Modeling water hyacinth growth dynamics

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Abstract: This study aimed to evaluate the biomass growth of water hyacinth (*Eichhornia crassipes* [Mart.] Solms) under partially controlled conditions during a 70-day test using a mixture of municipal wastewater and water from a shaft as a source of nutrients. The water hyacinth in a moderately continental climatic condition at a latitude of 43°N can achieve productivity of an average of 18.25 kg/m^2 in partially controlled conditions, whereas under natural conditions and under conditions of controlled harvesting, larger amounts of biomass can be obtained. Considering the large amounts of biomass of over 1.5 t/ha per day, i.e. over 180 t/ha per year, produced, water hyacinth can be successfully used in wastewater treatment plants with very favorable economic effects if the biomass generated is used for energy production, as a nutrient or food, and for many other needs. The following models were used to model the dynamics of water hyacinth biomass growth: the exponential model (average MSE 0.3117, average R^2 to 0.9793), second-order polynomial model (average MSE 0.0952, average R^2 0.9937) and logistic model (average MSE 0.0508, average R^2 0.9966). All models have high accuracy; however, the exponential model and the second-order polynomial model give a continuous increase in biomass over time, practically to infinity, without taking into account that under conditions of increased plant density and reduced availability of resources, biomass growth slows down, and therefore, they are not suitable for application in real conditions. The logistic model (average environmental capacity 18.25 kg/m^2, average growth rate 0.0571 g/g·day after about 150 days) adequately describes the growth of water hyacinth biomass with high accuracy, which enables the monitoring and control of the process operation and the achievement of the required quality of the treated wastewater.

Keywords: water hyacinth; floating macrophyte; water hyacinth biomass production; biomass growth model

Abbreviations: daily increase rate (DIR); daily relative growth rate (RGR); biomass doubling time (DT); dry weight (DW), wet weight (WW); probable biomass after time t on wet biomass basis (W_t); initial biomass on wet biomass basis (W_o); growth limit value of the population or load capacity (K); the rate constant or growth (r), integration constant (a); mean squared error (MSE); root mean square error (RMSE); mean absolute error (MAE); coefficient of determination (R^2)

INTRODUCTION

Water hyacinth (*Eichhornia crassipes* [Mart.] Solms), an aquatic free-floating plant native to the Amazon Basin [1], is considered one of the most productive plants and one of the ten worst weeds in the world [2]. It is a species of great ornamental value used in horticulture and aquaristics due to the beauty of its leaves and flowers [3], which is why it has been extended to other tropical and subtropical regions around the world. Currently, *E. crassipes* is widely present throughout tropical and subtropical areas between the latitudes of 39°N and 39°S [3].

E. crassipes occurs in about 62 countries in Africa, Asia, North America and Europe where it creates extremely serious ecological, economic and social problems [4]. *E. crassipes* is included in the IUCN (International Union for Conservation of Nature) list of 100 most dangerous invasive species [3], as well as in the list of invasive alien species of concern in the EU [5].

Most of the problems associated with *E. crassipes* occur due to its rapid growth, ease of propagation and its ability to compete successfully with other aquatic plants. These characteristics generate enormous amounts of biomass covering the water surface of a large number of habitats, creating serious ecological problems and often hindering the use and management of water resources [3].

E. crassipes is responsible for drastic changes in the plant and animal communities of freshwater environments. It suppresses autochthonous flora and occupies ecological niches, disrupting the interactions and balance between plants, animals and the physical environment [6]. In freshwater environments in areas infested with water hyacinth, temperature, pH, dissolved oxygen and bicarbonate alkalinity are lower, but the concentration of dissolved free carbon dioxide is higher than in open water areas that are not infested [7]. Water hyacinth can also change water clarity and reduce the concentration of nitrogen, phosphorus, heavy metals and other pollutants [8]. A decrease in dissolved oxygen in water creates an environment that is not suitable for aquatic organisms and leads to a decrease in the growth, abundance and activity of phytoplankton and fauna [6,9]. Sometimes there is complete exhaustion of dissolved oxygen, which leads to the death of fish [10].

Water hyacinth creates blockages of waterways, makes navigation difficult, slows down the flow of water and significantly increases the level of flood waters and the risk of flooding, interferes with the recreational use of water systems, reduces the efficiency of irrigation and hydropower generation and increases the risk of mechanical damage to hydropower systems [3,6]. It also increases water losses due to increased evapotranspiration and creates favorable conditions for carriers of serious human and animal diseases [11].

The invasion of water hyacinth in freshwater systems creates problems for many human needs. The most direct impacts are on boat access and navigability, as well as the consequent isolation from water sources, gardens, markets and health services [6,8]. Difficult access to fishing areas and a decrease in fish catch also occur. Increased water losses due to increased evapotranspiration can be a serious problem in areas with small waterbodies and limited water supply [8]. In freshwater systems that are used as sources of water for agriculture, industry and the population, serious problems occur due to changes in the water quality and increased costs of water treatment [8].

Biological and socioeconomic impacts are often not immediately apparent, damage can increase over time as a result of synergistic biological or economic interactions [12], and because of the numerous problems caused by water hyacinth, measures are being taken to control it around the world. Regardless of the measures implemented in different countries, there is limited success in achieving water hyacinth control objectives [3], and the physical, mechanical, chemical and biological measures applied can cause complications. Herbicides used as a chemical means of water hyacinth control pollute waterbodies, the introduction of predators as a biological means of control can have a secondary catastrophic impact [13], and physical and mechanical means, which are the most practical, are expensive [14]. Also, harvested water hyacinth biomass can create problems of waste, if not properly managed [15].

For the above reasons, in the last few years, there have been numerous attempts to address the control of water hyacinth by using its biomass in practical applications, which would also contribute to reducing the costs of its elimination [3]. The rapid reproduction and high productivity of water hyacinth provide many opportunities for its use as a sustainable resource [15] that can contribute to economic growth [16]. There is a wide range of possibilities for using water hyacinth that includes various sectors such as agriculture, energy, metallurgy, civil engineering, pharmacology, arts and crafts, etc. [17-19].

Based on previous research, only some potential uses of water hyacinth biomass have been considered, but this is an area in which extensive research is yet to arrive. Numerous studies on the potential use and conversion of water hyacinth biomass into products with economic value have determined that water hyacinth has the potential for use as human food [4], livestock [20-22] and fish feed [22], organic fertilizer [17,20], bio-based building material [17], in medicine [2,4,22,24], for the production of biopolymers [17], cellulose [17], paper [20,23], furniture, bioenergy [17,22,24], as well as in wastewater treatment (phytoremediation) [17,22].

The use of water hyacinth for energy production appears to be very useful [11] and the option of producing briquettes, bioethanol and biogas [17,22,23], according to previous research, not only improves energy availability but also environmental sustainability and reduces greenhouse gas emissions [17]. As water hyacinth belongs to the group of fastest-growing plants, its biomass has the potential to become a renewable energy source and replace conventional fossil fuels, perhaps already within the next decade [24].

The possibility of using floating macrophytes in the removal of a wide spectrum of pollutants from water and wastewater is attracting great attention worldwide. Floating macrophytes use nutrients from the water and incorporate them into their biomass and they can be effectively used to reduce pollutant levels in waterbodies [25-26], as well as to treat wastewater at treatment plants [4,28]. Water hyacinth has potential in the removal of organic and inorganic pollutants and toxic chemicals present in different types of wastewater, both urban and industrial, and it can be the best tool for sustainable management of wastewater treatment [4].

Intensive research in this field started in the 1970s and almost at the same time in Serbia. Initial results were obtained in the period 1975-1979 at the Faculty of Civil Engineering in Niš and the wastewater treatment plant in Sokobanja, which was considered a training facility for the staff of this faculty [28]. During the eighties, in cooperation with experts from the USA, numerous biological unit operations (floating macrophytes, aquacultures, aquapolycultures, hydroponics, vermicultures) were studied as laboratory models and then brought to the level of macro models, i.e. as parts of the existing facilities for wastewater processing in Sokobanja and Blace [28]. Research in this field at the Faculty of Civil Engineering and Architecture of Niš has continued to the present day [28-30].

The obtained results show that the application of floating macrophytes and other macrobiological unit operations for addressing the biochemical oxygen demand (BOD), the treatment of wastewater and the effective removal of nitrogen, phosphorus and numerous other pollutants, including heavy metals [24,26,27], is a sustainable alternative that is more favorable than expensive classical technology.

The economic considerations of floating macrophytes and other macrobiological unit operations, including wastewater treatment technologies, are very positive if one considers the potential for nutrient recirculation and the value of the produced biomass, especially in terms of its energy potential. For smaller settlements, water hyacinth could be used as an integrated approach in decentralized wastewater treatment systems in conjunction with the production of biogas and compost, as well as numerous other useful products from the produced biomass [24].

There are many studies investigating water hyacinth growth dynamics, but they have mostly been performed for water hyacinth-endangered areas with high air temperatures that favor the rapid growth of water hyacinth. In areas outside this zone and with a moderate climate, there are almost no such studies. Therefore, the aim of this study was to examine the behavior of water hyacinth biomass in environmental conditions that are generally favorable for its increase, and to determine the growth dynamics and define a reliable mathematical model of water hyacinth biomass growth dynamics. The dynamics of biomass growth and its mathematical representation are the starting point in analyzing the possibility of using water hyacinth in the treatment of wastewater in smaller settlements under conditions of a moderate-continental climate and in the planning and control of the treatment process. The effects of removing various pollutants have been well studied and stated in numerous works [24,28], and understanding the dynamics of water hyacinth biomass growth for certain climatic conditions is the most important element in designing a treatment process, and a reliable predictive mathematical model of biomass growth is necessary for the planning and control of the treatment process from the aspect of the projected effects of removing certain polluting substances from wastewater.

