Biomass and Productivity of Water Hyacinth and Their Application in Control Programs

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Abstract

Water hyacinth is controllable if management programs take account of plant dynamics and factors that influence plant behaviour. The project for reclamation of water bodies in Mexico considered water hyacinth standing crop, coverage and growth. The method proposed served to characterise the initial population and monitor the control process. The growth model used was reliable in predicting the effective reduction in the weed in response to control pressure. Change in growth over an annual cycle was characterised by a sigmoid curve. The maximum relative percentage growth rate was 9.34%, with a duplication time of 7.4 days from April to June. During winter, growth decreased by up to 90%. In a dam, 144 t/ha/year of dry matter was produced, characteristic of water plants with a high nutrient content. The water hyacinth population can be reduced by 90% through water level management and mechanical destruction. For example, approximately 3600 t/day was removed over 181 days to reduce the infestation to manageable levels. Physical, chemical and biological methods are used to maintain these levels, but input of urban and industrial contaminants must be controlled for long term rehabilitation.

OUTBREAKS of aquatic plants is the result of changes in the physical, chemical and biological conditions brought about by the uncontrolled flow of nutrients from urban, agricultural and industrial centres and in silt eroded from watersheds (Gutiérrez et al. 1994).

Water hyacinth is successful owing to its life cycle and survival strategies that have given it a competitive edge over other species. Its adaptability to little competed ecological conditions make eradication of this plant virtually impossible and control extremely difficult (Gutiérrez et al. 1996). In Mexico, more than 40,000 ha were infested and specific management programs were needed. The Aquatic Weed Control Program (AWCP) was created in 1993 to combat the excessive presence of the weed in the nation's watercourses.

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The aims of the AWCP included to:

- reduce the weed to a manageable level and maintain this level through a maintenance program developed for the body of water;
- use methods most suitable to ecosystem and water uses;
- formulate an integral watershed program which will include the control and maintenance operations; and
- establish biological control using insects and fungi.

Under a national program to control the water hyacinth, guidelines to deal with the related environmental, social, technical and economic factors, and specific strategies to reduce coverage were developed. The environmental factors included the identification of the characteristics of the affected areas and the consequences of the proposed treatments. The social aspects embraced the stimulation of user awareness of the importance of water quality, the creation of organisations to coordinate user-sponsored control activities, and the awakening of the community identity.

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Basic to all are the technical and economic aspects which make the activities feasible and operational (Gutiérrez et al. 1996).

Most of the water hyacinth control methods have been used in Mexico; harvesting by hand and machine, mechanical crushing, and treatment with herbicides and biological agents. Experience indicated that water hyacinth is controllable if the process takes account of plant dynamics and factors that influence plant behaviour. The project considered biomass, cover and growth to be important. The objective of this work was to characterise the initial population of the weed to assist with and assess control programs.

Materials and Methods

The best control strategy is that which reduces the biomass of the water hyacinth in a reasonable time and at an acceptable cost, i.e. the use of one or several control methods that effectively reduce the amount of plants faster than its natural reproduction, without negatively affecting the ecosystem. Even though there are many interacting variables and components, the behaviour of the plants is one of the most important factors. In terms of weed control, plant behaviour can be studied through three parameters: biomass, infestation level (surface area covered), and growth rates. These factors vary in time and space and are site-specific.

Biomass

The biomass is defined as the amount of weed mass in a particular area or volume. The effect of a water hyacinth population over the water ecosystem depends on this characteristic. The excessive increase in biomass is an indication of an increment in the energy conversion rate caused by the availability of resources. Water hyacinth is an example of an exotic plant that competes effectively for the space.

Concerning mechanical control, Hutto and Sabol (1986) mention that the effectiveness of a cropping system depends mainly on the standing crop because that determines a machine's movement rate throughout a work site and the number of loads that can be transported. Biomass of plants also influences the efficacy of herbicides. In practice, it seems unlikely that 100% control of water hyacinth using herbicide can be obtained when it grows in heavy infestations because adjacent plants screen one another (Gutiérrez 1993). These considerations show the need to measure the standing crop of water hyacinth in the infested water bodies where a control program is to be established.

