73,6	23,7	68,9	194,8	28,5	?	?	66,5	95,0	?
Densely crowded population	60,4	45,6	35,0	11,3	32,8	94,4	14,3	?	?	31,0	44,8	?
mated area of population as % of full surface area of reservoir												
Loosely crowded population	152,7	115,9	87,6	28,2	82,0	231,9	33,9	?	?	79,2	113,1	?
Densely crowded population	71,9	54,3	41,7	13,4	39,0	112,4	17,0	?	?	36,9	53,3	?

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TABLE 5. — Ratios calculated between specific growth rates (estimated maximum specific growth rates) measured for *E. crassipes* growing in loosely and densely crowded field populations in a maturation pond (Musil, 1982)

Growing interval	Specific growth rate g fresh mass $g^{-1} d^{-1}$		Ratio
Dates	Loosely crowded	Densely crowded	Densely crowded / Loosely crowded
01/01 – 16/02/78	0,1498	0,0324	0,2163
17/02 – 01/03/78	0,1698	0,0357	0,2102
02/03 – 14/03/78	0,1534	0,0259	0,1688
16/03 – 29/03/78	0,1481	0,0312	0,2107
31/03 – 11/04/78	0,1146	0,0403	0,3516
14/04 – 26/04/78	0,0936	0,0231	0,2468
12/05 – 24/05/78	0,1084	0,0203	0,1873
26/05 – 07/06/78	0,0987	0,0242	0,2452
15/09 – 27/09/78	0,1179	0,0248	0,2103
29/09 – 12/10/78	0,1239	0,0262	0,2115
13/10 – 24/10/78	0,1358	0,0299	0,2202
25/10 – 08/11/78	0,1223	0,0268	0,2191
10/11 – 22/11/78	0,1147	0,0255	0,2223
24/11 – 06/12/78	0,1292	0,0271	0,2097
Mean	0,1271	0,0281	0,2236
Standard deviation	0,0219	0,0053	0,0417
Standard error	0,0059	0,0014	0,0111
Standard error as % of mean	4,6	5,0	5,0

been removed daily by the water hyacinth population using the yield coefficient (Yc) values (fresh mass basis) of 1 768,5 for N and 17 248 for P derived for *E. crassipes* in culture (Musil & Breen, 1985a). The Yc expresses the relationship between mass of plant material produced and mass of limiting nutrient absorbed (Musil & Breen, 1985a). For example, during August, 1979 the proportion of the limiting P inflow load estimated to have been removed by the water hyacinth population was 265 kg P (Table 3) or 265/31 kg P d^{-1}. The potential yield (Xpy) of water hyacinth during this month was predicted as follows:

$$Xpy = \frac{265}{31} \times 17\,248$$
$$= 147{,}4 \text{ metric tonnes of fresh water hyacinths } d^{-1}$$

Predictions of the potential yields of water hyacinth in the impoundment for the period August, 1979 to July, 1980, are given in Table 4. These ranged from 86,7 to 886,7 metric tonnes of fresh water hyacinths d^{-1}.

Population size

Population sizes (loosely and densely crowded) required to produce the predicted potential yields of water hyacinth in the impoundment were estimated using the following form of the general growth equation (Malek & Fencl, 1966, Radford, 1967):

$$Xo + Xpy = Xoe^{ut}$$

where Xo = population size metric tonnes; Xpy = potential yield metric tonnes d^{-1}; u = specific growth rate g fresh mass $g^{-1} d^{-1}$; t = time interval between initial biomass (Xo) and final biomass (Xo + Xpy) days.

For example, population sizes (loosely and densely crowded) required to produce the predicted potential yield of water hyacinth during August, 1979 of 147,4 metric tonnes of fresh water hyacinths d^{-1} at a predicted specific growth rate of (i) 0,0267 and (ii) 0,0060 g fresh mass $g^{-1} d^{-1}$ for loosely and densely crowded populations respectively, were estimated as follows:

$$Xo + 147{,}4 = Xoe^{0{,}0267 \times 1} \quad \text{(i)}$$

Xo (loosely crowded) = 5,4 × 10^3 metric tonnes of fresh water hyacinths

$$Xo + 147{,}4 = Xoe^{0{,}0060 \times 1} \quad \text{(ii)}$$

Xo (densely crowded) = 24,5 × 10^3 metric of fresh water hyacinths

Estimates of population sizes (loosely and densely crowded) in the impoundment for the period August, 1979 to July, 1980 are given in Table 4. These ranged from 1,0 × 10^3 to 8,2 × 10^3 and from 4,6 × 10^3 to 38,3 × 10^3 metric tonnes of fresh water hyacinths for loosely and densely crowded populations respectively.