MATERIALS AND METHODS

Location

The experiment was conducted on the terrace above the hall of the Faculty of Civil Engineering and Architecture of Niš (43.33°N, 21.89°E).

Characteristics of water hyacinth

Water hyacinth (*Eichhornia crassipes*), also known as floating/common water hyacinth, is a free-floating plant belonging to the family Pontederiaceae, genus *Eichhornia*, containing seven species of which *Eichhornia crassipes* is most widely present [22].

A fully grown plant consists of long, hanging roots, rhizomes, stolons, spongy stems with circular to oval leaves, an inflorescence with 6-10 attractive lilac to blue flowers, and fruits (Supplementary Fig. S1). The presence of air in the stems and leaves allows the plant to float on the surface of the water [22]. The average height of the plant is about 40-60 cm, and it can grow to a height of 1 m. The plant can be propagated vegetatively through the generation of stolons and sexual reproduction through seeds, which are able to survive in water for up to 15 years [22].

The ecological, morphological, developmental and biological attributes of water hyacinth include its ability to adapt to a wide range of environmental conditions, where its growth is easily stimulated in the presence of nutrients, especially with excess concentrations of nitrates and phosphates, although it can also tolerate low concentrations of nutrients.

The optimum pH of water for plant growth is 6-8, but it can tolerate pH values of 4-10. The optimum water temperature for growth is 28-30°C, while the optimum air temperature is 21-30°C. Temperatures above 33°C inhibit further plant growth [32]. Water hyacinth growth ceases when the water temperature falls below 10°C, and prolonged low temperatures, below 5°C, cause plant death, limiting the distribution of water hyacinth at higher latitudes [33].

Water hyacinth has a very high vegetative reproduction rate and biomass growth dynamics, which is why it is considered one of the most productive plants in the world [2, 33]. If the water temperature is between 27°C and 33°C, the plant mass of water hyacinth doubles in one to two weeks. Under favorable conditions of temperature and availability of nutrients in tropical regions, the average annual productivity can reach 50 kg/m^2 of dry water hyacinth per year [24], and sometimes more. A fresh water hyacinth plant contains 95.5% moisture, 0.04% nitrogen, 1.0% ash, 0.06% P_2O_5, 0.20% K_2O and 3.5% organic matter [24].

Plant material

Every year in the middle of May, when the daily temperatures stabilize above 15°C in the shaft at the hydraulic engineering demonstration facility of the Faculty of Civil Engineering and Architecture in Nis, which is filled with atmospheric runoff from the surrounding grassy areas, water hyacinth and water lettuce are sown from the plant material that is stored as parent material for the following season in the laboratory during the winter at the wastewater treatment plant in Sokobanja, given that plants in our climate cannot survive the winter.

Experimental procedure

The tests of *E. crassipes* growth dynamics were performed on an intermittent model of the system (Supplementary Fig. S2) in partially controlled conditions. Tests were carried out in a series of 5 basins of the same shape and size (total basin depth 0.5 m, bottom surface area 0.30 m^2, top area, bottom area 0.40 m^2). The basins were positioned outdoors on the terrace above the hall of the Faculty of Civil Engineering and Architecture in Nis (Supplementary Fig. S3) so the climate impact on plant biomass growth would be included in the analysis. The tests were started on June 29th, 2004, after stabilization of the minimum air temperature above 15°C and completed on September 7th, 2004. The results have not been published previously, but have become increasingly relevant with the actualization of solving the problem of wastewater treatment in Serbia.

The initial amount of water in each basin was 50 L and it was obtained by mixing 50% of water from the shaft at the hydraulic engineering demonstration facility and 50% of sewage water collected at the outlet of the main collector of the general sewage system of the city of Nis near the village of Medoševac. Three water hyacinths and three water lettuces of approximately the same composition were initially sown in each basin. After sowing the plants, the initial water level was marked in all basins.

Before sowing the plants, the starting wet biomass of water hyacinth was measured in each basin individually. The growth of aquatic plants in the system was monitored on a weekly basis. During the test, the wet biomass of the plants in each basin was individually measured every seven days. The wet biomass of the plants was measured with a digital analytical balance with an accuracy of 0.1 g. Before measuring, the plants were carefully removed from the basins and left on a paper towel for 5-7 min to drain the water from the root system.

The starting assumption of the experiment was that nutrients are not a limiting factor for the growth of floating macrophytes. To ensure a constant water level in the basins, every 7 days the amounts of water removed by evapotranspiration were added to maintain the initial levels. To replenish the nutrients in the aquatic environment necessary for the normal growth and development of plants, sewage wastewater captured on the same day at the outlet of the main collector of the general sewage system was added to the basins.

Statistical analysis

For the analysis of the growth rate of water hyacinth biomass and to compare the results to the results obtained in different locations and in other waterbodies, the following values were calculated: daily increase rate (DIR) relative to initial biomass [35] in (%/day), daily relative growth rate (RGR) [36] in (g/g·day) and biomass doubling time (DT) [37] in (day):

$$DIR = ((W_t-W_o)/(t-t_o))\cdot 100/W_o$$
$$RGR = (\ln W_t-\ln W_o)/(t-t_o)$$
$$DT = \ln 2/RGR$$

In previous research, the most often used models for the growth dynamics of water hyacinth were the exponential (Malthusian) growth model, the second-order polynomial model and the logistical model (Verhulst growth model) of growth.

The exponential model is presented with the equation [29,38]:

$$W_t = W_o\cdot e^{rt}$$

The second-order polynomial model is presented with the equation [29]:

$$W_t = W_o + a_1\cdot t + a_2\cdot t^2$$

The logistical model is presented with the equation [37]:

$$W_t = K/(1+e^{a-rt})$$

where W_t is the probable biomass after time t on wet biomass basis (kg/m^2), W_o is the initial biomass on wet biomass basis (kg/m^2) (initial state), K is the growth limit value of the population or load capacity (kg/m^2), r is the rate constant or growth (g/g·day), a is the integration constant, a_1 and a_2 are the regression coefficients and t is the time (day).

The integration constant in the logistical model is defined through the expression:

$$a = \ln ((K-W_o) / W_o),$$

with the coordinate of the first point of inflection of the logistical curve determined as 1/r in a day.

The agreement of the model with the experimental data was assessed via the m mean squared error (MSE) that measures the average of the squares of the errors or deviations (the difference between the estimator and what is estimated).

The root mean square error (RMSE) is the square root of the arithmetic mean of the squares of a set of numbers (a measure of imperfection of the fit of the estimator to the data).

The mean absolute error (MAE) is used to measure how close forecasts or predictions are to eventual outcomes.

The coefficient of determination (R^2) is interpreted as the proportion of the variance in the dependent variable that is predictable from the independent variable.

The method of defining the best model can differ, and it could be the model that has the highest R^2 or the model with the least MSE, RMSE or MAE.

For data processing and analysis Microsoft Excel 2019, the free component-based software suite for machine learning and data mining Orange v3.32 and IBM SPSS Statistics 26 were used.

RESULTS

This paper presents the results of water hyacinth research. The results of the water lettuce research will be presented in a separate paper.

Climate conditions

For the entire test period, daily meteorological data (air temperature, precipitation, relative humidity, sunshine) were obtained from the RHMZ (Republic Hydrometeorological Service of Serbia) (Supplementary Table S1. and S2.). During the test period of 10 weeks, the average daily air temperature was 15.5°C-29.5°C, average 21.8°C, minimum daily air temperature

9.7°C-20°C, average 15°C, and maximum daily air temperature 19.9°C-38.6°C, average 29.3°C. Daily sunshine ranged from 0-12.8 h/day, with an average of 8.5 h/day, including short one-day intervals with less sunshine. It rained for 18 days, mostly briefly, with an average of 1.1 mm, with the exception of days 14 and 29 when there was significant rainfall of more than 15 mm (Supplementary Tables S1. and S2).

At the beginning of the 11th week, 71 days from the start of the test, there was a sudden drop in the morning air temperature to 7.4°C and the minimum daily temperature to 5.7°C. Low morning and minimum daily temperatures continued during the 11th week and reached the minimum on September 11, 2004, when the morning air temperature was 5.4°C and the minimum daily temperature was 2.5°C (Supplementary Table S1). The drop in air temperature had a negative impact on the growth and development of the plants. Almost immediately after the drop in air temperature, there was a change in the color of the water hyacinth leaves, drying of the leaves and a slow decay of the plants in all the basins. Due to the deterioration of the plant material during the 11th week, which is a consequence of conducting the tests in partially controlled conditions, the tests were interrupted and the biomass at the end of the 11th week was not measured.

Water hyacinth biomass growth

The measured biomass of water hyacinth is converted into kg/m^2 for easier comparison. The measured values of water hyacinth wet biomass for the entire research period for each basin individually are presented in Supplementary Table S3. The results of the calculation dW/dT (g/m^{2}day), DIR (%/day), RGR (g/g·day) and DT (day) for each basin individually are presented in Supplementary Tables S4-S8. The calculation procedure and all results are presented in the Excel file output_results.xlsx attached to the Supplementary Material. The average values of dW/dT, DIR, RGR and DT for the entire research period for each individual basin are presented in Table 1.