Plant biomass was obtained by weighing samples from the field and estimating the weight of the population. One square metre samples were collected, drained for 5–7 minutes, and weighed using a 50 kg (± 1 kg) scale. Sub samples of 1 kg were dried to constant weight and weighed.

The number of samples per sampling, N, was determined according to Madsen (1993):

$$N = \frac{s^2}{\left(0.1 \times \bar{x}\right)^2} \qquad (1)$$

where s is the standard deviation and $\bar{x}$ is the mean.

Cover

Cover was defined as the space covered by the weed as seen from above (Brower and Zar 1977). To estimate cover on small water bodies, estimates were made by mapping the infestation, at different times, while standing on a predetermined, elevated set-point. The area covered was then determined for each date by comparing the mapped infestation with the known area of the water body. The area was used with the estimated weight per unit area to calculate total biomass.

Landsat-TM satellite images were used to estimate cover on large water bodies. In the images a 'false colour' compound is generated through the Satellite Image Automatic Detection System (SIADIS), by highlighting areas and combining bands 1, 2, 3, 4, 5 and 7, using blue, green and red filters, respectively.

Growth

Weed growth was determined from the weight increase of the water hyacinth mass per area unit and per time unit, i.e. its productivity (Westlake 1963).

Quantification of rate of growth is important for control. The rate is affected by factors such as nutrients, climate, space and compaction.

To measure growth four 1 m^2 compartments were installed into the edges of water hyacinth mats. All material was removed from inside the compartments. One kg of selected ramets (healthy, undamaged, with 3–5 leaves, of uniform size and weighing 30 to 45 g each) was placed into each compartment and allowed to grow. After 30, 60 and 90 days, the wet weight of the 2 m^2 was obtained using the same procedure for biomass determination described above.

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For comparison purposes between sites and other data obtained in different water bodies, the daily relative growth rate (RGR%) and the biomass doubling-time (DT) were calculated according to Mitchell (1974, cited in Sastroutomo et al. 1978):

$$RGR\% = \frac{\ln X_t}{\ln X_0}(100) \quad (2)$$

$$DT = \frac{\ln 2}{RGR} \quad (3)$$

where X_0 is initial weight and X_t is weight after *t* days.

The three parameters (biomass, cover and growth rates) were obtained in seven water bodies whose main characteristics are shown in Table 1. These reservoirs were classified mesotropic if phosphorus concentrations were between 10 and 35 mg/m^3 or eutrophic if phosphorus concentrations were 35 to 100 mg/m^3 (Vollenweider 1983).

Results and Discussion

The highest biomass average was 49.6 (2.79) kg/m^2, and a maximum value of 76 (4.27) kg/m^2, occurred in Cruz Pintada Dam. This was the smallest dam studied and had the highest level of compaction. In general, these values are similar to those obtained in other parts of the world, except for a value of 5.96 kg/m^2 dry weight observed in Jaipur, India (Trivedy 1980).

Maximum cover generally occurred when the surface area was smallest, and consequently, storage volume lowest. The extraction of water from the dams stranded a great part of the water hyacinth on banks where some died of desiccation. Other plants recovered when water levels increased.

The purpose of measuring water hyacinth growth was to know the relative behaviour of the biomass in an environment that is generally favourable for its increase. The form of this increase and its mathematical representation can be used as a starting point to plan a control program.

It will not be possible to reduce plant infestation while the removal rate of the biomass, either by harvesting, crushing or another procedure, is less than its growth recovery rate.

Table 3 shows the weight changes measured at Requena Dam. Data for location (a) in Table 3, the most comprehensive data set, are also presented as Figure 1.

This ratio showed a growth approximated to the logistic equation 4.

$$W_t = \frac{K}{1 + e^{a-rt}} \quad (4)$$

where:

W_t is wet weight for each determined time (kg/m^2);

r is growth rate per day;

K is growth limit value of the population or load capacity (kg/m^2);

t is time; and

a is an integration constant defining curve position in relation to its origin.

