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Ecosystem Model of Water Hyacinth to Predict Management Options for Bolgoda Lake

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Abstract— *Water hyacinth (Eichhornia crassipes (Mart.) Solms) is a perennial, herbaceous, aquatic weed of the family Pontederiaceas. Water hyacinth is considered as a serious pest in many parts of the world in the tropical and sub-tropical regions due to its prolific growth. A dynamic numerical model was developed to simulate the growth dynamics and production of water hyacinth. Two state variables, shoots and roots, were considered to illustrate the growth of the water hyacinth. The net growth of the shoots was imperative effects of photosynthesis, respiration, mortality and allocation for root growth. Biomass data reported in the literature was used to calibrate the model. Model parameters were allowed to vary as a result of acclimation, following experimental data reported in the literature. Model simulations show a good agreement with observed data with a similar biomass temporal dynamics. The effect of harvesting on the net production of water hyacinth was also analysed for different harvesting rates.*

Keywords: Water hyacinth, mathematical modelling, weed management, Bolgoda Lake

1 Introduction

1.1 Background

The introduction of the open economy by the Government of Sri Lanka in 1977 was aimed at developing the national economy through investments in export-oriented industries throughout the country. As a result, a number of large and small-scale industries evolved near lake ecosystems. Industrial wastes from these industries were directly or indirectly discarded into the lakes. As a result, most of the lakes in Sri Lanka started to get polluted. Also due to the growth of population, ignorance and lack of awareness of people living in the vicinity, pollution of lakes became severe. At present the water hyacinth menace has become a major problem to which a solution is desperately needed.

1.2 Water hyacinth

Water hyacinth (Eichhornia crassipes (Mart.) Solms) is a well-known vascular aquatic weed of South American origin. Water hyacinth often grows as floating plants or mats, as islands of plants floating freely on the water, or mixed with other vegetation on the banks. The high specific gravity of the submerged portion and the low specific gravity of the bulbous petioles tend to keep the shoot erect. The adventitious root system is usually suspended in the water although the plants may become rooted if stranded in moist soil or in shallow water [1].

Water hyacinth has also been studied for its potential in controlling water pollution, to serve as animal feed, for manure or mulch, for the production of biogas, and use for paper manufacture [2]. Among those, water hyacinth is utilized mainly for biogas production and paper manufacture in many countries. The penology, growth and nutrient storage of water hyacinth have been extensively studied in the field and in laboratories by [3-6].

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1.3 Implications of Water Hyacinth in the Bolgoda Lake

Serious problems have resulted from water hyacinth infestation in the Weras Ganga and the Bolgoda Lake in the Moratuwa-Ratmalana area. Rapid invasion has been observed since 1997. In the year 1997 fishermen near the Bolgoda North Lake had earned on average about Rupees 500 to 600 per day, which used to be the main income source for their families. Today this has been completely or partly cut off as a result of water hyacinth infestation.

The total economic loss caused by water hyacinth is not clearly known but it is considered to be quite substantial. The spread of mosquito species is promoted by providing protection to larvae from predators and also through facilitation of surface breathing by larvae by restricting the movement of water. During high tide water hyacinth flows to the overland areas and remains stagnant, which then creates a bad odour in the area upon decomposition (Figure 1). Evidence shows that some villages bordering Bolgoda Lake were cut off, navigation of boats was adversely affected, and snakes and other dangerous animals were carried by water hyacinth.

Figure 1: Water hyacinth flows to the over land areas and remain stagnant creating a bad order

Some of the other problems associated due to the infestation by water hyacinth in Bolgoda Lake are degradation of recreational facilities, deterioration of fish habitat, and the adverse effects on public health.

1.4 Objectives of this study

Mathematical modelling can be used as a way to synthesize the results of both *in situ* and laboratory experiments [7]. Although many experiments have been carried out to analyse the growth dynamics of water hyacinth, few researches have attempted to analyse the growth dynamics using numerical simulation models. Mitsch [8] developed an ecosystem model of water hyacinth growth on Lake Alice, Gainesville, Florida and found that the water hyacinth population would be reduced by 50% or more if the wastewater was diverted from the lake. If the correct mechanisms are included in the model, it is expected that the model results will mimic the observed dynamics reasonably well. Therefore the objectives of this study are to develop a mathematical model to simulate biomass and productivity of water hyacinth, to use the model to test the importance of some physical and environmental factors in biomass production, to quantify water hyacinth production, and to quantify the impact of harvest on production.