Water hyacinth growth dynamic modeling

To model the growth dynamics of water hyacinth, exponential, second-order polynomial and logistic models were created in the Orange v3.32 program (Supplementary Fig. S4). Parameters of the three models of water hyacinth growth dynamics are presented in Tables 2, 3 and 4. The amount of water hyacinth wet biomass, observed and modeled by the exponential and logistic models, and variation of dW/dt over time, observed and modeled by the logistic model, for each basin individually are presented in Fig. 1. (A.1-A.5).

Table 1. Average values of biomass growth dW/dT, DIR, RGR and DT for the entire research period.

Basin	dW/dt (g WW/m^{2}day)	DIR (%/day)	RGR (g/g·day)	DT (day)
Basin 1	167.40	15.19	0.0351	22.35
Basin 2	157.14	14.97	0.0349	21.76
Basin 3	161.82	16.47	0.0361	23.87
Basin 4	159.19	17.30	0.0368	21.66
Basin 5	156.31	14.50	0.0344	21.77
Average	160.37	15.69	0.0355	22.28

Absolute daily biomass growth (dW/dt); daily increase rate (DIR); daily relative growth rate (RGR); biomass doubling time (DT).

Table 2. Parameters of the exponential water hyacinth growth dynamics model.

Basin	W_o (kg/m^2)	r (g/g·day)	MSE	RMSE	MAE	R^2
1	1.4752	0.0320	0.3838	0.6196	0.5564	0.9767
2	1.2917	0.0329	0.2648	0.5146	0.4590	0.9813
3	1.1399	0.0350	0.3103	0.5571	0.4959	0.9799
4	1.1698	0.0344	0.3583	0.5986	0.5289	0.9759
5	1.3025	0.0327	0.2410	0.4909	0.4384	0.9827
Average	1.2758	0.0334	03117	0.5561	0.4957	0.9793

Initial biomass on wet biomass basis (W_o); the rate constant or growth (r); mean squared error (MSE); root mean square error (RMSE); mean absolute error (MAE); coefficient of determination (R^2).

Table 3. Parameters of the second-order polynomial water hyacinth growth dynamics model.

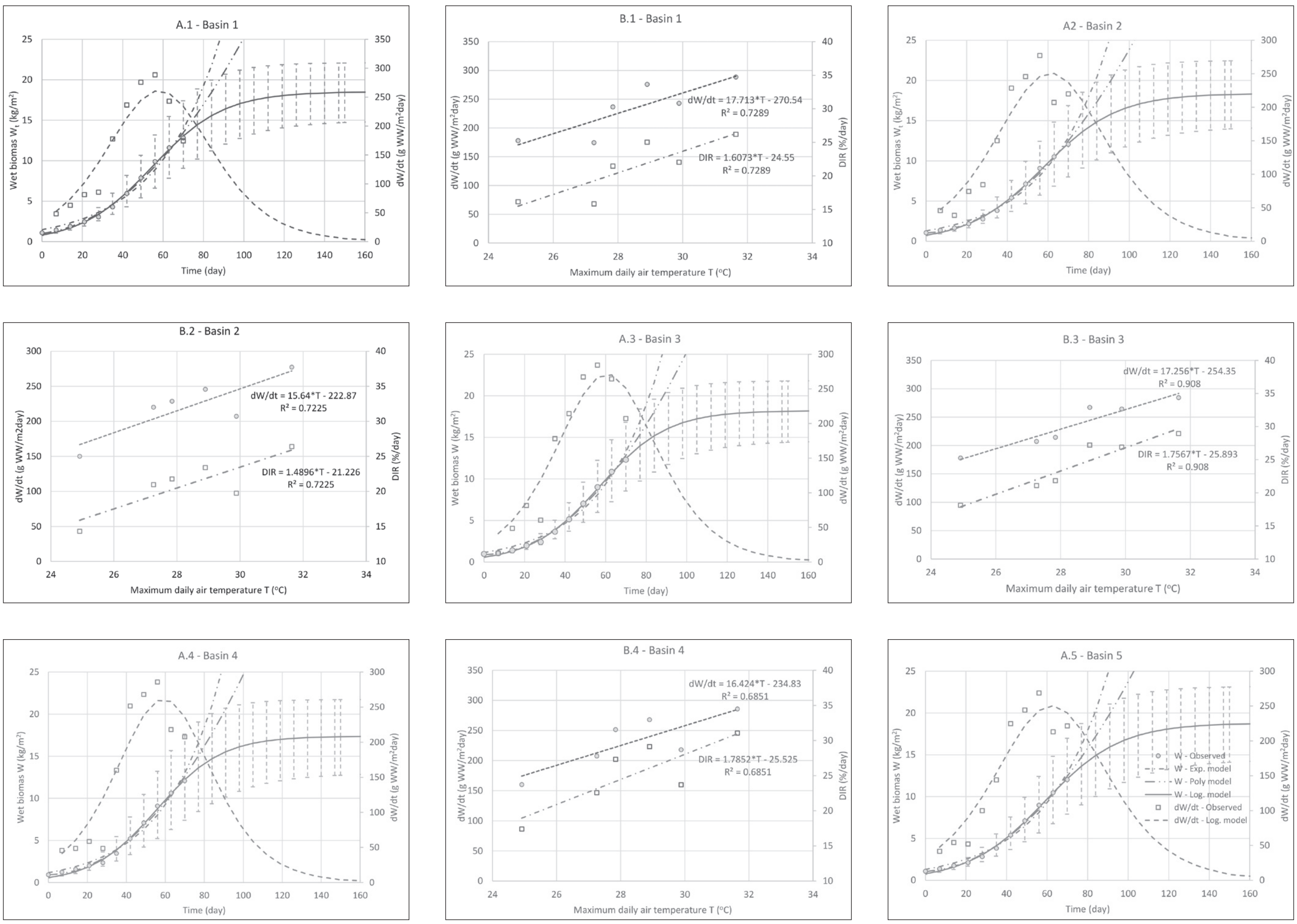
Basin	W_o (kg/m^2)	a_1	a_2	MSE	RMSE	MAE	R2
1	1.0008	0.0293	0.0021	0.1207	0.3474	0.2802	0.9927
2	1.0029	0.0142	0.0021	0.0757	0.2752	0.2151	0.9946
3	0.8861	0.0008	0.0024	0.0811	0.2847	0.2225	0.9948
4	0.9161	0.0036	0.0023	0.1317	0.3629	0.2861	0.9911
5	1.0406	0.0137	0.0021	0.0667	0.2582	0.2121	0.9952
Average	0.9693	0.0123	0.0022	0.0952	0.3057	0.2432	0.9937

Initial biomass on wet biomass basis (W_o); regression coefficients (a_1, b_2); mean squared error (MSE); root mean square error (RMSE); mean absolute error (MAE); coefficient of determination (R^2)

Table 4. Parameters of the logistical water hyacinth growth dynamics model.

Basin	K (kg/m²)	a	r (g/g·day)	W_o (kg/m²)	1/r (day)	MSE	RMSE	MAE	R2
1	18.5181	3.0927	0.0566	0.8039	17.6567	0.0521	0.2282	0.2110	0.9968
2	18.3735	3.1640	0.0548	0.7449	18.2356	0.0431	0.2075	0.1689	0.9970
3	18.2117	3.4143	0.0599	0.5801	16.7010	0.0423	0.2057	0.1821	0.9973
4	17.3699	3.3676	0.0605	0.5789	16.5352	0.0763	0.2761	0.2398	0.9949
5	18.7906	3.1419	0.0535	0.7782	18.6963	0.0403	0.2008	0.1746	0.9971
Average	18.2528	3.2361	0.0571	0.6972	17.5650	0.0508	0.2237	0.1953	0.9966

Initial biomass on wet biomass basis (W_o); growth limit value of the population or load capacity (K); the rate constant or growth (r), integration constant (a); mean squared error (MSE); root mean square error (RMSE); mean absolute error (MAE); coefficient of determination (R^2)



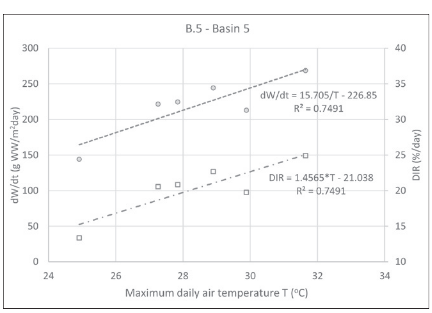


Fig 1. Measured and modeled amount of water hyacinth biomass W_t and daily biomass growth dW/dt over time (A.1-A.5) and variation of dW/dt and DIR as a function of maximum daily air temperature (B.1-to B.5), with error bars indicating 95% confidence interval for the predicted values.

Correlations between production values and temperature data

One of the main factors affecting the growth of water hyacinth biomass, in addition to the availability of nutrients, is air temperature. There is a strong correlation between the absolute (dW/dt) and relative (DIR) variations in daily biomass growth and the average maximum weekly air temperature, i.e. the average weekly air temperature, so a regression dependence can be established between these values [35]. Between dW/dt and the mean maximum weekly air temperature, as well as DIR and mean maximum weekly air temperature, a linear regression dependence was established using the Trendline Excel command. Variation of dW/dt and DIR as a function of the maximum daily air temperature, observed and modeled by linear regression for each basin individually, are presented in Fig 1. (B.1 to B.5). A similar regression dependence can be established between dW/dt and the average weekly air temperature, as well as DIR and the average weekly air temperature.

