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Physical Description of Water Hyacinth Mats to Improve Harvester Design[1]

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ABSTRACT

More efficient water hyacinth (*Eichhornia crassipes* (Mart.) Solms) harvesting methods can result from equipment design based on a better understanding of the physical characteristics of mats which affect machine performance. For this purpose, descriptions or ranges of the following physical characteristics of water hyacinths were determined for plants obtained from different habitats: plant size distribution, rhizome length, areal density and connectivity. The latter, a new property, is a measure of plant entanglement by petioles and stolons. Plant mass was normally distributed in established mats of water hyacinth and not in mats of small plants or plants subjected to regular harvesting. Rhizome length was correlated with plant mass. Population density was correlated with average plant height and biomass density. Connectivity and buoyancy are

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independent properties that define the mechanics of vertical plant support. A plant entangled with other plants is erect due mostly to its connectivity, while a free-floating plant is erect when it develops leaves with floats.

Key words: harvesting, *Eichhornia crassipes*, physical properties, biomass, buoyancy, connectivity.

INTRODUCTION

Before this investigation was initiated, information on the physical characteristics of water hyacinths was limited to dimensions and description of plant components, specific gravity and biomass. A review of this information follows.

In nutrient poor conditions, shoot-to-root length ratio of 1-2 is common, and 53% of the total plant dry matter can be in the leaves and petioles, and in nutrient-rich conditions, shoot to root ratios can be 4-6, and up to 85% of the dry matter can be in the foliage (Reddy, 1988).

Roots of plants from different habitats and seasons vary little in diameter but may vary greatly in length. Diameter along a length of root varies from 0.4 to 1.5 mm. Length varies from 4 to 15 cm in small plants, 10 to 36 cm in medium plants and 12 to 22 cm in large plants (Penfound and Earle, 1948 and Zamora et al., 1982). The diameter of a typical rhizome varies from 1 to 3 cm and its length from 1 to 30 cm (Zamora et al., 1982). Water hyacinth petiole length increases with increasing density of plants (Tucker, 1981). At 5 kg/m^2 (wb), petiole length was 22 cm; at 20 kg/m^2 (wb), length was 43 cm; and at 40 kg,/m^2 (wb), length was 50 cm in this study. Generally, leaves with floats are arrayed almost horizontally (15 to 45° from horizontal) whereas equitant leaves (i.e. leaves whose bases overlap within or above them) approach verticality (75° from the horizontal) (Penfound and Earle, 1948). In dense stands, leaves grow upright rather than horizontally over the water surface (Reddy, 1988). A stolon is relatively short and vertical in dense mats but long and horizontal in open conditions. Typically, the diameter of a stolon is 1 to 2.5 cm; length is 4 to 22 cm in open stands and 5 to 8 cm in close stands (Penfound and Earle, 1948; Zamora et al., 1982).

Densities of various parts of water hyacinth plants were determined by Penfound and Earle (1948) using the volume weight method; the specific weights were 0.782 for a root, 0.805 for a rhizome, 0.818 for a stolon, 0.136 for a float, and 0.741 for a blade. They observed the load capacity, defined as the pressure required to submerge a 1.5 m^2 mat of plants, to be 177 to 430 Pa (N/m^2).

The objective of this study was to determine other physical characteristics of water hyacinth plants and mats and their interrelationships with dimensions and description of plant components. They are: areal density, plant mass, rhizome length, mat buoyancy and connectivity. The latter is a measure of mat interconnectedness. Generally, these characteristics vary according to habitat, season and plant age and size, and they affect harvesting performance and design. For instance, number and shape of rhizomes and roots, the principal plant parts projecting into the water, influence the viscous forces generated when the plants are towed. Biomass density, in combination with harvesting speed and width, determines the capacity of a harvester and the power requirements for conveying and transportation systems. Plant mass affects inertial forces encountered in a towing operation. Mat buoyancy, the force required to submerge a given area of water hyacinths, is useful for the design of conveyors, booms and containment structures, because plants under certain conditions roll under such devices. Information on degree of plant inter-connectedness through leaf entanglements and stolons (connectivity) is useful when a mat is to be separated into smaller units for towing or lifting from the water.

MATERIALS AND METHODS

Mats were sampled in ponds and lakes. Ponds visited are located at the Swine Research Unit and Zellwood Field Laboratory of the University of Florida Institute of Food and Agricultural Sciences. The lakes visited, Lake Alice and Biven's Arm, are located in Gainesville, FL. The samples represented growth in nutrient-rich and -poor waters and populations of young, dynamic and older, established plants.

Before data were gathered, the physical characteristics of plants that might be useful in predicting population density, rhizome length and mat buoyancy were not known. Therefore plant length, leaf length, plant mass, root length and leaf number were recorded as possibly useful attributes. The number of plants sampled in a mat was seven, and the sample size was a compromise based on time constraints and calculation of sample variance of plant length, confidence interval and confidence level. Preliminary data indicated that sampling indicated a bivariate distribution with plant mass considerably more variable than the other attributes which had similar variances (see Results). Seven plants gave a value of mean plant length within 10% of the true mean ($\alpha = 0.05$), and the measurement of all the attributes took approximately 1 hour to perform.