2 Management Options

2.1 Harvesting or Mechanical control.

Manual removal or mechanical harvesting as a means of reducing water hyacinth infestation has been widely practiced in many countries. But the weed problem is so staggering and the technique of harvesting and disposal is so inadequate that it has been written off by many as serving no more than cosmetic value. Harvesting has, however, still been used in many places because of its certain obvious advantages [2].

2.2 Biological control

Biological control may have a self-perpetuating and long lasting effect. As the biotic agent can reach inaccessible areas, a uniform control of an area may be achieved. It is believed that on long term basis biological control will be relatively cheaper than other methods of control [2]. It has been demonstrated that a few arthropod species are host specific (Neochetina eichhornia, Neochetina bruchi, Orthogalumna terebrantis) to water hyacinth [2].

2.3 Chemical control

The need for trained personnel for safe and effective use of herbicides has been stressed [2]. Considerable damage may result on the environment and operating personnel by faulty use of these chemicals by untrained persons. Besides, satisfactory quality control of the chemicals and formulations used is very important [2]. Harmful contaminants may cause serious damage. For this very reason, it is highly desirable to avoid the use of chemicals for aquatic weed control if a suitable alternative is available.

3 Model Formulation

Two state variables, the shoots and the roots biomass per square meter, were considered in the model. The above-water plant stand was divided into 1 cm thick horizontal layers in which the dry matter budget and elongation were calculated separately. The plant growth is considered to be insensitive to fluctuations on a time scale of less than one day. The equations described in this model are similar to the equations described by Nimal Priyantha [7]. The governing equation of shoots and roots growth is described by;

$$\frac{db_{sht}(i)}{dt} = [Pg_{sht}(i) - R_{sht} - D_{sht}]b_{sht}(i) - G_{rt}\left(\frac{b_{sht}(i)}{B_{sht}}\right) - H_{sht}\left(\frac{b_{sht}(i)}{B_{sht}}\right) \quad (1)$$

$$\frac{dB_{rt}}{dt} = G_{rt} - R_{rt}B_{rt} - D_{rt}B_{rt} - H_{rt} \quad (2)$$

where $b_{sht}(i)$ is the dry weight of above-ground biomass at ith layer(g dry wt. m^{-2} per one cm height); B_{rt} is the total root biomass (g dry wt. m^{-2}); $Pg_{sht}(i)$ is gross growth rate of shoots at the ith layer (day^{-1}); R_{sht} and R_{rt} are the respiration rate of shoots and roots (day^{-1}); D_{sht} and D_{rt} are the mortality rates of shoots and roots (day^{-1}); G_{rt} is the supply of photosynthesized material for root growth (g dry wt. m^{-2} day^{-1}); H_{sht} and H_{rt} are the harvesting rates of shoots and roots (g dry wt. m^{-2} day^{-1}); and B_{sht} is the total shoot biomass (g dry wt. m^{-2}). The total shoots biomass is given by;

$$B_{sht} = \sum_{i=1}^{n} b_{sht}(i) \quad (3)$$

where n is the number of layers in the plant canopy. The total biomass is equal to;

$$B_{Total} = B_{sht} + B_{rt} \quad (4)$$

and the total harvesting rate is equal to;

$$H_{Total} = H_{sht} + H_{rt} \quad (5)$$

The gross growth rate of the shoot biomass is assumed to be controlled by air temperature, water nutrients, and irradiance. The gross daily growth rate at the ith layer is given by the Michaelis-Menthen type equation;

$$Pg_{sht}(i) = Pg_{max}\theta^{(T-20)} \times \frac{I_{PAR}e^{-k_cF_i}}{K_{PAR} + I_{PAR}e^{-k_cF_i}} f(N)f(P) \quad (6)$$

where Pg_{max} is the maximal photosynthetic growth rate (day^{-1}); θ is the Arrhenius constant; T is the daily averaged temperature; I_{PAR} is the photosynthetically active radiation (J m^{-2} day^{-1}) which is about 40-45% of daily total global radiation; k_c is the light extinction coefficient within the plant canopy; K_{PAR} is the half saturation constant for irradiance (J m^{-2} day^{-1}); F_i is the cumulative leaf area index of the stand above the layer I is given by;

$$F_i = \sum_{i=1}^{i} LAI(i) \quad (7)$$

A relationship of shoot biomass and leaf area index (LAI) was established by us using the measured data obtained from Center and Spencer [1].

$$\sum_{i=1}^{i} LAI(i) = 0.0047\sum_{i=1}^{i} b_{sht}(i) - 1.0 \times 10^{-6}\left(\sum_{i=1}^{i} b_{sht}(i)\right)^2 \quad (8)$$