DISCUSSION

Climatic conditions

During the test period of 10 weeks, the air temperature ranged from 9.7°C to 38.6°C. The average mean daily air temperature was 21.8°C, the average minimum daily air temperature was 15°C, the average maximum daily air temperature was 29.3°C, and the average daily sunshine was 8.5 h/day so that the meteorological data for the entire test period were mostly within the limits required for plant growth. The drop in air temperature during the eleventh week had a negative effect on the growth and development of the plants and there was a deterioration in the plant material, which is a consequence of conducting the test in partially controlled conditions. Due to the deterioration of the plant material, the tests were discontinued. It should be noted that there was no decay of plants in the well (shaft) at the hydraulic engineering demonstration facility of the Faculty of Civil Engineering and Architecture of Niš, which indicates that the most likely reason for the decay of plants in the basins was the small amount of water and rapid drop in water temperature due to the drop in air temperature. Although the tests were discontinued because of the deterioration of the plant material, the data obtained for the test period of 10 weeks represent a good basis for the analysis of water hyacinth biomass growth dynamics in conditions of a temperate-continental climate. The obtained results and the observed effects justify further analysis.

Water hyacinth productivity

Weed growth was determined from the weight increase of the water hyacinth mass per area unit and per time unit, i.e. its productivity [37]. A wide range of values for water hyacinth productivity has been registered in the literature, with values expressed in different ways [33]. It is known that the most important factors affecting the growth dynamics of water hyacinth are the availability of nutrients, temperature and sunlight. However, these factors do not fully explain the wide range of variation in water hyacinth growth reported in the literature. Water hyacinth can cover a water surface with a relatively low density of 10 kg WW/m^2 and can reach maximum densities of 50 kg WW/m^2 [39] and even more. Depending on the environmental conditions, different yields of biomass of 500-2200 g DW/m^2 (about 10-44 kg WW/m^2) [35], 100-1500 g DW/m^2 (about 2-30 kg WW/m^2) [35], 5-40 kg WW/m^2 [40], 30-33 kg WW/m^2 [35] appear in the literature. In some wetlands in North America, the annual productivity of water hyacinth is 350-1700 t/ha [41]. This information shows that water hyacinth has a very wide range of productivity, so in order to get a realistic picture of the obtained results, it is of interest to compare our results with the results of studies in locations in similar latitudes to the research location in this study.

On seven waterbodies in Mexico (19°N to 22°N) the highest amount of biomass occurred on the Cruz Pintada dam (18.4°N), with an average of 49.6 kg WW/m^2 (2.79 kg DW/m^2) and a maximum 76.0 kg WW/m^2 (4.27 kg DW/m^2) [37]. The highest RGR value 0.0934 g/g·day and DT 8.2-8.45 day were obtained at the Requena Dam [37]. At the Tropical Fish Research Center in Brazil (22°C), in experimental conditions (at water temperatures ranging between 21.0 and 26.7°C and with lower concentration of nitrogen and phosphorus) the relative growth rate was 0.025 g/g·day [42]. At the Research and Education Center in Sanford, Florida (28.5°N) the measured biomass densities for three experimental areas were 23 kg WW/m^2 after 96 days, 60 kg WW/m^2 after 165 days and 67 kg WW/m^2 after 180 days [43]. The results of measuring at the Guadiana River Basin, Portugal and Spain (37°N to 39°N), provided an RGR between 0.04 and 0.06 g/g·day and DT between 10 and 60 days, depending on the experimental conditions. [44]. At the location of Saint-Gely-du-Fesc, Languedoc Region, France (43.78°N), on an experimental area with wastewater at air temperatures between 15 and 35°C and an initial amount of biomass of 5 kg WW/m^2 with no plant harvesting, at the end of the period of 4.5 months (May-October) the obtained amount of water hyacinth biomass was around 40 kg WW/m^2 [25]. At air temperatures lower than 15°C there is no increase in biomass, for temperatures between 20°C and 30°C the biomass increase is between 220-450 g WW/m^2day (10 and 20 g DV/m^2day) and for temperatures higher than 33°C the biomass growth is higher than 650 g WW/m^2day (30 g DV/m^2day) [25].

The productivity of water hyacinth at Raffinerie de Provence, La Mede, France (43.4°N) in a period of 2 months at air temperature 13-35°C amounted to a maximum of around 110 g WT/m^2day (6.1 g DT/m^2day), and in a period of 15 days at 20-36°C to a maximum of around 300 g WT/m^2day (16.8 g DT/m^2day) [45].

At the Faculty of Civil Engineering and Architecture of Niš (43.33°N) the measured amount of biomass after 70 days was 12.02 to 12.82 kg WW/m^2, and the annual productivity after around 150 days obtained by modeling was 17.37 to 18.79 kg WW/m^2. The average dW/dt was 160.37 g/m^2day, average DIR 15.69 %/day, average RGR 0.0354 g/g·day and average DT 22.28 day. In general, these values are similar to those obtained at locations at similar latitudes. The annual productivity of 17.37 to 18.79 kg WW/m^2 is lower than at the site of Saint-Gely-du-Fesc, Languedoc Region, France, where it was about 40 kg WW/m^2, which can be explained by the partially controlled conditions of the experiment as well as the growth of water hyacinth in polyculture with water lettuce.

Modeling water hyacinth growth dynamics

The exponential model is a relatively simple model of plant biomass growth based on the assumption that biomass grows exponentially with time and that environmental conditions are optimal during the entire period of plant biomass growth. The average coefficient of determination of 0.9793 and low values of the MSE, RMSE and MAE indicators show a high agreement of the exponential model with the measured amounts of biomass in all the basins. The growth rate of the exponential model (average of 0.0334 g/g·day for 70 days) was in agreement with the previously conducted research of 0.02914 g/g·day for 21 days of research [29], i.e. 0.015 g/g·day for the average air temperature of 10°C, 0.035 g/g·day for the average air temperature of 20°C and 0.082 for the average air temperature of 30°C, for the period of 30 days [38]. The obtained average value of the coefficient of determination of 0.9937 of the second-order polynomial model is higher than that of the exponential model, and the obtained average values of the indicators MSE, RMSE and MAE of the second-order polynomial model are lower than those of the exponential model, which shows a better agreement of the second-order polynomial model with the measured amounts of biomass in all basins in relation to the exponential model. The average values of the initial biomass and the regression coefficients of the second-order polynomial model are generally in agreement with previous research [29], with a note that the starting biomasses of water hyacinth were approximately the same in both studies. The average value of the initial biomass W_o of 0.9693 kg/m^2 obtained in this study is in agreement with the average value of W_o of 1.0308 kg/m^2 obtained in earlier studies [29]. The average value of the regression coefficient a_1 of 0.0123 kg/day for 70 days obtained in this research is slightly lower than the average value of a_1 of 0.0311 kg/day for 21 days obtained in earlier studies, and the average value of the regression coefficient a_2 of 0.0021 kg/day obtained in our research is slightly higher than the average value of a_2 of 0.0007 kg/day, which could be expected considering the shorter test time with a smaller number of available data and the different climatic conditions of earlier studies [29].

Considering the instability of the water system, primarily in terms of resource availability, it is to be expected that the plant biomass growth dynamics will vary and that in conditions of increased plant density and reduced resource availability, the biomass growth slows down. However, in accordance with the initial assumption of the exponential model that the environmental conditions are optimal during the entire period of plant biomass growth, with increasing time, this model gives a continuous increase in biomass, practically to infinity. The second-order polynomial model behaves very similarly, however with increasing time, the amount of water hyacinth biomass obtained by the second-order polynomial model is significantly smaller than with the exponential model. Water hyacinth biomass amounts for 70 days of 12.82-3.90 kg/m^2 obtained by the exponential model, and 12.44-13.46 kg/m^2 obtained by the second-order polynomial model are in agreement with the measured biomass values of 12.02-12.82 kg/m^2. However, the amount of water hyacinth biomass for 100 days of 34.14-37.87 kg/m^2 obtained by the exponential model, and 23.71-25.24 kg/m^2 obtained by the second-order polynomial model, and especially the amount of water hyacinth biomass for 150 days of 174.79-218.32 kg/m^2 obtained by the exponential model, and of 51.02-55.62 kg/m^2 obtained by the second-order polynomial model, are very large and unrealistic for the climatic conditions in which the test was conducted. This is one of the main reasons why the exponential and second-order polynomial plant biomass growth models, regardless of their high accuracy in the initial stages of biomass growth, cannot be applied in a real environment.

Research on water hyacinth growth showed that the growth of fresh water hyacinth biomass can be represented by a logistic equation [37]. Research on the growth of water hyacinth in a pond with unlimited nutrients in the central part of Florida, USA, showed that the growth of water hyacinth biomass can be defined by a growth curve characterized by three phases: (i) a delay phase followed by exponential growth, (ii) a linear growth phase and (iii) a slow exponential growth phase [37]. The logistic model well describes the biomass growth of water hyacinth defined in the mentioned study. The logistic growth assumes that biomass grows exponentially to the point of inflection, and then the growth rate slows down to the capacity of the environment K. From this movement of biomass growth dynamics, a characteristic S-shaped curve is obtained. The obtained results of water hyacinth biomass growth are very similar to the results obtained in the aforementioned study, and the logistic model describes very well the water hyacinth growth dynamics. The average coefficient of determination of 0.9966 and the low values of the MSE, RMSE and MAE indicators show a high agreement of the logistic model with the measured amounts of biomass in all basins.