Population area

Assuming stand densities (dry mass basis) of 2,21 and 21,3 metric tonnes ha^{-1} for loosely and densely crowded populations respectively (Boyd & Scarsbrook, 1975) and a mean water content of water hyacinth of 94,75% (Penfound & Earle, 1948; Westlake, 1963; Bock, 1969), it is possible to calculate the areas occupied by the loosely and densely crowded populations and express these as percentages of the surface area of the impoundment, which at full supply level is 84 ha (Everitt, 1980). For example, the estimated population sizes in the impoundment during August, 1979 were 5,4 × 10^3 and 24,5 × 10^3 metric tonnes of fresh water hyacinths for loosely and densely crowded populations respectively. The areas occupied by the populations in (i) loosely and (ii) densely crowded situations were, therefore, calculated as follows:

$$\frac{5,4 \times 10^3}{2,21} \times \frac{5,25}{100} \quad \text{(i)}$$

= 128,3 ha (152,7% of the full surface area of the impoundment)

$$\frac{24,5 \times 10^3}{21,3} \times \frac{5,25}{100} \quad \text{(ii)}$$

= 60,4 ha (71,9% of the full surface area of the impoundment)

Estimates of the areas occupied by loosely and densely crowded populations in the impoundment for the period August, 1979 to July, 1980 are given in Table 4. These ranged from 23,7 to 194,8 ha (28,2 to 231,9% of the full surface area of the impoundment) and from 11,3 to 94,4 ha (13,4 to 112,4% of the full surface area of the impoundment) for loosely and densely crowded populations respectively.

Everitt (1980) visually estimated a 50% coverage of the impoundment by water hyacinth during March, 1980, when the population was compressed by light wind action. However, the reservoir was only ca 65% full at the time with the water surface area covering ca 75% of that at full supply level (A. M. Howes, pers. comm.). Consequently, the water hyacinth population in the reservoir under crowded conditions in actual fact covered only ca 31,5 ha or 37,5% of the full surface area of the impoundment. This visual estimate of cover compares favourably with the areas estimated to have been occupied by densely crowded populations in the reservoir, when expressed as percentages of the full surface area of the impoundment (Table 4), during May, 1980 (36,9%), December, 1979 (39,0%), October, 1979 (41,7%) and even during September, 1979 (54,3%) and June, 1980 (53,3%). It, however, does not compare favourably with those during November, 1979 (13,4%), January, 1980 (112,4%) and February, 1980 (17,0%). Inaccurate estimates of the proportions of N inflow loads removed by the water hyacinth population during these months may partly explain this.

Predictions based on a 20 ha population

Presently, ca 20 ha of water hyacinths are retained in the impoundment behind a floating boom (Howes, 1983). The population is maintained in moderately crowded situations with up to 100 metric tonnes of fresh water hyacinths being harvested daily (P. A. Larkan, pers. comm.). The potential yields, amounts and frequencies of harvest required and quantities of N and P, i.e. assuming no luxury uptake of these nutrients by the water hyacinths, that could be removed by a 20 ha moderately crowded population in the impoundment were predicted as follows. Estimates were based on the period August, 1979 to July, 1980, since chemical and hydrological data for the impoundment after this period was incomplete. It was assumed that (i) the 20 ha moderately crowded population had an average stand density of 11,7 metric tonnes ha^{-1} (dry mass basis), i.e. a mean value of 2,21 and 21,3 metric tonnes ha^{-1} (dry mass basis) for loosely and densely crowded populations respectively, (ii) the water hyacinths had a mean water content of 94,75% and (iii) specific growth rates were mean values of those predicted for loosely and densely crowded populations in the impoundment in Table 4.

Potential yield

The potential yields of a 20 ha moderately crowded population, i.e. 20 × 11,7/5,25 × 100 = 4 457,1 metric tonnes of fresh water hyacinths, in the impoundment were predicted using the general growth equation (Malek & Fencl, 1966; Radford, 1967). For example, the potential yield of 4 457,1 metric tonnes of fresh water hyacinths at an estimated specific growth rate of 0,0163 g fresh mass g^{-1} d^{-1}, i.e. a mean value of 0,0267 and 0,0060 g fresh mass g^{-1} d^{-1} for loosely and densely crowded populations respectively (Table 4), during August, 1979 was:

$$Xpy = 4\,457,1e^{0,0163 \times 1} - 4\,457,1$$
$$= 73,2 \text{ metric tonnes of fresh water hyacinths } d^{-1}$$

Predictions of the potential yields of a 20 ha moderately crowded population in the impoundment for the period August, 1979 to July, 1980 are given in Table 6. These ranged from 73,2 to 287,9 metric tonnes of fresh water hyacinths d^{-1}.

Harvesting interval

Assuming that 100 metric tonnes of fresh water hyacinths are harvested daily from the impoundment, the time required for a 20 ha moderately crowded population to produce an additional 100 metric tonnes of fresh water hyacinths was estimated using the general growth equation (Malek & Fencl, 1966; Radford, 1967) and is referred to as the harvesting interval, viz:

$$t = \frac{\ell n\ Xt - \ell n\ Xo}{U}$$

where: Xt = final biomass (Xo + 100) metric tonnes; Xo = initial biomass of 20 ha population (moderately crowded) metric tonnes; U = specific growth rate (moderately crowded population) g fresh mass g^{-1} d^{-1}; t = harvesting interval, i.e. time interval between Xo and Xt days; $\ell n = \log_e$ (natural logarithm).