When supposing a growth of this type, the parameters *r* and *a* can be calculated, and the logistic equation transformed into its rectilinear form (equation 5):

$$W_t = \frac{K - W}{W} = a - rt \quad (5)$$

The results of this exercise are shown in Table 3(a). Even though the correlation of the points was very high (0.986), a significance test of the regression was carried out according to Zar (1974). This test rejected, with a probability higher than 99%, the possibility that the points over the straight line are adjusted by chance. The same test was carried out to the data in Table 3(b) and 3(c) resulting also in the rejection of the possibility that the points are adjusted to a straight line by chance, except that for both cases the reliability level was 95%.

It is accepted that the water hyacinth growth is close to logistic growth. Sato and Kondo (1983) established that the biomass increase (fresh weight per surface unit) closely approximates the logistic equation; and Del Viso et al. (1968) demonstrated that the annual growth cycle of this plant in Argentina can be represented by a sigmoid curve.

Reddy and Debusk (1984), in growth evaluations with plants cultivated in a pond with unlimited nutritional conditions, determined the growth characteristics of water hyacinth in the central part of Florida, USA. They obtained a growth curve characterised by three phases: 1. a delay phase followed by exponential growth; 2. a linear growth phase, and 3. a slow exponential growth phase. These characteristics are very similar to the results obtained in this study, where behaviour was measured directly in the field.

We considered that the carrying capacity of the system (*K*), was reached during the periods when maximum biomass was obtained: 51 kg/m^2 for July to

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February (Table 3a), 51 kg/m^2 for December to March (Table 3b) and 55 kg/m^2 for April to June (Table 3c). These values are not shown in the respective tables because the values shown are averages. Reddy and Debusk (1984) suggested that the water hyacinth growth cycle was complete when the maximum density of plants was reached and therefore an additional significant biomass increment was not observed. They found a maximum biomass close to 2,300 g /m^2 in dry weight, while in this study a range of 2,101–3,916 g /m^2 was estimated.

The *r* and *K* parameters from the logistic equation provide an objective comparison between different water systems. They also provide a foundation for a prospective model of the water hyacinth behaviour on a water body, as influenced by different rates of biomass removal.

Table 1. Characteristics of the seven water bodies under study (modified from Bravo et al. 1992)

Parameter	Chairel Lagoon	Cruz. Pintada Dam	Sanalona Dam	Solís Dam	Requena Dam	Endhó Dam	Valle de Bravo Dam
North latitude	22° 16'	18° 26'	24°48'	20° 04'	19° 57'	20° 04'	19° 21'
West longitude	97° 54'	99° 01'	107° 09'	100° 35'	99° 18'	99° 20'	100° 11'
Altitude (m)	0	1,011	135	1,880	2,110	2,018	1,830
Climate	Hot	Hot	Hot	Temperate	Temperate	Temperate	Temperate
Temperature (°C)	24.3	22.0	24.4	21.5	15.4	17.0	18.1
Precipitation (mm)	1,096	800–1,000	814	734	553	609.4	1236.9
Surface area (km^2)	38.790	0.100	24.000	57.02	5.4	8.43	17.3
Volume ('000 m^3)	28,794	400	473,000	794,000	30,300	107,900	300,000
Depth (m)	1 a 3	4	19.7	14.0	5.0	15	19.4
Trophic level	mesothropic	eutrophic	mesothropic	eutrophic	eutrophic	eutrophic	mesothropic

Table 2. Weight per m^2, surface area covered and total biomass of seven water bodies in Mexico (modified from Bravo et al. 1992)

Reservoir	Standing crop wet (dry) weight		Cover		Total biomass (t)
	Average (kg/m^2)	Maximum (kg/m^2)	Average (ha)	%	
Chairel Lagoon	39.5 (2.22)	50.5 (2.84)	376	10	148,520
Cruz Pintada Dam	49.6 (2.79)	76 (4.27)	7.5	75	3,720
Sanalona Dam	42.6 (2.39)	57 (3.20)	790	33	336,540
Solís Dam	38.8 (2.18)	63 (3.54)	3,378	59	1,310,664
Requena Dam	35.74 (2.0)	51 (2.87)	498	70	175,803
Endhó Dam	33.5 (1.88)	51 (2.87)	818	80	220,000
Valle de Bravo Dam	45.7 (2.57)	67 (3.76)	109	6	50,00

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Table 3. Comparitive studies at Requena Dam at three locations (a), (b) and (c).