From the obtained results it can be seen that the specific growth rate (% daily increase) of water hyacinth is highest at low plant density and decreases as plant density increases. The plant growth cycle ends when the maximum plant density is reached, i.e. the environmental capacity K, and there is no additional increase in biomass growth. It was found that the environmental capacity in partially controlled growth conditions for water hyacinth ranges from 17.37 kg/m^2 up to 18.79 kg/m^2, average 18.25 kg/m^2, achieved with the growth rate of the logistic model from 0.0535 g/g·day to 0.0605 g/g·day, average 0.0571 g/g·day, after about 150 days, which coincides with the period of favorable climatic conditions for a temperate-continental climate, which is 5-6 months, from May to October.

The environmental capacity obtained in this study is lower than the environmental capacity of 51-55 kg/m^2 obtained at the Requena Dam site in Mexico (19.95°N) [37], while the growth rates of the logistic model are in agreement with the growth rates of 0.0162 g/g·day to 0.0722 g/g·day obtained at the Requena Dam site. The lower environmental capacity obtained in this research (43.33°N) compared to the Requena Dam site in Mexico (19.95°N) is explained by the more favorable climatic conditions at site in Mexico and, as already mentioned, by the partially controlled conditions of the experiment and the growth of water hyacinth in polycultures with water lettuce. The high accuracy of the logistic models with an average coefficient of determination of 0.9966 is also in agreement with the high accuracy of the model and the coefficient of determination of 0.96-0.99 obtained at the Requena Dam site in Mexico (19.95°N) [37].

The biomass growth per unit area and time is maximum in the linear phase of the growth curve, between the first and second inflection points. The first inflection point is determined at 16.5 to 18.7 days, and the second inflection point at about 60 to 65 days. The plant density at this stage is defined as the "facility operational density" and is the density range at which the biomass production system is used to achieve the highest possible yield. Taking all the above into account, it is accepted that the logistic model describes the increase in water hyacinth biomass with high accuracy.

Correlations between production values and temperature data

For the analysis of the dependence between the variations in dW/dt and DIR and the mean maximum weekly air temperature, the data in the initial phase of the test were not taken into account because in this phase the plants were adapting to the new environmental conditions and the daily biomass growth was small and not representative for the analysis. The analysis took into account data from 35-70 days in the phase of stable exponential growth between the inflection points. The correlation coefficient between changes in dW/dt and mean maximum weekly air temperature, average for all basins 0.7587 for the period from 35 to 70 days of the test, shows a strong correlation between these quantities. Based on the observed data and linear regression equations, the analysis of the dependence between changes in daily biomass growth dW/dt and DIR, and the mean maximum weekly air temperature, it can be concluded that there is no biomass production when the mean maximum temperature of the observed period is lower than 14-15°C; that the mean daily production of biomass is between 80 and 260 g WW/m^2day, DIR between 7.5 and 28%/day for the maximum air temperatures between 20°C and 30°C, and that the mean daily production is between 300 and 315 g WW/m^2day, DIR 26 to 31%/day for the maximum temperatures higher than 33°C. With the relationships thus established, extrapolation for different climatic conditions can easily be carried out. This enables the formation of prognostic models for the management of the wastewater treatment process.

CONCLUSIONS

The conducted research gave the expected results, which important for the application of floating macrophytes at wastewater treatment plants in conditions of a moderately continental climate. These results provide reliable daily and annual results of water hyacinth biomass production that can be obtained in the wastewater treatment process, a reliable model for modeling water hyacinth growth dynamics, which enables the planning and control of the treatment process, and the correlation of production data with temperature data, which makes it possible to extrapolate production for different climatic conditions.

Water hyacinth in moderately continental climatic conditions at a latitude of about 43°N can achieve an average productivity of 18.25 kg/m^2 with an average growth rate of 0.0571 g/g·day after about 150 days in partially controlled conditions, while in natural conditions and under conditions of controlled harvesting, larger amounts of biomass can be achieved. Considering that this is a large amount of biomass of over 1.5 t/ha per day, i.e. over 180 t/ha per year, water hyacinth can be successfully used in wastewater treatment plants in temperate-continental climate conditions.

The logistic model adequately describes the water hyacinth increase in biomass, which facilitates the monitoring and control of the process operation and the achievement of the required quality of treated wastewater while maximizing the production of water hyacinth biomass. According to the results, the period when water hyacinth can be used for wastewater treatment in outdoor conditions is limited to 5-6 months, but it can be extended under greenhouse conditions with additional heating, which, considering the large quantities of biomass produced and the possibility of using it for energy production, does not increase treatment costs. It is very important that under conditions of a moderate continental climate, water hyacinth does not pose a danger to natural aquatic ecosystems because the average air temperatures in the winter months are less than 0°C, and prolonged low temperatures, below 5°C, lead to plant death.

The obtained results confirmed the earlier research conducted at the pilot facility in Sokobanja and at the Faculty of Civil Engineering and Architecture in Niš and the suitability of hydrophytoculture technologies for removing nutrients from wastewater. The obtained results open up the field of phytoremediation and management of pollution of natural environments. The study of the growth dynamics of water hyacinth was performed on an intermittent system model in partially controlled conditions, which certainly had an impact on the obtained results. To verify the obtained results and parameters of the water hyacinth growth dynamics model, further research should examine the dynamics of water hyacinth biomass growth on a flow model in real environmental conditions. Possible inhibiting factors that can influence the growth dynamics of water hyacinth biomass, such as salinity, pH, certain pollutants that may be present in the water and the threshold values of those factors at which biomass growth stops or are lethal for water hyacinth, should also be examined. From the point of view of the application of water hyacinth in wastewater treatment, it is necessary to test the most suitable configuration of the pool (pool with polyculture, or a series of pools with monoculture), the initial degree of coverage of the water surface, the density and amount of water hyacinth biomass and the dynamics of partial biomass removal (removal interval, amount of biomass to be removed, etc.) in order to ensure optimal water hyacinth biomass growth and the effects of wastewater treatment.

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Data availability: The data presented in this study are available in the Supplementary Material, and at https://www.serbiosoc.org.rs/NewUploads/Uploads/8436-Supplementary%20Material-xlsx_output.xlsx.

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SUPPLEMENTARY MATERIAL

Supplementary Table S1. Meteorological data for the research period.

Day	Year	Month	Day	Air temperature 07 h (°C)	Air temperature 14 h (°C)	Air temperature 21 h (°C)	Mean daily air temperature (°C)	Minimal air temperature (°C)	Maximal air temperature (°C)	Precipitation (mm)	Mean daily air pressure (mb)	Mean daily relative humidity (%)	Mean daily cloud cover in 1/10	Sunshine (h)
0	2004	6	29	20.3	19.4	18.2	19.0	18.2	28.0	2.8	997.4	84	6.7	8.1
1	2004	6	30	17.2	24.8	16.5	18.8	14.1	26.8	5.6	997.6	65	1.3	12.4
2	2004	7	1	15.6	28.4	20.6	21.3	11.4	30.4	0	994.3	54	0.3	12.5
3	2004	7	2	19.6	32.0	25.6	25.7	14.0	33.5	0	989.8	57	1.0	11.9
4	2004	7	3	19.0	22.2	18.7	19.7	15.8	25.6	0	994.7	68	6.0	7.9
5	2004	7	4	17.2	29.7	22.7	23.1	13.5	30.7	0	996.1	53	1.3	12.3
6	2004	7	5	18.6	31.0	25.4	25.1	15.0	32.4	0	995.0	61	4.0	11.1
7	2004	7	6	23.6	33.4	24.9	26.7	17.0	34.7	0	993.7	47	0.3	12.3
8	2004	7	7	20.9	33.3	25.3	26.2	15.6	34.3	0	994.4	60	0.3	11.2
9	2004	7	8	22.1	34.3	27.0	27.6	18.0	35.7	0	994.5	53	0.0	12.3
10	2004	7	9	22.7	37.3	29.0	29.5	18.5	38.4	0	991.2	46	1.7	9.1
11	2004	7	10	25,0	37.9	27.0	29.2	20.0	38.6	0	987.1	49	4.3	11.5
12	2004	7	11	20.9	30.1	19.5	22.5	19.5	30.8	0	986.7	56	5.0	9.6
13	2004	7	12	17.7	23.0	16.0	18.2	15.0	25.0	1.9	985.8	80	9.0	4.4
14	2004	7	13	15.5	17.1	14.6	15.5	14.0	20.7	15.2	985.9	87	8.3	1.7
15	2004	7	14	14.7	21.4	16.7	17.4	12.5	22.5	1.8	991.7	68	7.7	4.9
16	2004	7	15	16.5	21.0	15.0	16.9	12.2	22.4	0	992.8	61	5.3	7.1
17	2004	7	16	15.7	24.5	17.7	18.9	12.9	26.0	0	996.0	67	5.3	7.0
18	2004	7	17	16.8	28.6	21.3	22.0	12.6	30.6	0	998.4	58	0.7	12.3
19	2004	7	18	18.9	31.4	23.3	24.2	13.2	33.2	0	998.1	55	0.7	12.8
20	2004	7	19	19.3	33.5	24.3	25.4	14.8	34.7	0	996.0	51	0.3	12.2
21	2004	7	20	21.4	34.2	24.5	26.2	15.7	35.0	0	994.6	55	1.0	12.1
22	2004	7	21	20.0	34.2	24.9	26.0	17.0	35.0	0	994.3	58	0.7	12.2
23	2004	7	22	21.0	34.8	24.6	26.3	17.5	36.3	0	994.0	61	1.7	11.4
24	2004	7	23	21.3	33.7	24.3	25.9	18.0	35.2	0	993.0	56	1.0	11.0
25	2004	7	24	23.7	30.4	24.5	25.8	19.4	31.5	0	990.6	57	6.3	11.6
26	2004	7	25	21.5	29.2	23.6	24.5	18.6	31.8	0	987.4	64	6.3	6.9
27	2004	7	26	22.5	26.1	18.2	21.3	18.2	28.4	0	986.0	73	7.3	5.3
28	2004	7	27	18.9	19.7	16.3	17.8	15.8	20.5	3.2	986.3	92	10.0	0
29	2004	7	28	16.2	18.4	14.8	16.1	14.8	19.9	19.5	991.1	84	9.0	0.6
30	2004	7	29	14.6	18.5	15.3	15.9	12.3	20.8	1.2	992.2	81	9.3	3.1
31	2004	7	30	15.0	21.2	17.0	17.6	13.0	24.0	0.6	993.7	78	8.0	6.6
32	2004	7	31	16.2	20.9	18.9	18.7	15.4	22.7	0.2	993.5	80	9.3	1.5
33	2004	8	1	18.2	27.1	19.3	21.0	16.6	28.2	3.1	991.4	74	3.3	9.2
34	2004	8	2	16.2	27.7	21.4	21.7	14.5	28.6	0	990.4	73	2.7	9.8
35	2004	8	3	17.0	29.3	20.9	22.0	14.5	30.2	0	988.6	67	5.7	10.6
36	2004	8	4	16.8	28.6	19.9	21.3	14.6	29.7	0	988.4	66	2.0	11.1
37	2004	8	5	16.9	28.8	22.0	22.4	14.6	29.9	0	989.0	67	1.7	11.9
38	2004	8	6	20.0	23.4	19.2	20.5	15.8	26.8	0	989.8	78	9.7	0.8
39	2004	8	7	19.1	27.8	21.1	22.3	17.5	29.0	0	990.9	71	4.3	7.0