For example, it was predicted that a 20 ha moderately crowded population, or 4 457,1 metric tonnes of fresh water hyacinths, would produce 73,2 metric tonnes of fresh plant material daily during August, 1979 at an estimated specific growth rate of 0,0163 g fresh mass g^{-1} d^{-1} (Table 6). The time (t) required for this population to produce an additional 100 metric tonnes of fresh water hyacinths was:

$$t = \frac{\ell n\ (4\,457,1 + 100) - \ell n\ (4\,457,1)}{0,0163}$$

$$= 1,4 \text{ days}$$

The harvesting interval in this example was 1,4 days. After this period, one day's removal would need to be initiated and this would have to be repeated after a further 1,4 days growth.

LE 6.—Predicted yields, growth rates and nutrient removal potentials of a 20 ha population of water hyacinths confined in moderately crowded sitations in the Vernon Hooper Dam (August, 1979 to July, 1980)

	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.
iomass of 20 ha population metric tonnes of fresh water	4457,1	4457,1	4457,1	4457,1	4457,1	4457,1	4457,1	4457,1	4457,1	4457,1	4457,1	4457,1
ecific growth rate g fresh mass $g^{-1} d^{-1}$ (× 100 = % d^{-1})	0,0163	0,0190	0,0356	0,0515	0,0575	0,0626	0,0624	0,0582	0,0429	0,0287	0,0243	0,0178
tential yield of the population metric tonnes of fresh inths d^{-1}	73,2	85,5	161,5	235,5	263,8	287,9	287,0	267,1	195,3	129,8	109,6	80,0
arvesting interval days (assuming 100 metric tonnes of hyacinths harvested daily)	1,4	1,2	0,6	0,4	0,4	0,3	0,3	0,4	0,5	0,8	0,9	1,2
antities of N removed by the population kg N d^{-1}	41,4	48,3	91,3	133,2	149,2	162,8	162,3	151,0	110,4	73,4	62,0	45,2
ow load kg N d^{-1}	652,2	853,0	714,7	238,0	399,0	955,0	369,6	85,2	99,5	132,4	136,9	-
of N inflow load retained or lost by chemical and ransformations	26,3	*-6,5	37,7	32,1	37,3	35,8	46,0	86,8	78,4	22,9	18,1	22,7
roportion of N inflow load readily available for plant N d^{-1}	480,7	?	445,2	161,6	250,2	613,1	199,6	11,2	21,5	102,1	112,1	?
antities of N removed as % of estimated available N	8,6	?	20,5	82,4	59,6	26,5	81,3	1348,2	513,5	71,9	55,3	?
antities of P removed by the population kg P d^{-1}	4,2	4,9	9,4	13,6	15,3	16,7	16,6	15,5	11,3	7,5	6,3	4,6
w load kg P d^{-1}	51,5	49,5	41,1	26,2	-	7,2	19,9	6,0	7,4	9,9	4,3	-
of P inflow load retained or lost by chemical and ransformations	78,9	79,5	61,4	67,1	65,7	48,9	74,6	93,3	87,2	65,4	68,0	74,4
roportion of P inflow load readily available for plant P d^{-1}	10,9	10,1	15,9	8,6	?	3,7	5,0	0,4	0,9	3,4	1,4	?
antities of P removed as % of estimated available P	38,5	48,5	59,1	158,1	?	451,3	332,0	3875,0	1255,5	220,6	450,0	?

value indicates export; ? undeterminable; - data incomplete or unavailable

Harvesting intervals estimated for a 20 ha moderately crowded population in the impoundment for the period August, 1979 to July, 1980 are given in Table 6. The results indicate that during winter (May to August) 100 metric tonnes of fresh water hyacinths harvested daily would more or less be adequate to account for the predicted potential yields of the population. The estimated harvesting intervals ranging from ca 0,8 to 1,4 days. During summer (September to April), however, this quantity of fresh water hyacinths harvested daily would generally be insufficient. Approximately two to three times as much fresh plant material (ca 161,5 to 287,9 metric tonnes) would generally need to be harvested daily from the impoundment during summer to contain the predicted potential yields of the population.

With respect to the amounts of harvest, it should be pointed out that the 100 metric tonnes of fresh water hyacinths apparently harvested daily from the impoundment (P. A. Larkan, pers. comm.) are high when compared with those reported in the literature for various mechanical water hyacinth removal operations. Van Dyke (1971), for example, reported that a stationary, land-based mechanical harvester prototype (Sarasota Weed and Feed Incorporation) was only capable of removing an average of ca 5,9 metric tonnes of fresh water hyacinths per hour of operating time, i.e. ca 47 metric tonnes of fresh water hyacinths per day assuming an 8 hour working day, when time required for general maintenance and repairs and that lost due to unfavourable weather was taken into consideration. Similar results were obtained by Phillippy & Perryman (1972b) using an Aquamarine S–650 Shore Conveyor (Linder Industrial Machine Company, Florida) where an average of ca 52 metric tonnes of fresh water hyacinths were removed per 8 hour working day of operating time. Somewhat higher values, however, have been obtained by Touzeau (1972), using an Aquamarine H–650 Harvester combined with an S–650 Shore Conveyor system (Linder Machine Company, Florida), where an average of ca 74 metric tonnes of fresh water hyacinths were removed per 8 hour working day of operating time and by Phillippy & Perryman (1972a), using a modified, stationary, land-based mechanical harvester prototype (Sarasota Weed and Feed Incorporation), where an average of ca 96 metric tonnes of fresh water hyacinths were removed per 8 hour working day of operating time. The latter was the highest value that could be traced in the literature.