	Date	Time (days)	Biomass (kg/m^2)	Logistic equation parameters	Doubling time (days)
(a)	16-07-86	0	0.25	a = 4.7073	8.2–8.45
	14-08-86	29	2.70	r = 0.0499	
	17-09-86	63	15.4	K = 51 kg	
	13-10-86	89	26.0	Corr. = 0.9860	
	18-11-86	125	39.0	Reliability:	
	10-12-86	147	45.0	greater than 99%	
	19-01-87	187	50.0		
	17-02-87	216	50.5		
(b)	10-12-86	0	0.250	a = 5.2780	2.03–34.66
	19-01-87	40	0.563	r = 0.0162	
	17-02-87	69	0.675	K = 51 kg	
	17-03-87	97	1.288	Corr = 0.9838	
				Reliab. = 95%	
(c)	28-04-87	0	1.0	a = 3.2746	9.34–7.42
	12-05-87	14	3.7	r = 0.0722	
	12-06-87	48	22.0	K = 55 kg	
	30-07-87	93	53.5	Corr = 0.9598	
				Reliab. = 95%	

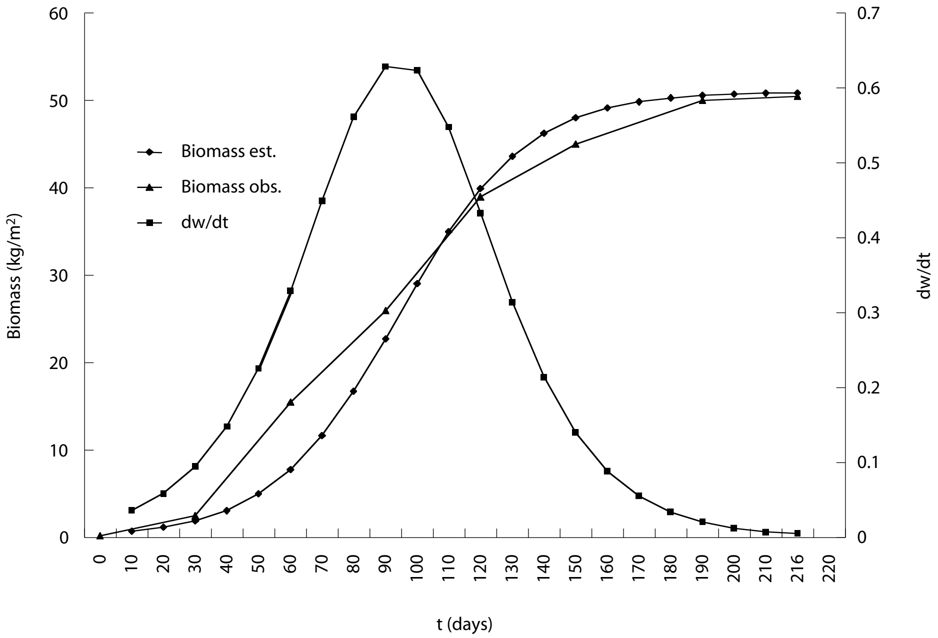

Figure 1. Weight changes for water hyacinth at Requena Dam

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Regarding the growth rate, in Florida an average rate of 52 g/m^2/day was observed during June and July, with a maximum value of 64 g/m^2/day. At the Requena Dam, rates of 59.1 and 60.4 g/m^2/day were estimated for the July to February and April to June periods. The growth rates in both studies were calculated from the slope of the growth curve, adjusted by square minimums. If we consider an average growth rate of 0.551 tonne/ha/day, during the growth season (April to November, 244 days), approximately 134.4 tonne/ha/year can be produced in the dam. Westlake (1963) qualified the water hyacinth as a very productive plant. From data of Louisiana, USA and the Nile, Africa, he estimated that if this species grows under good conditions, with a good density and without space limitations and a continuous predominance of young plants, it can produce as much as 110–150 tonnes of organic matter/ha/year, a value very close to the value estimated in this study.