Nitrogen limitation and phosphorous limitation for the growth of the plants are given by;

$$f(N) = \frac{N}{K_N + N} \quad (9)$$

$$f(P) = \frac{P}{K_p + P} \quad (10)$$

where N and P are concentrations of inorganic nitrogen and phosphors in water (mg m^{-3}); K_N and K_P are half saturation constant for nitrogen and phosphors uptake (mg m^{-3}). Root growth is given by;

$$G_{rt} = g_m \theta^{(T-20)} \frac{K_{rt}}{K_{rt} + Age_{rt}} B_{rt} \quad (11)$$

where g_m is the maximum specific growth rate of roots at 20^{0}C (day^{-1}); K_{rt} is the half saturation coefficient of root age (days), and Age_{rt} is the age of roots (days). Respiration for shoots and roots are given by;

$$R_{sht} = \beta_{sht} \theta^{(T-20)} \quad (12)$$

$$R_{rt} = \beta_{rt} \theta^{(T-20)} \quad (13)$$

where β_{sht} and β_{rt} are rate coefficients for respiration of shoots and roots (day^{-1}). Detrital production, D of Equation (1), occurs when conditions are poor for growth, or when conditions are optimal and death is caused by dense, overcrowding of plants. When conditions are optimal, water hyacinths vegetatively reproduce to cover the water surface and then continue to grow vertically. At high densities, growth will continue, but plant material lower in the canopy will die. Mitsch [8] simulated detrital production in dense conditions by matching all growth above 2667 g/m^2 with an equal amount of detrital production. Mortality of the shoots and roots is given by;

$$D_{sht} = \gamma_{sht} \theta^{(T-20)} \quad (14)$$

$$D_{rt} = \gamma_{rt} \theta^{(T-20)} \quad (15)$$

where γ_{sht} and γ_{rt} are specific rate of mortality at 20^{0}C. A time step of one day was used in the model calculations. The fourth order Runge-Kutta method was used in this model in order to solve the simultaneous differential equations representing state variables.

4 Results

3.1 Model Calibration

Sato and Kondo [3] grew water hyacinth in 500 litre tanks of water of surface area of 0.66 m^2 in a green house located at the University of Osaka Prefecture, Japan. They used four different nutrient solutions for their experiment carried out from August 2 to September 19, 1977. Mineral composition of the standard (1-fold) culture solution was in mg/l 3.5 for NH_4-N, 24.5 for NO_3-N, 7.7 for P, 29.3 for K, 18.2 for Mg, 20.0 for Ca, 2.5 for Fe, 0.2 for B, 0.2 for Mn, for 23.0 Na. The initial fresh biomass of each tank was 57.1 g. The fresh weight was converted to dry weight using the dry weight to fresh weight ratio of 3.94 % which was estimated by Sato and Kondo [3].

Concentrations of available nitrogen and phosphorus have been often cited as the most important factors in limiting water hyacinth growth [4-6]. The half-saturation coefficients for water hyacinth grown under constant conditions have been found to be from 0.05 to 1 mg/mL for total nitrogen and from 0.02 to 0.1 mg/mL for phosphates. Water hyacinth growth quickly tails off below the lower limits.

The observed and simulated growth curves for two different culture solutions are given in Figures 2 and 3. Several values of each parameter, within an expected range defined by the literature, were tested before arriving at growth curves which closely matched observed results. The parameter values used in the model calibration are given in the Table 1. As can be seen in Figures 2 and 3, model predictions matched observations well, particularly for the early growth period.

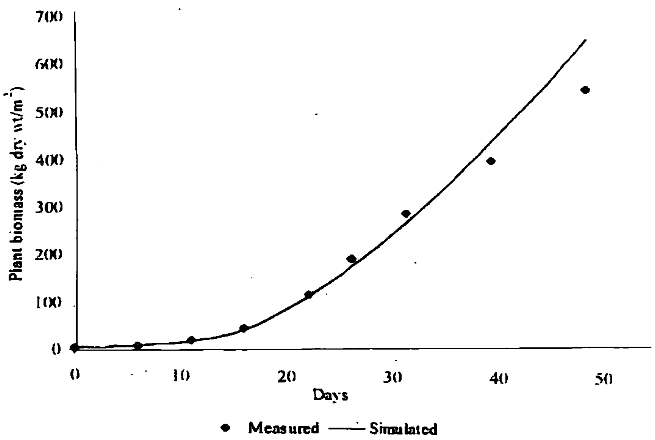

Figure 2 Calibration of water hyacinth growth model using measured data from 1-fold culture solution of Sato and Kondo [3]

3.2 Model Verification

Water hyacinth growth data from the growth study conducted in Bolgoda Lake was used for model verification. This study was conducted by cultivating healthy plants of the same size and weight in an area of 15 ft x 15 ft separated by a bamboo fence [9].