Nitrogen and phosphorus removal

The quantities of N and P that could be removed daily by a 20 ha moderately crowded population in the impoundment were estimated from the predicted potential yields of the population (Table 6) using the yield coefficient (Yc) values (fresh mass basis) of 1 768,5 for N and 17 248 for P. These were expressed as percentages of those proportions of N and P inflow loads estimated not to have been retained or lost by chemical and biological transformations in the system, i.e. those proportions of N and P inflow loads assumed to be readily available to the water hyacinths for growth. For example, the predicted potential yield of a 20 ha moderately crowded population in the impoundment during August, 1979 was 73,2 metric tonnes of fresh water hyacinths d^{-1} (Table 6). The quantities of (i) N and (ii) P that could be removed daily by the population during this month were estimated as follows:

$$\frac{73{,}2 \times 1\,000}{1\,768{,}6} = 41{,}4 \text{ kg N d}^{-1} \ldots\ldots\ldots\ldots \text{(i)}$$

$$\frac{73{,}2 \times 1\,000}{17\,248} = 4{,}2 \text{ kg P d}^{-1} \ldots\ldots\ldots\ldots \text{(ii)}$$

During August, 1979, 20 218 kg N and 1 598 kg P entered the impoundment (Table 2), or daily inflow loads of 652,2 kg N d^{-1} and 51,5 kg P d^{-1}, of which 26,3% with respect to N and 78,9% with respect to P were estimated to be retained or lost by chemical and biological transformations in the system (Table 1). Consequently, the proportions of daily (i) N and (ii) P inflow loads estimated to have been readily available to the water hyacinths for growth during August, 1979 were:

$$652{,}2 \times \frac{100-26{,}3}{100} = 480{,}7 \text{ kg N d}^{-1} \ldots \text{(i)}$$

$$51{,}5 \times \frac{100-78{,}9}{100} = 10{,}9 \text{ kg P d}^{-1} \ldots \text{(ii)}$$

The predicted quantities of 41,4 kg N d^{-1} and 4,2 kg P d^{-1} that could be removed by a 20 ha moderately crowded population during August, 1979, expressed as percentages of the estimated available N and P inflow loads of 480,7 kg N d^{-1} and 10,9 kg P d^{-1} were:

$$\frac{41{,}4 \times 100}{480{,}7} = 8{,}6\% \text{ for N} \ldots\ldots\ldots\ldots \text{(i)}$$

$$\frac{4{,}2 \times 100}{10{,}9} = 38{,}5\% \text{ for P} \ldots\ldots\ldots\ldots \text{(ii)}$$

Predictions of the quantities of N and P that could be removed by a 20 ha moderately crowded population in the impoundment for the period August, 1979 to July, 1980 are given in Table 6. The results indicate that such a population could, at least during most of the above-mentioned period, remove larger quantities of P daily than those entering the system that were readily available for water hyacinth growth. The predicted quantities of P that could be removed daily by the population, expressed as percentages of the estimated available P inflow loads, ranging from 158,1 to 3 875,0% except during August, September and October, 1979 when these ranged from only 38,5 to 59,1% (Table 6). In contrast to P, the results indicate that the population would generally remove smaller quantities of N daily than those entering the impoundment that were readily available for water hyacinth growth. The predicted quantities of N that could be removed daily by the population, expressed as percentages of the estimated available N inflow loads, ranging from 8,6 to 82,4% except during March and April, 1980 when these ranged from 513,5 to 1 348,2% (Table 6).

The above estimates were based on the minimum quantities of N and P that could be removed daily by

TABLE 7.—A comparison of chemical treatment costs for the different water quality types in the Vernon Hooper Dam, prior to and following the retention of ca. 20 ha of water hyacinths behind a floating boom and the introduction of harvesting, according to Howes (1983)

Chemical mg/ℓ	Unit Cost/t	Water classification				
		Normal (1)	Algal laden (2) (50/mℓ)	Manganese (3) (0,2 mg/ℓ)	Hyacinth Cont. (4) (1st 6 months)	Hyacinth Cont. (5) (2nd 6 months)
Alum	R 200	35	55	90	62	80
Chlorine	R 940	4	8	21	5	9
Lime	R 110	Nil	15	55	Nil	Nil
$CuSO_4$	R1155	1,5	1,5	Nil	Nil	Nil
Cost/m^3		R0,013	R0,022	R0,044	R0,017	R0,024

the population. Luxury uptake of N and P by the water hyacinths during growth, however, would result in greater quantities of N and P removed by the population than actually estimated.