A wide range of values for the productivity of this plant has been registered in the literature. These values have been calculated in different ways (Gopal 1987). Knipling et al. (1979) estimated that the annual production can be as high as 269 t/ha. Boyd (1976, cited in Gopal 1987) obtained an average productivity of 194 kg/ha/day in an enriched pond. Wooten and Dodd (1976) and Yount and Crossman (1970) determined, respectively, a daily productivity of 290 and 540 kg/ha; the latter value corresponds to a eutrophic lake. Singh et al. (1984) and Wolverton and McDonald (1979, cited in Gopal, 1987), estimated a daily production of biomass of 26 and 72 g/m^2, the latter for wastewater effluent.

This information shows that water hyacinth has a wide productivity range. However, the values that are closer to those obtained in this study are similar to those generated in waters with high content of nutrients, wastewater effluents and eutrophic water bodies.

The determinations made are considered a good approximation to the net primary productivity of this species. Corrections were not made for death, disease and herbivory. Westlake (1963) indicate that unless herbivory is visually obvious, it is probably not important. Herbivory was not observed in this study.

Rates of loss due to natural plant death vary from place to place. Because leaf production is constant and proportional to leaf mortality, each mature shoot maintains a relatively constant number of leaves (Center et al. 1984; Center 1987). Generally, the losses are not higher than 2–10% of the maximum biomass (Harper 1918; Borutskii 1950; Westlake 1965; all cited by Sculthorpe 1967). In tropical and subtropical habitats, mortality occurs throughout the year, usually as much as new material is produced, so that the biomass remains more or less constant (Sculthorpe 1967).

For comparison purposes, it is appropriate to calculate the relative percentage growth rate (RGR%) and the DT of the water hyacinth biomass. The RGR% and the DT were calculated for the first measurement of each experimental lot. They are shown in Table 3.

The daily RGR% was between four to five times greater in summer and spring than in winter, resulting in a shorter DT of the biomass. These results are similar to those obtained by Sastroumoto et al. (1978) who determined in Chiba, Japan, that the RGR% and the DT of the water hyacinth was five times higher and four times faster in summer than in winter. These authors observed that if fertiliser (10 kg N, P, and K) were added, the RGR became eight times higher and the DT five times shorter. We concluded that the differences between spring–summer and winter found in the Requena Dam are the result of differences in water quality rather than in temperature.Table 4 shows RGR%, DT, K and r values estimated in the other water bodies that were assessed. In Mexico, the highest RGR% value obtained was in Requena Dam (9.34%). Higher values were obtained in Florida, 12% (Cornwell et al. 1977) and in the Sudan, 11.8% (Pettet 1964), both in summer and under natural conditions. Growth of water hyacinth is influenced by a number of factors. However, in Mexico its growth varies across a range from 1.07 to 12%.

We did not determine the cause of the variation in growth. The most important factors that influence water hyacinth growth are known to be nutrient availability and temperature. However, those factors do not explain why in places lower than expected rates of growth occurred, for example, Solís Dam or Sanalona Dam.

Control model

The logistic model expressed in equation 4 is the result of the differential equation (equation 6) that, once integrated, represents the growth characteristics found in the Requena Dam:

$$\frac{dW}{dt} = rW - \frac{r}{k}W^2 \qquad (6)$$

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However, to consider the effect of biomass removal, it is necessary to include the corresponding term into equation 6. Thus the expression is (Romero et al. 1989);

$$\frac{dW}{dt} = rW - \frac{r}{k}W^2 - \frac{R}{A} \qquad (7)$$

where R is the amount of water hyacinth that can be removed (kg/day) and A is the reservoir area (m^2) covered with water hyacinth.