Figure 4 illustrates a rapid growth of Water Hyacinth during this first nine weeks and the growth stabilized during the next three weeks. This may be due to the density of the plants, which inhibited its growth. When salinity exceeded 1.5 ppt in the 11^{th} week, the plant biomass started to decline [9]. Therefore, for the model verification, only growth data of up to week 11 were used. Simulated and measured plant growth variation show a good agreement (Figure 5).

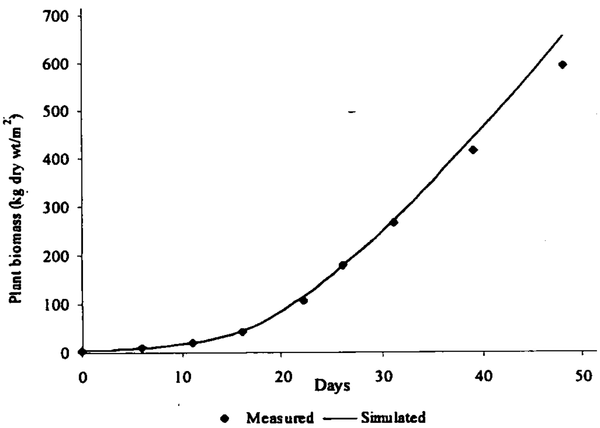

Figure 3 Calibration of water hyacinth growth model using measured data from 3-fold culture solution of Sato and Kondo [3]

Table 1: Parameter values used for the model calibration

Parameter	Value	Parameter	Value
Pg_{max}	0.68	g_m	0.025
θ	1.09	K_{rt}	30
k_c	0.63	β_{sht}	0.0016
K_{PAR}	2365×10^6	β_{rt}	0.001
K_N	20	γ_{sht}	0.001
K_P	50	γ_{rt}	0.001

3.3 Model Application

Water hyacinth has been employed for treating sewage effluents, agricultural drainage water and eutrophic lake water [2]. Therefore it is required to find an efficient way to harvest the biomass of water hyacinth in order to attain the maximum sustainable yield. By this type of harvest strategy, it is possible to remove the maximum amount of nutrients from water and simultaneously remove the aquatic plants to use them in beneficial ways.

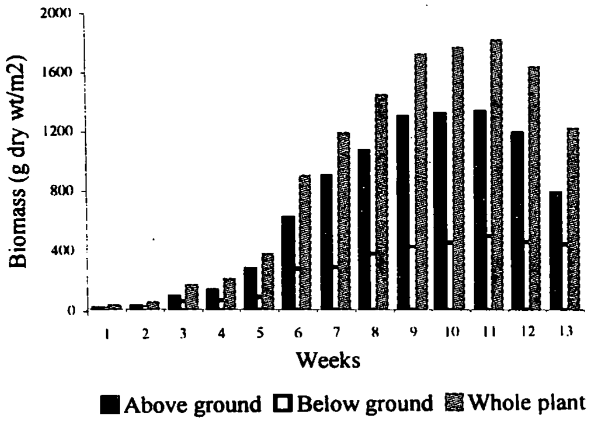

Figure 4 Biomass variation during the study

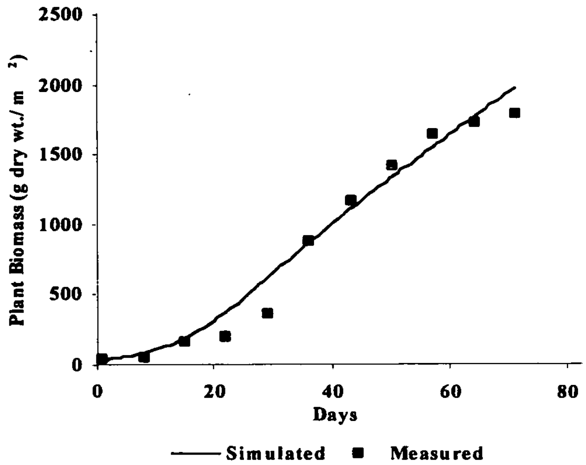

Figure 5 Simulated biomass of water hyacinth using the growth model

The model was used to assess the growth of water hyacinth after harvesting at different time intervals. Figure 6 shows the growth curve after harvesting to an initial biomass of 20 g dry wt/m^2. It was found that if water hyacinth was harvested at 30 day intervals the maximum harvest would be 348 g of dry wt./m^2 and if the harvesting interval was 40 days the maximum harvest would be 566 g dry wt./m^2.