Water quality

A comparison of chemical treatment costs reported by Howes (1983) for the different 'water quality types' in the Vernon Hooper Dam, prior to and after retention of ca 20 ha of water hyacinths behind a floating boom and the introduction of harvesting are presented in Table 7. A reduction of 61% in chemical treatment costs was achieved initially through the introduction of harvesting. The cost reduction dropped to 45% during the second six month period of harvesting due primarily to increased nutrient loading and poor rainfall. Cost of harvesting and disposal of water hyacinths varied between R600 and R1 000 per day which was initially justified by savings in chemical treatment costs when treating in excess of 37 Mℓ d^{-1}. Justification no longer exists financially. However, the resultant reduction in algal concentrations, i.e. improvement in quality of the 'Algal laden' water, is highly beneficial (Howes, 1983).

Whether the ca 20 ha of water hyacinths presently confined in the impoundment could reduce nutrient concentrations in the water to levels limiting for algae and account for the observed reduction in algal concentrations is difficult to ascertain. The average N : P ratio in the water is ca 25,5 (Archibald & Warwick, 1980) suggesting that P may be the nutrient most frequently limiting for algae in the impoundment. Furthermore, it was predicted that a 20 ha moderately crowded population in the impoundment during the period August, 1979 to July, 1980 could generally remove larger quantities of P daily than those entering the system that were readily available for plant growth (Table 6). However, this does not necessarily mean that the present population could reduce P concentrations in the water of the reservoir to levels limiting for algae. This would be dependent on a number of factors, viz: (i) rate and efficiency of P uptake by water hyacinths, (ii) magnitude of P inflow loads, (iii) residence time of inflowing water beneath the water hyacinth mat, (iv) extent of mixing between inflowing water and reservoir water and (v) influence of the water hyacinth population on chemical and biological transformations in the impoundment. It is clear that a large proportion of the P entering the impoundment is retained by adsorption onto sediments (Hepher, 1958; Hayes & Phillips, 1968). This source of P is potentially available to plants for growth, since sediment P and dissolved P exist in equilibrium (Hepher, 1958; Pomeroy *et al.*, 1965). The equilibrium concentration increases with increased P content in the sediment (Pomeroy *et al.*, 1965). Removal of P from the water by hyacinths during growth could, therefore, displace the P equilibrium allowing additional P to be released from sediments into the overlying water. In addition, anoxic conditions that might be produced beneath the water hyacinth mat could also provide conditions conducive for the release of sediment P (Mortimer, 1941; Vollenweider, 1972).

Available chemical and hydrological data for the impoundment after July, 1980 are incomplete. However, they do indicate that since the end of 1981, when ca 20 ha of water hyacinths were retained behind a floating boom in the impoundment and harvesting was initiated (Howes, 1983), the magnitude of the monthly P inflow loads have generally not been very much different from those during 1979 and 1980 (Table 8). Consequently, if one extrapolates from the predicted quantities of P that could be removed by a 20 ha population, relative to the estimated available inflow loads, for the period August, 1979 to July, 1980, it would appear that the 20 ha of water hyacinths confined in the impoundment since the end of 1981 could have removed those proportions of P inflow loads not removed by processes other than water hyacinth uptake in the system. Furthermore, during summer the reservoir is stratified and a well defined thermocline develops at a depth of 6 to 8 m (Archibald & Warwick, 1980). Therefore, one may speculate that the development of this thermocline and consequent density gradient in the impoundment could allow the water hyacinth population to reduce P concentrations in the epilimnion to levels that could be limiting for algae, at least during summer when maximum algal growth rate and production would be expected. Any P released from sediments into the hypolimnion would theoretically be restricted from diffusing into the epilimnion by the thermocline. This may partly explain the observed reduction in algal concentrations in the reservoir since the introduction of harvesting.

TABLE 8. — Inflow and P loading data for the Vernon Hooper Dam (monthly averages)

	1976		*1979/1980		1982	
Month	Inflow Mℓ	Total P inflow load kg	Inflow Mℓ	Total P inflow load kg	Inflow Mℓ	Total P inflow load kg
Jan.	19421	2410	2718	224	2434	450
Feb.	22530	3292	2921	578	1214	692
Mar.	32007	4097	954	187	1840	1063
Apr.	23103	3269	1006	221	-	-
May	5844	687	833	306	-	-
Jun.	2909	428	519	128	1001	402
Jul.	2360	551	-	-	974	581
Aug.	2921	822	*6509	*1598	843	1314
Sep.	2484	890	*6104	*1484	931	1520
Oct.	22191	3259	*6034	*1275	-	-
Nov.	5337	864	*3045	* 785	-	-
Dec.	3291	692	*3857	* -	-	-