This model presupposes that the biomass of the plants (W) is distributed evenly in the surface of the water body. The growth rate (r) is proportional to the density when density is low; as density increases, the growth rate diminishes slowly until the maximum biomass (K) is reached. Normally the biomass in K (load capacity), that is, the asymptote in equation 4, stays without apparent changes, which can be caused when impacting a control process or removal of the weed, included in the model with the term – [R/A].

This model consists of four components:

1. a variable growth rate (r) determined by the amount of initial biomass;
2. a measurement of the population size (W);
3. a measure of the limiting factor of growth (– $[r/k]W^2$); and
4. a measurement of the biomass loss (– $[R/A]$).

Romero (1989) deduced from equation 7 that this point can represented as in equation 8.

$$R^* = \frac{ArK}{4} \qquad (8)$$

with R^* in kg/day.

This expression is of practical usefulness because it allows us to mathematically predict the total biomass behaviour of water hyacinth in the Requena Dam at its maximum infestation and the effect exercised by the crusher and other actions for its decline.

Thus, if we have:

Requena Dam area	A = 4,928,300 m^2
Growth rate	r = 0.049 kg/kg/day
Load capacity	K = 51.0 kg/m2
Removal capacity	R

Substituting these data in equation 8 we obtain:

$R^* = ArK/4$ = 3,080,000 kg/day = 3,080 t/day

If the actual rate of removal was lower than R^* the cover would never be reduced. However, if low initial biomass was present, reduction of cover (or biomass) would be possible. The model greatly depends on the initial density of the water hyacinth, i.e. the biomass per m^2 when population removal begins.

If the removal rate was greater than R^*, reduction in cover would be achieved. Figure 2 shows the biomass behaviour in each of the seven dams under a particular control level. For example, Figure 2e shows the decline in water hyacinth in Requena Dam, if 3,600 tonne/day was removed. A theoretical zero biomass value would be reached at about 200 days.

Table 4. The relative growth rate (RGR), doubling time (DT), carrying capacity (K) and intrinsic rate of increase (r) for water hyacinth in seven water bodies of the Mexican Republic (modified from Bravo et al. 1992).

Water body		Relative growth rate (RGR) (%)	Doubling time (DT) (days)	Load capacity K (kg/m^2)	Intrinsic growth rate r (1/days)
		4.45			
Chairel		1.49	15.58	46.1	0.038
Cruz Pintada		1.07	46.53	60.7	0.152
Sanalona		2.66	64.56	49.0	0.0110
Solís		4.45	26.07	51.1	0.0274
Requena	Summer	8.20	8.45	51	0.049
	Winter	2.03	34.60	51	0.016
	Spring	9.34	7.42	55	0.072
Endhó		7.07	9.9	55	0.065
Valle de Bravo		1.93	13.0	47	0.052