Supplementary Table S1. continuited.

40	2004	8	8	17.7	29.0	21.6	22.5	14.6	30.5	0	990.0	72	5.7	7.6
41	2004	8	9	19.8	24.9	18.6	20.5	18.5	24.9	0.4	989.9	83	5.3	1.8
42	2004	8	10	17.3	21.6	20.4	19.9	16.5	24.1	6.3	991.6	83	8.3	2.8
43	2004	8	11	17.9	28.3	20.5	21.8	15.3	29.7	3	991.6	71	3.0	11.2
44	2004	8	12	16.9	31.3	22.9	23.5	14.0	32.4	0	990.2	60	2.0	11.9
45	2004	8	13	20.5	33.2	25.5	26.2	18.0	34.0	0	986.6	58	4.3	8.8
46	2004	8	14	21.4	19.4	17.1	18.8	16.7	25.5	0	989.2	83	8.7	0
47	2004	8	15	16.5	22.5	17.2	18.4	13.9	23.6	0	993.0	78	7.7	4.5
48	2004	8	16	16.1	25.8	19.1	20.0	12.9	27.1	0	993.9	65	3.0	9.9
49	2004	8	17	14.9	28.3	20.0	20.8	11.4	30.0	0	994	53	0.7	11.9
50	2004	8	18	14.9	31.4	21.6	22.4	10.8	32.3	0	995.1	59	0	11.8
51	2004	8	19	18.2	34.0	23.5	24.8	14.7	34.6	0	993.7	57	0	12.7
52	2004	8	20	19.4	35.5	25.3	26.4	16.5	36.8	0	988.0	51	0	11.8
53	2004	8	21	20.4	35.9	25.7	26.9	18.0	36.6	0	985.5	50	0	11.6
54	2004	8	22	19.1	21.9	15.6	18.1	15.6	25.7	0	993.9	70	5.7	7.4
55	2004	8	23	16.6	24.8	18.4	19.6	14.5	26.0	0.2	999.1	63	4.7	7.9
56	2004	8	24	13.4	27.9	19.7	20.2	10.8	29.5	0	997.7	60	0	11.1
57	2004	8	25	16.8	33.8	24.3	24.8	12.5	34.3	0	992.2	47	2.3	10.0
58	2004	8	26	20.8	34.7	21.9	24.8	17.5	35.6	0.7	985.1	49	4.7	9.1
59	2004	8	27	16.1	17.2	15.5	16.1	14.7	21.9	3.5	989.1	90	9.7	0
60	2004	8	28	15.9	23.0	16.6	18.0	14.6	24.5	7.6	992.7	70	6.0	4.3
61	2004	8	29	13.8	26.8	19.4	19.9	12.0	28.5	0	994.7	69	0.7	10.6
62	2004	8	30	15.3	30.2	20.0	21.4	13.6	31.8	0	993.7	66	1.0	10.9
63	2004	8	31	16.4	32.0	22.4	23.3	14.0	32.6	0	991.6	57	4.3	10.1
64	2004	9	1	17.0	26.2	19.2	20.4	15.8	27.4	0	995.8	67	3.0	10.1
65	2004	9	2	15.9	28.2	22.1	22.1	14.5	29.0	0	996.6	67	0.3	10.1
66	2004	9	3	17.5	28.4	21.5	22.2	15.4	29.6	0	999.5	65	6.0	8.4
67	2004	9	4	14.9	26.9	19.6	20.3	14.0	27.5	0	999.8	63	2.7	10.0
68	2004	9	5	15.5	24.7	19.2	19.7	13.8	25.5	0	999.7	65	5.0	1.2
69	2004	9	6	14.6	25.3	17.6	18.8	11.3	26.1	0	1002.3	51	3.3	7.6
70	2004	9	7	14.6	25.1	16.2	18.0	9.7	25.7	0	1002.3	41	0.3	10.9
71	2004	9	8	7.4	24.9	19.6	17.9	5.7	26.0	0	998.5	56	2.7	9.5
72	2004	9	9	13.9	20.5	12.0	14.6	12.0	21.5	0.9	1001	52	3.3	9.5
73	2004	9	10	7.6	17.9	10.0	11.4	5.5	19.1	0	1004.5	51	3.7	9.3
74	2004	9	11	5.4	21.8	12.3	13.0	2.5	24.5	0	1003.5	52	0	10.7
75	2004	9	12	6.2	27.9	16.2	16.6	4.0	29.0	0	997.9	52	1.7	10.0
76	2004	9	13	13.4	26.8	18.5	19.3	8.5	28.6	0	996.5	56	2.0	9.2
77	2004	9	14	12.8	29.8	19.0	20.2	11.6	31.5	0	996.4	61	2.3	9.9
Average				17.3	27.4	20.2	21.3	14.3	29.0	1.0	993.3	63.8	3.8	8.6
Min				5.4	17.1	10.0	11.4	2.5	19.1	0.0	985.1	41.0	0.0	0.0
Max				25.0	37.9	29.0	29.5	20.0	38.6	19.5	1004.5	92.0	10.0	12.8

Supplementary Table S2. Mean values of meteorological data by weeks during the research period.

Week	Year	Air temperature 07 h (°C)	Air temperature 14 h (°C)	Air temperature 21 h (°C)	Mean daily air temperature (°C)	Minimum daily air temperature (°C)	Maximum daily air temperature (°C)	Precipitation (mm)	Mean cloud cover in 1/10	Sunshine (h)
1	2004	18.69	28.79	22.06	22.91	14.40	30.59	0.80	2.03	11.49
2	2004	20.69	30.43	22.63	24.10	17.23	31.93	2.44	4.09	8.54
3	2004	17.61	27.80	20.40	21.57	13.41	29.20	0.26	3.00	9.77
4	2004	21.27	29.73	22.34	23.94	17.79	31.24	0.46	4.76	8.34
5	2004	16.20	23.30	18.23	19.00	14.44	24.91	3.51	6.76	5.91
6	2004	18.23	26.30	20.40	21.34	16.01	27.84	0.96	5.29	6.14
7	2004	17.74	26.97	20.33	21.36	14.60	28.90	0.43	4.20	8.31
8	2004	17.43	30.20	21.40	22.63	14.41	31.64	0.03	1.49	10.61
9	2004	16.44	28.24	20.01	21.19	14.13	29.89	1.69	4.10	7.86
10	2004	15.71	26.40	19.34	20.21	13.50	27.26	0.00	2.94	8.33
11	2004	9.53	24.23	15.37	16.14	7.11	25.74	0.13	2.24	9.73

Supplementary Table S3. Results of observed water hyacinth wet biomass for each basin.

Time (Week)	Observed wet biomass (kg/m²)				
	Basin 1	Basin 2	Basin 3	Basin 4	Basin 5
0	1.10	1.05	0.98	0.92	1.08
7	1.44	1.37	1.07	1.24	1.37
14	1.88	1.64	1.41	1.58	1.75
21	2.45	2.16	1.98	1.99	2.11
28	3.05	2.75	2.40	2.33	2.81
35	4.30	3.80	3.65	3.45	3.82
42	5.95	5.40	5.15	5.21	5.39
49	7.88	7.12	7.02	7.09	7.10
56	9.90	9.06	9.01	9.09	8.98
63	11.60	10.51	10.86	10.61	10.47
70	12.82	12.05	12.31	12.06	12.02

Supplementary Table S4. Results of calculation of dW/dT, DIR, RGR and DT for basin 1.

t (day)	Mean daily air temperature (°C)	Minimum daily air temperature (°C)	Maximum daily air temperature (°C)	Observed wet biomass (kg/m²)	Exponential model wet biomass (kg/m²)	Second-order polynomial model wet biomass (kg/m²)	Logistic model wet biomass (kg/m²)	Observed dW/dt (g/m²day)	Logistic model dW/dt (g/m²day)	DIR (%/day)	RGR (g/g·day)	DT (day)
0	20.86	13.73	28.87	1.10	1.48	1.00	0.80					
7	22.91	14.40	30.59	1.44	1.85	1.31	1.17	48.29	52.34	4.38	0.03822	18.14
14	24.10	17.23	31.93	1.88	2.31	1.83	1.69	62.86	73.93	5.70	0.03809	18.20
21	21.57	13.41	29.20	2.45	2.89	2.55	2.40	81.43	102.09	7.39	0.03783	18.32
28	23.94	17.79	31.24	3.05	3.62	3.49	3.36	85.71	136.69	7.78	0.03129	22.15

Supplementary Table S4. continuited.