- data incomplete or unavailable

Under conditions of increased inflow and P loading, evident from monthly inflow and P loading data for the impoundment for the period January to December, 1976 (Table 8), a larger population would, however, generally be needed in the reservoir to remove those proportions of P inflow loads not removed by processes other than water hyacinth uptake in the system. This is evident from the predicted specific growth rates, potential yields and N and P removal potentials of a 20 ha moderately crowded population in the impoundment for this period (Table 9). The results indicate that such a population would, at least during 8 months of the above-mentioned period, remove smaller quantities of P daily than those entering the impoundment that were readily available for plant growth. The predicted quantities of P that could be removed daily by the population, expressed as percentages of the estimated available P inflow loads, ranging from 21,4 to 97,8%, except during March, June, September and December, 1976 when they ranged from 104,3 to 115,2%. Using the model, the population sizes that would be required in the impoundment to remove the estimated available P inflow loads were predicted. These ranged from 20,6 to 93,4 ha, except during March, June, September and December, 1976 when they ranged from 17,3 to 19,2 ha only (Table 9). An example of the derivation is as follows: during January, 1976 the daily P inflow load was 77,7 kg P d^{-1} of which 39,7 kg P d^{-1} was estimated to have been readily available to plants for growth (Table 9). The potential yield (Xpy) of water hyacinth during this month would be:

$$Xpy = 39{,}7 \times 17\,248$$
$$= 684{,}7 \text{ metric tonnes of fresh water hyacinths } d^{-1}$$

The population size required to produce this potential yield at a predicted specific growth rate of 0,0449 g fresh mass g^{-1} d^{-1} for a moderately crowded population (Table 9) would be:

$$Xo + 684{,}7 = Xoe^{0{,}0449 \times 1}$$
$$= 14\,910{,}7 \text{ metric tonnes of fresh water hyacinths}$$

Assuming an average stand density (dry mass basis) of 11,7 metric tonnes ha^{-1} for a moderately crowded population and a mean water content of water hyacinth of 94,75%, the area occupied by the population would be:

$$14\,910{,}7 \times \frac{5{,}25}{11{,}7 \times 100}$$
$$= 66{,}9 \text{ ha}$$

CONCLUSIONS

Harvesting water hyacinth growing in eutrophied aquatic systems directly addresses the problem of nutrient enrichment of water and not only the excessive aquatic plant growth which is a manifestation of the problem. In designing an effective harvesting strategy for water hyacinth, the model serves as a useful aid for identifying the limiting nutrient and predicting population sizes, yields, growth rates and frequencies and amounts of harvest, under varying conditions of nutrient loading and climate, to control both nutrient inputs and excessive growth in eutrophied aquatic systems. However, accurate predictive estimates using the model will require the incorporation of mathematical expressions from which those proportions of N and P inflow loads retained or lost by chemical and biological transformations in such systems can be predicted. Such mathematical expressions will also need to integrate the influence of the water hyacinth population on these transformations. Furthermore, the relationship between maximum specific growth rate of water hyacinth and density of the population will need to be mathematically formulated, since this presents a potential constraint to the model's application. It is clear that the nutrient removal capacity of water hyacinth is a function of the population size, its density and growth rate. An inverse relationship exists between the two latter

LE 9.—Predicted yields, growth rates and nutrient removal potentials of a 20 ha population of water hyacinths confined in moderately crowded situations in the Vernon Hooper Dam (January to December, 1976)

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
centration in water ug N ℓ^{-1}	1545	1244	1505	2477	2355	2238	2335	2686	2732	2383	1971	1539
pecific growth rate as % of maximum specific growth rate	61,3	56,0	60,7	71,7	70,7	69,6	70,5	73,3	73,7	70,9	66,9	61,2
entration in water ug P ℓ^{-1}	121	69	76	103	59	58	53	65	75	99	81	78
pecific growth rate as % of maximum specific growth rate	56,2	42,3	44,7	52,2	38,5	38,1	36,0	40,8	44,3	51,3	46,2	45,3
rient	P	P	P	P	P	P	P	P	P	P	P	P
iomass of 20 ha population metric tonnes of fresh water	4457,1	4457,1	4457,1	4457,1	4457,1	4457,1	4457,1	4457,1	4457,1	4457,1	4457,1	4457,1
ir temperature °C	22,5	22,6	22,2	20,8	18,4	16,0	15,5	16,5	18,1	19,7	21,1	22,0
ecific growth rate fresh mass $g^{-1}d^{-1}$ (X 100 = % d^{-1})	0,0449	0,0340	0,0349	0,0367	0,0225	0,0185	0,0168	0,0206	0,0253	0,0331	0,0332	0,0348
tential yield of the population metric tonnes of fresh inths d^{-1}	204,7	154,1	158,3	166,6	101,4	83,2	75,5	92,7	114,2	150,0	150,5	157,8
arvesting interval days (assuming 100 metric tonnes of hyacinths harvested daily)	0,5	0,6	0,6	0,6	1,0	1,2	1,3	1,1	0,9	0,7	0,7	0,6
antities of N removed by the population kg N d^{-1}	115,7	87,1	89,5	94,2	57,3	47,0	42,7	52,4	64,6	84,8	85,1	89,2
ow load kg N d^{-1}	790,1	995,8	1332,3	1552,3	397,1	216,0	259,8	313,5	207,2	1567,4	339,9	241,1
of N inflow load retained or lost by chemical and ransformations	35,8	46,0	86,8	78,4	22,9	18,1	22,7	26,3	*-6,5	37,7	32,1	37,3
roportion of N inflow load readily available for plant N d^{-1}	507,2	537,7	175,9	335,3	306,2	176,9	200,8	231,0	?	976,5	230,8	151,2
antities of N removed as % of estimated available N	22,8	16,2	50,9	28,1	18,7	26,6	21,3	22,7	?	8,7	36,9	59,0
antities of P removed by the population kg P d^{-1}	11,9	8,9	9,2	9,6	5,9	4,8	4,4	5,4	6,6	8,7	8,7	9,1
w load kg P d^{-1}	77,7	117,6	132,2	109,0	22,2	14,3	17,8	26,5	29,7	105,1	28,8	23,1
of P inflow load retained or lost by chemical and ransformations	48,9	74,6	93,3	87,2	65,4	68,0	74,4	78,9	79,5	61,4	67,1	65,7
roportion of P inflow load readily available for plant P d^{-1}	39,7	29,9	8,8	13,9	7,7	4,6	4,5	5,6	6,1	40,6	9,5	7,9
antities of P removed as % of estimated available P	30.0	29,8	104,5	69,1	76,6	104,3	97,8	96,4	108,2	21,4	91,6	115,2
pulation size required to remove the estimated available ad	66,9	66,9	19,2	28,8	26,2	19,1	20,6	20,8	18,4	93,4	21,8	17,3