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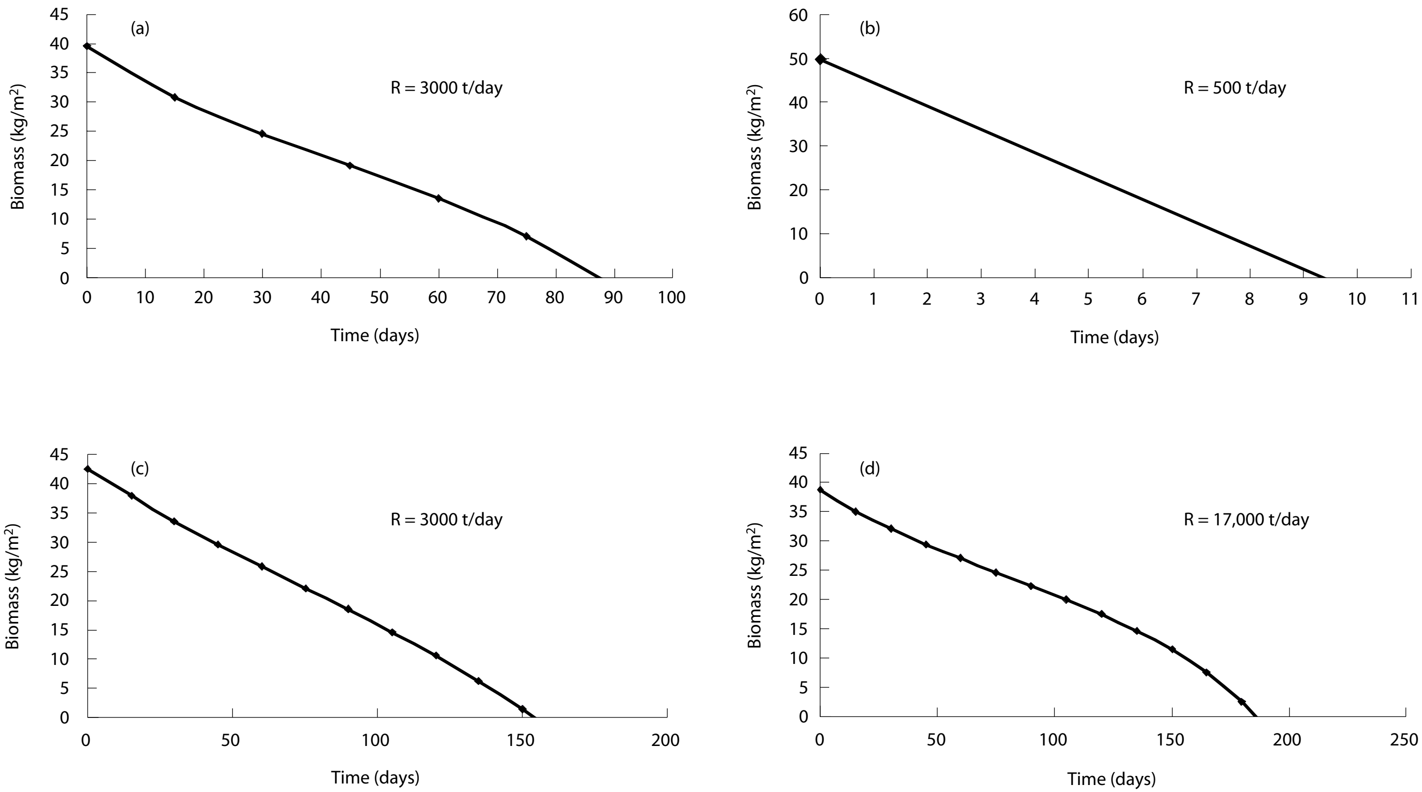

Figure 2. The estimated rate of removal and the duration to achieve a theoretical 100% removal of water hyacinth from each of seven dams; (a) Chairel lagoon; (b) Cruz Pintada dam; (c) Sanalona dam; (d) Solís dam