35	19.00	14.44	24.91	4.30	4.53	4.63	4.59	177.86	175.63	16.14	0.0489	14.17
42	21.34	16.01	27.84	5.95	5.67	5.98	6.09	236.43	214.10	21.45	0.0466	14.89
49	21.36	14.60	28.90	7.88	7.09	7.54	7.80	275.71	244.86	25.02	0.0401	17.27
56	22.63	14.41	31.64	9.90	8.88	9.30	9.62	288.57	260.42	26.19	0.0326	21.26
63	21.19	14.13	29.89	11.60	11.11	11.28	11.42	242.86	256.43	22.04	0.0226	30.62
70	20.21	13.50	27.26	12.82	13.90	13.46	13.06	174.29	234.04	15.82	0.0143	48.52
77					17.40	15.85	14.45		199.26			
84					21.77	18.45	15.57		159.85			
91					27.25	21.26	16.43		122.22			
98					34.10	24.27	17.06		90.06			
105					42.68	27.50	17.51		64.58			
112					53.41	30.93	17.83		45.40			
119					66.84	34.57	18.05		31.48			
126					83.65	38.41	18.20		21.62			
133					104.68	42.47	18.30		14.75			
140					131.01	46.73	18.37		10.02			
147					163.95	51.20	18.42		6.78			
154					205.18	53.18	18.45		4.58			
161					256.78	60.77	18.47		3.09			
Average	21.83	14.99	29.34					167.40	175.05	15.19	0.0351	22.35

Supplementary Table S5. Results of calculation of dW/dT, DIR, RGR and DT for basin 2.

t (day)	**Mean daily air temperature (°C)**	**Minimum daily air temperature (°C)**	**Maximum daily air temperature (°C)**	**Observed wet biomass (kg/m²)**	**Exponential model wet biomass (kg/m²)**	**Second-order polynomial model wet biomass (kg/m²)**	**Logistic model wet biomass (kg/m²)**	**Observed dW/dt (g/m²day)**	**Logistic model dW/dt (g/m²day)**	**DIR (%/day)**	**RGR (g/g·day)**	**DT (day)**
0	20.86	13.73	28.87	1.05	1.29	1.00	0.74					
7	22.91	14.40	30.59	1.37	1.63	1.21	1.07	45.71	46.89	4.35	0.03800	18.24
14	24.10	17.23	31.93	1.64	2.05	1.62	1.53	38.57	65.75	3.67	0.02570	26.97
21	21.57	13.41	29.20	2.16	2.57	2.25	2.17	74.29	90.42	7.07	0.03934	17.62
28	23.94	17.79	31.24	2.75	3.24	3.08	3.01	84.29	121.06	8.03	0.03450	20.09
35	19.00	14.44	24.91	3.80	4.08	4.12	4.11	150.00	156.41	14.29	0.04620	15.00
42	21.34	16.01	27.84	5.40	5.13	5.38	5.46	228.57	193.04	21.77	0.05020	13.81
49	21.36	14.60	28.90	7.12	6.46	6.84	7.04	245.71	225.21	23.40	0.03950	17.55
56	22.63	14.41	31.64	9.06	8.13	8.52	8.76	277.14	246.13	26.39	0.03442	20.14
63	21.19	14.13	29.89	10.51	10.23	10.40	10.51	207.14	250.51	19.73	0.02121	32.68
70	20.21	13.50	27.26	12.05	12.88	12.49	12.17	220.00	237.16	20.95	0.01953	35.48
77					16.21	14.80	13.64		209.63			
84					20.40	17.31	14.86		174.33			
91					25.67	20.03	15.83		137.78			
98					32.31	22.97	16.56		104.57			
105					40.66	26.11	17.10		76.96			
112					51.18	29.46	17.48		55.36			
119					64.41	33.03	17.76		39.17			

Supplementary Table S4. continuited.

126					81.06	36.80	17.95		27.40			
133					102.02	40.78	18.08		19.00			
140					128.40	44.97	18.17		13.11			
147					161.60	49.38	18.24		9.01			
154					203.38	51.33	18.28		6.17			
161					255.96	58.81	18.31		4.22			
Average	21.83	14.99	29.34					157.14	163.26	14.97	0.0349	21.76

Supplementary Table S6. Results of calculation of dW/dT, DIR, RGR and DT for basin 3.

t (day)	Mean daily air temperature (°C)	Minimum daily air temperature (°C)	Maximum daily air temperature (°C)	Observed wet biomass (kg/m^2)	Exponential model wet biomass (kg/m^2)	Second-order polynomial model wet biomass (kg/m^2)	Logistic model wet biomass (kg/m^2)	Observed dW/dt (g/m^{2}day)	Logistic model dW/dt (g/m^{2}day)	DIR (%/day)	RGR (g/g·day)	DT (day)
0	20.86	13.73	28.87	0.98	1.14	0.89	0.58					
7	22.91	14.40	30.59	1.07	1.46	1.01	0.87	12.67	41.09	1.29	0.01235	56.12
14	24.10	17.23	31.93	1.41	1.86	1.37	1.29	48.57	59.97	4.94	0.03939	17.60
21	21.57	13.41	29.20	1.98	2.38	1.97	1.89	81.57	85.83	8.30	0.04854	14.28
28	23.94	17.79	31.24	2.40	3.04	2.81	2.72	60.29	119.44	6.14	0.02758	25.14
35	19.00	14.44	24.91	3.65	3.88	3.89	3.84	178.00	159.87	18.12	0.05966	11.62
42	21.34	16.01	27.84	5.15	4.96	5.20	5.27	214.29	203.21	21.81	0.04918	14.09
49	21.36	14.60	28.90	7.02	6.34	6.75	6.96	267.14	241.99	27.20	0.04425	15.66
56	22.63	14.41	31.64	9.01	8.11	8.54	8.83	284.29	266.75	28.94	0.03565	19.44
63	21.19	14.13	29.89	10.86	10.36	10.57	10.72	264.29	270.15	26.90	0.02668	25.98
70	20.21	13.50	27.26	12.31	13.24	12.84	12.48	207.14	251.08	21.09	0.01790	38.72
77					16.92	15.34	13.98		215.42			
84					21.62	18.08	15.19		172.50			
91					27.63	21.06	16.11		130.65			
98					35.31	24.28	16.77		94.85			
105					45.13	27.73	17.24		66.75			
112					57.67	31.42	17.56		45.96			
119					73.69	35.35	17.78		31.17			
126					94.18	39.52	17.92		20.93			
133					120.35	43.93	18.02		13.95			
140					153.80	48.57	18.09		9.26			
147					196.54	53.46	18.13		6.12			
154					251.16	55.62	18.16		4.04			
161					320.96	63.94	18.18		2.67			
Average	21.83	14.99	29.34					161.82	169.94	16.47	0.0361	23.87

Supplementary Table S7. Results of calculation of dW/dT, DIR, RGR and DT for basin 4.

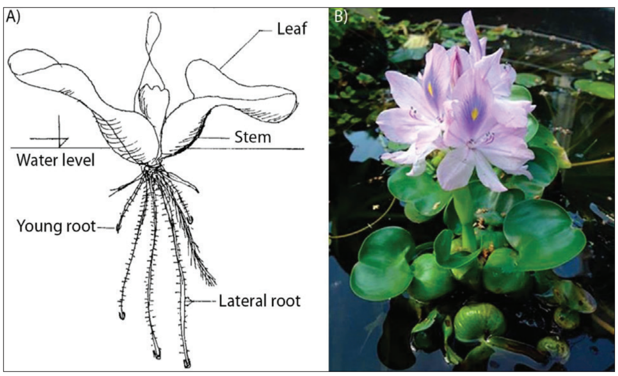
t (day)	Mean daily air temperature (°C)	Minimum daily air temperature (°C)	Maximum daily air temperature (°C)	Observed wet biomass (kg/m^2)	Exponential model wet biomass (kg/m^2)	Second-order polynomial model wet biomass (kg/m^2)	Logistic model wet biomass (kg/m^2)	Observed dW/dt (g/m^{2}day)	Logistic model dW/dt (g/m^{2}day)	DIR (%/day)	RGR (g/g·day)	DT (day)
0	20.86	13.73	28.87	0.92	1.17	0.92	0.58					
7	22.91	14.40	30.59	1.24	1.49	1.06	0.87	45.71	41.40	4.97	0.0426	16.26
14	24.10	17.23	31.93	1.58	1.89	1.42	1.29	48.57	60.54	5.28	0.0346	20.02
21	21.57	13.41	29.20	1.99	2.41	2.02	1.90	58.57	86.67	6.37	0.0330	21.03
28	23.94	17.79	31.24	2.33	3.07	2.85	2.74	48.57	120.42	5.28	0.0225	30.76
35	19.00	14.44	24.91	3.45	3.90	3.91	3.87	160.00	160.51	17.39	0.0561	12.36
42	21.34	16.01	27.84	5.21	4.96	5.19	5.28	251.43	202.53	27.33	0.0589	11.77
49	21.36	14.60	28.90	7.09	6.31	6.71	6.95	267.86	238.56	29.11	0.0439	15.78
56	22.63	14.41	31.64	9.09	8.03	8.45	8.77	285.71	259.26	31.06	0.0355	19.51
63	21.19	14.13	29.89	10.61	10.22	10.42	10.58	217.86	258.23	23.68	0.0222	31.27
70	20.21	13.50	27.26	12.06	13.00	12.62	12.23	207.57	235.80	22.56	0.0183	37.80
77					16.55	15.06	13.62		198.83			
84					21.05	17.72	14.72		156.71			
91					26.78	20.60	15.53		117.07			
98					34.08	23.72	16.12		83.99			
105					43.36	27.07	16.53		58.54			
112					55.17	30.65	16.81		39.97			
119					70.19	34.45	17.00		26.92			
126					89.30	38.49	17.13		17.96			
133					113.62	42.75	17.21		11.90			
140					144.56	47.24	17.26		7.86			
147					183.93	51.97	17.30		5.17			
154					234.02	54.06	17.32		3.40			
161					297.75	62.10	17.34		2.23			
Average	21.83	14.99	29.34					159.19	166.39	17.30	0.0368	21.66