value indicates export
inable

factors, i.e. the higher the population density the lower its specific growth rate (De Busk *et al.*, 1981). However, the productivity of waterhyacinth, the product of specific growth rate and density, defines a bell-shaped curve with maximum productivities being achieved at intermediate densities (De Busk *et al.*, 1981). A regular harvesting programme could maintain water hyacinth populations confined behind floating booms in large water bodies in moderately crowded situations and intermediate densities, although the strict control of population density would probably only be feasible on a small scale.

It would appear from the predictive estimates made using the model that, under present conditions of reduced inflow and nutrient loading in the Vernon Hooper Dam which have persisted since the introduction of harvesting, i.e. from ca December, 1981 to ca August, 1983, the ca 20 ha of water hyacinths confined in the impoundment has been adequate to remove those proportions of P inflow loads that are readily available for plant growth and account for the observed reduction in algal concentrations. However, the 100 metric tonnes of fresh water hyacinths harvested daily from the impoundment, although adequate during winter, would appear to be insufficient during summer. It is estimated that about two to three times as much fresh plant material (ca 161 to 288 metric tonnes) would need to be harvested daily from the impoundment during summer, under reduced nutrient loadings, to contain the predicted potential yields of the population. Under conditions of increased inflow and nutrient loading, such as those prior to 1979, the population size and the daily amounts of harvest would have to be increased accordingly. These can be predicted from the nutrient loading data using the model.

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UITTREKSEL

'n Model wat vir Eichhornia crassipes *(Mart.) Solms ontwikkel is, is gebruik om die beperkende voedingstof in die Vernon Hooperdam te identifiseer en om bevolkingsgroottes, opbrengste, groeitempo's en die frekwensies en hoeveelheid van oeste onder variërende toestande van voedingstoflading en klimaat te voorspel. Voorspelde data is gebruik om die doeltreffendheid van oesmaatreëls wat huidig vir die beheer van beide voedingstofinsette en die bevolkingsgrootte in hierdie dam gebruik word, te evalueer. Voorspellings van die bevolkingsgrootte voor die oes begin is, vergelyk oor die algemeen gunstig met dié wat op 'n visuele skatting gebaseer is. Voorspellings van die hoeveelhede P wat daagliks deur 'n 20 ha bevolking verwyder kan word, dui aan dat sodanige bevolking in hierdie dam P konsentrasie in die epilimnion gedurende somerstratifikasie tot vlakke kan verminder wat alge beperk. Dit kan die waargenome vermindering in algkonsentrasies sedert die instelling van oes verduidelik. Skattings van die hoeveelheid en frekwensies van oeste benodig om te verklaar vir die voorspelde potensiële opbrengste van 'n 20 ha bevolking, dui daarop dat die 100 metrieke ton vars waterhiasinte wat tans daagliks uit die dam geoes word, onder huidige toestande van verminderde voedingstoflading, gedurende die winter voldoende is, maar nie gedurende die somer nie.*

REFERENCES

AMERICAN PUBLIC HEALTH ASSOCIATION, AMERICAN WATER WORKS ASSOCIATION AND WATER POLLUTION CONTROL FEDERATION, 1975. *Standard methods for the examination of water and waste-water*, 14th edn, pp. 1193. New York.

ARCHIBALD, C. G. M. & WARWICK, R. J., 1980. Vernon Hooper Dam. In R. D. Walmsley & M. T. Batty, *Limnology of some selected South African impoundments*, 187–194. Pretoria: CSIR Press.

BOCK, J. H., 1969. Productivity of the water hyacinth *(Eichhornia crassipes). Ecology* 50: 460–464.

BOYD, C. E., 1970. Vascular aquatic plants for mineral nutrient removal from polluted waters. *Econ. Bot.* 24: 95–103.

BOYD, C. E. & SCARSBROOK, E., 1975. Influence of nutrient additions and initial density of plants on production of water hyacinth, *Eichhornia crassipes. Aquat. Bot.* 1: 253–261.

CHON, Y-K. & KNOWLES, R., 1979. Measurement of denitrification in two freshwater sediments by an *in situ* acetylene inhibition method. *Appl. Environ. Microbiol.* 37,6: 1067–1072.