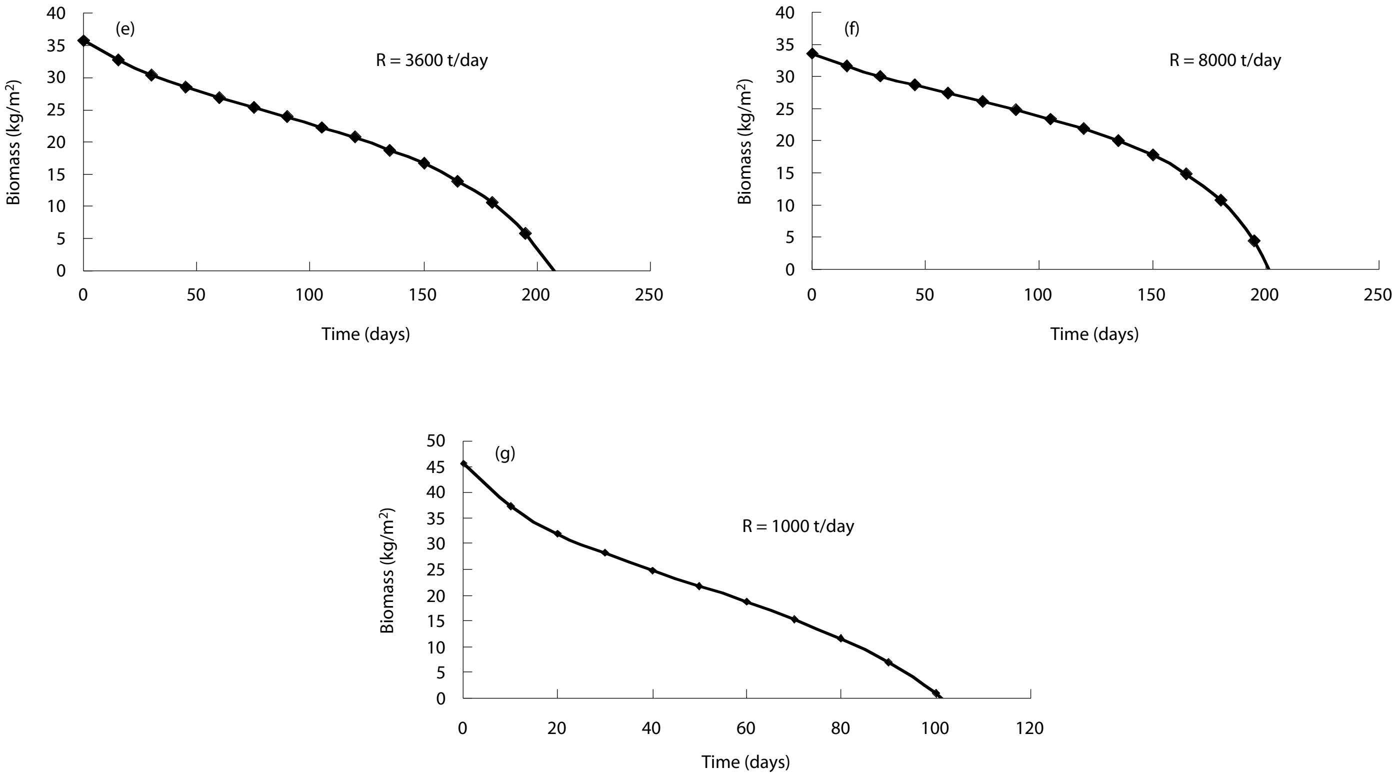

Figure 2. (cont'd) The estimated rate of removal and the duration to achieve a theoretical 100% removal of water hyacinth from each of seven dams; (e) Requena dam; (f) Endh dam; (g) Valle de Bravo dam

This removal logistic model was used to estimate the rate of removal required for a number of water bodies and was successfully applied.

The model assumes a uniform distribution of the water hyacinth over the whole surface of the water and assumes a constant rate of removal. In spite of these limitations the model allowed us to predict the biomass changes and was a useful tool in planning for the control of this weed.

The weed control program included 15 water bodies (Gutiérrez et al.1996). Aquatic weeds were removed by mechanically crushing in Requena Dam, Endho Dam and Valle de Bravo Dam (100% clear) and by mechanically harvesting in Chairel Dam and Cruz Pintada Dam (30% clear). Chemical control was used in Solís Dam, where 100% clean-up was obtained.

It is impossible to remove all water hyacinth due to germination of seeds and regrowth and so management strategies to keep the weed at lower infestation levels are required. Biological control is being used and *Neochetina* adults are produced and released in several water bodies every month. Between April 1994 and August 1998, 85,000 adults were released in 15 water bodies including Requena Dam, Endho Dam and Cruz Pintada Dam. Numerous feedings scars were observed on almost all plants and no substantial reduction in plant size, wet weight or number of plants per square metre was observed 4 years after initial releases of *Neochetina* species. Plant reproduction may be occurring much more rapidly than the weevils can inflict damage (J.M. Martinez, pers. comm. 2000).

Limitations of *Neochetina* in control of water hyacinth were recognised by Perkins (1973), DeLoach and Cordo (1976) and Perkins (1978). The effectiveness of biological control may be improved by the use of additional agents (Charudattan 1986; Forno and Cofrancesco 1993; Martinez et al. 2001). In some locations the *Neochetina* weevils are effective by themselves (Julien 2001). Studies have begun in Mexico to determine indigenous species of pathogens and to evaluate how the most promising of these may be applied as biological herbicides in areas where *Neochetina* is present, in order to enhance the control effect.

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