Supplementary Table S8. Results of calculation of dW/dT, DIR, RGR and DT for basin 5.

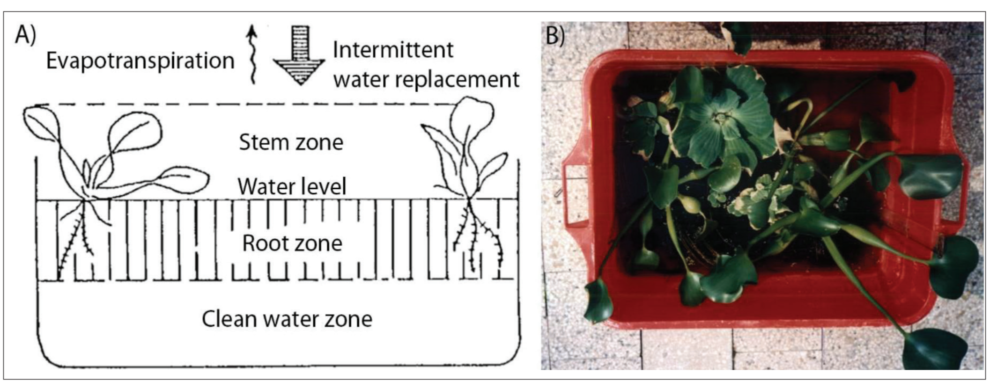
t (day)	Mean daily air temperature (°C)	Minimum daily air temperature (°C)	Maximum daily air temperature (°C)	Observed wet biomass (kg/m^2)	Exponential model wet biomass (kg/m^2)	Second-order polynomial model wet biomass (kg/m^2)	Logistic model wet biomass (kg/m^2)	Observed dW/dt (g/m^{2}day)	Logistic model dW/dt (g/m^{2}day)	DIR (%/day)	RGR (g/g·day)	DT (day)
0	20.86	13.73	28.87	1.08	1.30	1.04	0.78					
7	22.91	14.40	30.59	1.37	1.64	1.24	1.11	41.55	47.50	3.85	0.03412	20.32
14	24.10	17.23	31.93	1.75	2.06	1.65	1.57	54.12	66.02	5.02	0.03490	19.86
21	21.57	13.41	29.20	2.11	2.59	2.27	2.20	52.04	90.07	4.83	0.02704	25.63
28	23.94	17.79	31.24	2.81	3.25	3.09	3.04	99.67	119.80	9.24	0.04077	17.00
35	19.00	14.44	24.91	3.82	4.09	4.13	4.12	143.95	154.07	13.35	0.04378	15.83

Supplementary Table S8. continuited.

42	21.34	16.01	27.84	5.39	5.14	5.37	5.45	224.62	189.80	20.83	0.04927	14.07
49	21.36	14.60	28.90	7.10	6.45	6.83	7.00	244.29	221.79	22.66	0.03936	17.61
56	22.63	14.41	31.64	8.98	8.11	8.49	8.71	268.57	243.74	24.91	0.03356	20.66
63	21.19	14.13	29.89	10.47	10.20	10.36	10.46	212.86	250.43	19.74	0.02193	31.61
70	20.21	13.50	27.26	12.02	12.82	12.44	12.14	221.43	240.13	20.54	0.01972	35.14
77					16.11	14.72	13.65		215.49			
84					20.24	17.22	14.93		182.16			
91					25.45	19.93	15.95		146.38			
98					31.98	22.84	16.74		112.91			
105					40.20	25.96	17.33		84.37			
112					50.52	29.29	17.76		61.56			
119					63.50	32.83	18.07		44.14			
126					79.81	36.58	18.29		31.26			
133					100.31	40.54	18.44		21.94			
140					126.08	44.71	18.55		15.30			
147					158.47	49.08	18.62		10.63			
154					199.18	51.02	18.68		7.36			
161					250.35	58.46	18.71		5.08			
Average	21.83	14.99	29.34					156.31	162.34	14.50	0.0344	21.77

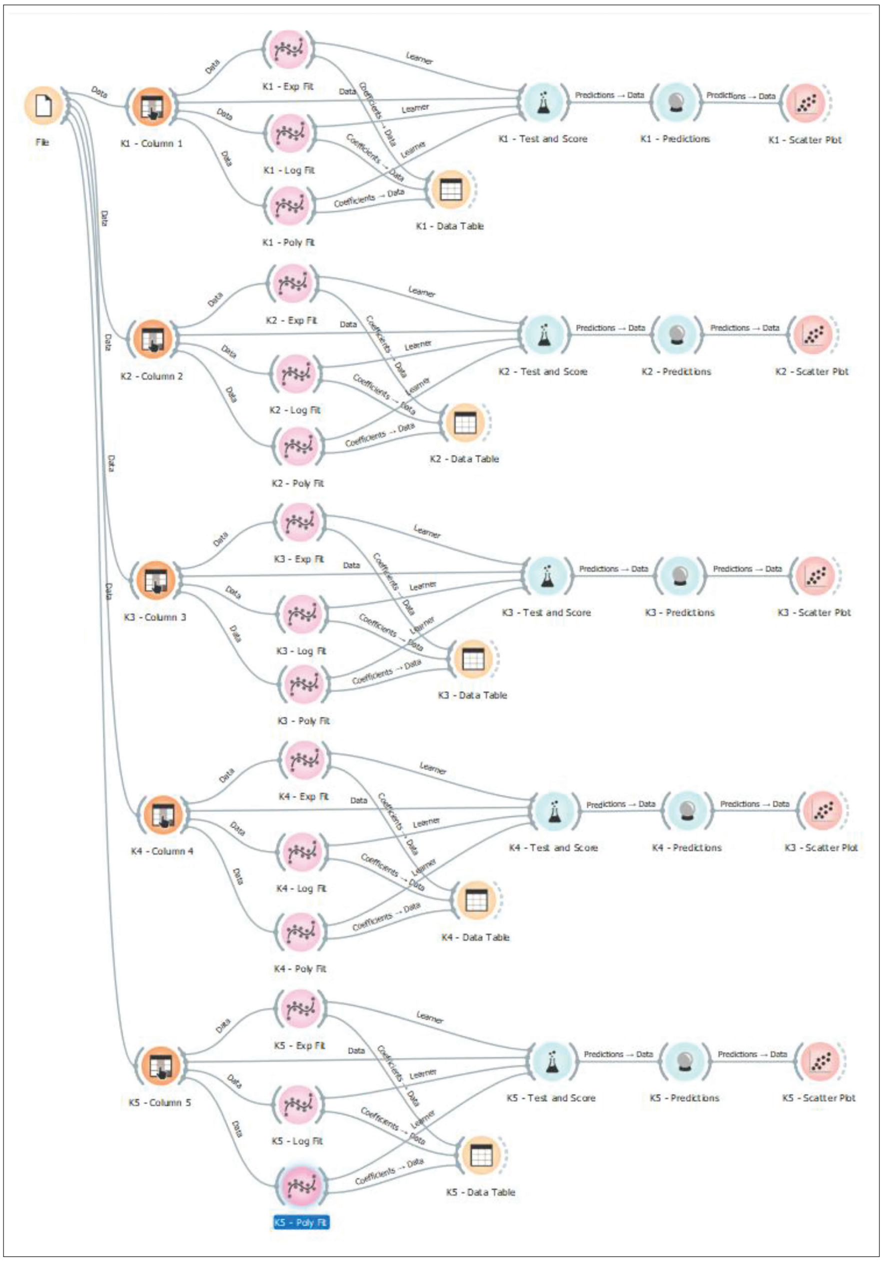


Supplementary Fig. S1. Schematic representation of parts (**A**) and appearance (**B**) of water hyacinth.



Supplementary Fig. S2. Scheme (**A**) and appearance (**B**) of the intermittent system model.

Supplementary Fig. S3. Appearance of experimental basins with the plants



Supplementary Fig. S4. Orange 3 workflow of exponential, second-order polynomial and logistic model of water hyacinth growth dynamics.

The data presented in this study are available as a **raw data set** that can be accessed via the following link: [https://www.serbiosoc.org.rs/NewUploads/Uploads/8436-Supplementary%20Material-xlsx_output.xlsx].