DE BUSK, T. A., RYTHER, J. H., HANISAK, M. D. & WILLIAMS, L. D., 1981. Effects of seasonality and plant density on the productivity of some fresh-water macrophytes. *Aquat. Bot.* 10,2: 133–142.

ENVIRONMENTAL PROTECTION AGENCY, 1974. *Manual of methods for chemical analysis of water and wastes*. Report No. EPA-625/6-74-003. Washington, D.C.: U.S. Environmental Protection Agency Office of Technological Transfer.

EVERITT, L., 1980. Water hyacinth — Shongweni Dam. Durban: City Engineer's Department.

HAYES, F. R. & PHILLIPS, J. E., 1968. Lake water and sediment. IV. Radio-phosphorus equilibrium with mud, plants and bacteria under oxidized and reduced conditions. *Limnol. Oceanogr.* 3: 459–475.

HEPHER, B., 1958. On the dynamics of phosphorus added to fish ponds in Israel. *Limnol. Oceanogr.* 3: 84–100.

HOWES, A. M., 1976. Report on the Shongweni catchment: water quality and treatment. Durban: City Engineer's Department.

HOWES, A. M., 1983. Shongweni water treatment and hyacinth control. Durban: City Engineer's Department.

KEENY, D. R., 1973. The nitrogen cycle in sediment water systems. *J. Environ. Qual.* 2,1: 15–29.

MALEK, I. & FENCL, Z., 1966. *Theoretical and methodological basis of continuous culture of micro-organisms*. Prague: Czechoslovak Academy of Sciences.

MORTIMER, C. H., 1941. The exchange of dissolved substances between mud and water in lakes. *J. Ecol.* 29: 280–329.

MUSIL, C. F., 1982. *The use of growth kinetics in the development of a predictive model for the growth of* Eichhornia crassipes *(Mart.) Solms in the field*. Ph.D thesis, University of Natal.

MUSIL, C. F. & BREEN, C. M., 1985a. The development from kinetic coefficients of a predictive model for the growth of *Eichhornia crassipes* in the field. I. Generating kinetic coefficients for the model in greenhouse culture. *Bothalia* 15: 689–703.

MUSIL, C. F. & BREEN, C. M., 1985b. The development from kinetic coefficients of a predictive model for the growth of *Eichhornia crassipes* in the field. II. Testing and refining the model under field conditions. *Bothalia* 15: 705–724.

MUSIL, C. F. & BREEN, C. M., 1985c. The development from kinetic coefficients of a predictive model for the growth of *Eichhornia crassipes* in the field. III. Testing a model for predicting growth rates from plant nutrient concentrations. *Bothalia* 15: 725–731.

PENFOUND, W. T. & EARLE, T. T., 1948. The biology of water hyacinth. *Ecol. Monogr.* 18: 448–472.

PHILLIPPY, C. L. & PERRYMAN, J. M., 1972a. Mechanical harvesting of water hyacinth *(Eichhornia crassipes)* in Gant Lake Canal, Sumter County, Florida, pp.21. Florida Game and Fresh Water Fish Commission. Unpubl.

PHILLIPPY, C. L. & PERRYMAN, J. M., 1972b. Mechanical harvesting of water hyacinth *(Eichhornia crassipes)* in Trout Lake, Lake County, Florida, pp.24. Florida Game and Fresh Water Fish Commission. Unpubl.

POMEROY, L. R., SMITH, E. E. & GRANT, C. M., 1965. The exchange of phosphate between estuarine water and sediments. *Limnol. Oceanogr.* 10: 167–172.

RADFORD, P. J., 1967. Growth analysis formulae — their use and abuse. *Crop Sci.* 7: 171–175.

TOUZEAU, L. F., 1972. Mechanical water hyacinth removal operations, Aquamarine Corporation, Blufton, Florida, pp.16. Florida Game and Fresh Water Fish Commission. Unpubl.

TWINCH, A. J. & BREEN, C. M., 1980. *Advances in understanding phosphorus cycling in inland waters — their significance for South African limnology.* South African National Scientific Programmes, Report No. 42.

VAN DYKE, J. M., 1971. Mechanical harvesting of water hyacinth *(Eichhornia crassipes)* in Shell Creek Reservoir, Charlotte County, Florida, pp.25. Florida Game and Fresh Water Fish Commission. Unpubl.

VOLLENWEIDER, R. A., 1972. *Input-output models with special reference to the phosphorus loading concept in limnology.* Paper given at Workshop Conference on Chemical – ecological considerations for defining the goal of water pollution control. Kaustanienbaum, Switzerland, April 19–21, 1972.

WEATHER BUREAU, RSA, 1954. *Climate of South Africa.* Climate Statistics, Part 1. WB19. Pretoria: The Government Printer.

WESTLAKE, E. F., 1963. Comparisons of plant productivity. *Biol. Rev.* 38: 385–425.

YOUNT, J. L. & CROSSMAN, R. A., Jr. 1970. Eutrophication control by plant harvesting. *J. Wat. Pollut. Control Fed.* 42: 173–183.