The model was then used to find the harvest by changing the initial weight of the water hyacinth.

Figure 7 shows the growth curve after harvesting to an initial weight of 50 and 100 g dry wt./m^2. If water hyacinth was harvested to an initial weight of 50 and 100 kg dry wt./m^2 the maximum harvest which could be obtained after 20 days were about 259 and 329 g dry wt/m^2.

5 Conclusions

A mathematical model was developed to simulate the growth of water hyacinth biomass. The model was calibrated using the data from Sato and Kondo [3] and used to simulate the water hyacinth growth in Bolgoda Lake, Sri Lanka. The model application shows how the model could be used to evaluate the management options for water hyacinth biomass production for nutrient removal. These options include setting the initial density after harvesting and the harvesting interval.

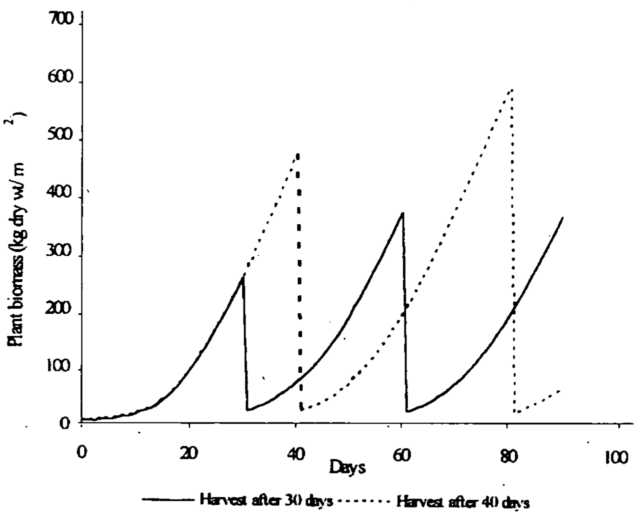

Figure 6 Simulation of growth of water hyacinth after 30 days and 40 days harvesting

It was found that if water hyacinth was harvested at 30 day intervals the maximum harvest would be 348 g of dry wt./m^2 and if the harvesting interval was 40 days the maximum harvest would be 566 g dry wt./m^2. If water hyacinth was harvested to an initial weight of 50 and 100 kg dry wt./m^2 the maximum harvest which could be obtained after 20 days were about 259 and 329 g dry wt/m^2.

This simulation study was carried out for the experimental data collected inside a green house. But in the actual field the plant can grow horizontally if the space is available. This effect could reduce the density of the plant canopy which was not included in this model. Salinity in the water can also affect the growth of the plant. Pathogen attacks can also retards the growth of the plant. Mortality of the plant due to salinity and pathogen attack was not included in this model.

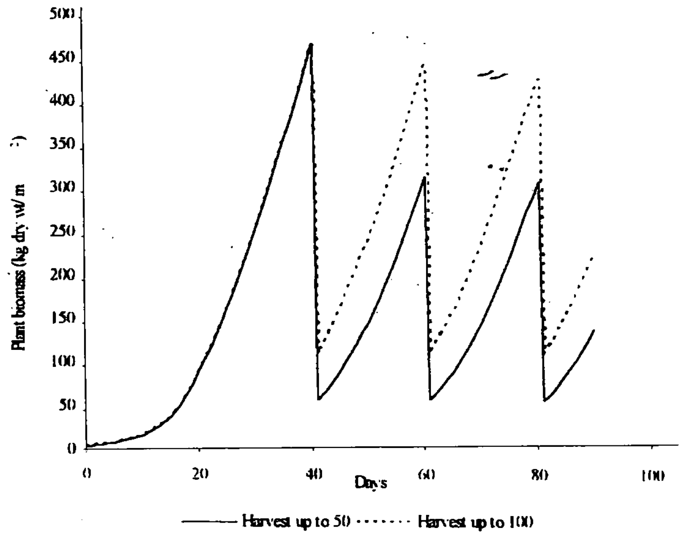

Figure 7 Simulation of growth after harvesting to a dry weight of 50 and 100 kg/m2 at 20 days interval

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Biographical Sketch

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