Connectivity, mat buoyancy, biomass density and population density were measured on the same portion of a mat. Methods existed for measuring all characteristics except connectivity. Its measurement was devised based on the principle that as connectivity increases in a mat, more weight is required to submerge a plant within the mat because it is supported in part by the rest of the mat. Without connectivity, each water hyacinth in a mat would be free floating and supported by buoyancy.

Connectivity, buoyancy, and standing density were measured with a 0.74 m^2 rigid, mesh steel frame, weights and a scale. The mesh steel frame was placed on top of an undisturbed mat in stagnant water, and weights were quickly placed on it until it was just submerged. Then the weights were removed, the mat under the frame was disconnected from surrounding plants by cutting, and weights were added again. After each test, individual plants under the frame were counted, seven plants were characterized, and the mat was weighed. Mat buoyancy equalled the pressure (Pa) required to submerge the mat under the frame when cut from support by the surrounding mat; connectivity was calculated as the difference of pressures (Pa) required to submerge connected and disconnected mat. The best least square relations predicting population density and bouyancy from other mat characteristics were sought.

In order to determine the distribution of mass within a mat and to compare different types of mats, ten to fifteen plants were sampled from mats located in different water conditions, and a classification system was developed to account for variability in plant size. Skewness was calculated to determine whether mass was distributed normally. Plants were then sorted by mass into tentative classes and relative frequencies of occurrence were recorded. A class was accepted as valid when mean mass and skewness calculated from a frequency table became similar to those calculated from the original data. This procedure was repeated until data from all mats tested were incorporated in the proposed classification system.

RESULTS AND DISCUSSION

Plant Mass Distribution. All but one data set on plant mass indicated normal distribution; however, mean values differed. Skewness ranged from -0.1 ± 0.6 to -0.3 ± 0.8 for the normal populations. Skewness was 1.5 ± 0.5 for the unsymmetrical distribution.

Plant mass in this study was classified into six classes and various subclasses indicated in Table 1 this system may need expansion by the addition of other subclasses to fit other sets of data. Class 0, containing plants weighing less than 0.1 kg, was subdivided because plants from the Swine Unit were small and a given population fell only into two adjoining classes (e.g. the the smallest plant fell into class 0 and the largest into class 1). Class 5 represents large plants weighing over 0.7 kg. The range of mass for each of classes 0 through 2 is 0.10 kg, while for classes 3 through 5 it is 0.20 kg because larger and older plants are structurally different than younger and smaller plants. Presence or absence of two extra leaves weighing approximately 40 g each on a large plant could shift it between two classes if a 0.10 kg range were used for each large plant class. Plants within classes 0 to 2 have floats, and larger plants usually have more biomass in leaves.

Plant mass of populations from well-established mats was normally distributed (Figures 1 to 3), and mean plant mass appeared to vary with age of culture or habitat. Application of the classification system to different mats indicated, for example, that water hyacinths from Biven's Arm mats averaged a class 4 mass while those from Zellwood averaged a class 2 mass.

TABLE 1. PLANT MASS CLASSES USED TO CHARACTERIZE WATER HYACINTH MATS.

Class	Subclass	Plant mass, kg
0	0.2	0.02-0.04
	0.4	0.04-0.06
	0.6	0.06-0.08
	0.8	0.08-0.10
1	1.0	0.10-0.13
	1.3	0.13-0.17
	1.7	0.17-0.20
2		0.20-0.30
3		0.30-0.50
4		0.50-0.70
5		<0.70

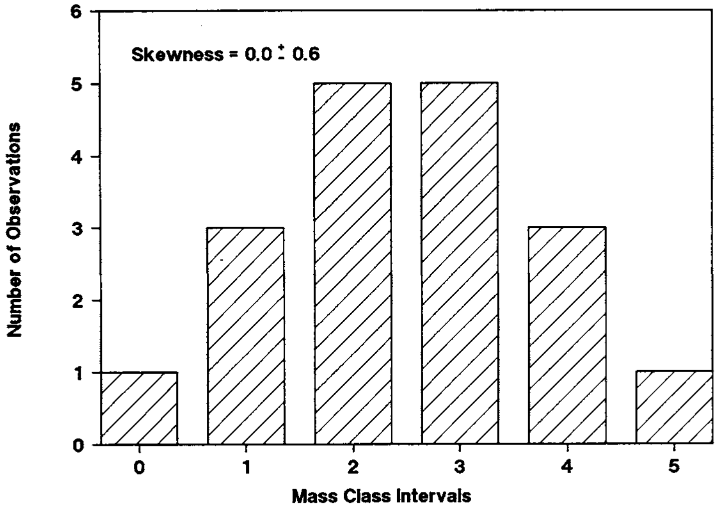

Figure 1. Water hyacinth mass classes in a well-established mat growing in Lake Alice. Classes 2 and 3 predominated.

One population of plants studied (Figure 4) had unsymmetrical mass distribution and consisted of more than one class of plants—predominately class 0, but higher classes were significant (Figure 5). This population of plants was not well established because it was controlled by regular harvests. Its bar graph of mass distribution illustrates that water hyacinth size can differ greatly from one location to another and even within a given location if the population is not well established. As mentioned before, plant mass within mats was statistically more variable than length. Typical standard deviations of plant mass for samples of seven plants were approximately 50% of the average mass, and standard deviation of plant length for the same samples were within 10% of the average value. The bivariate distribution is logical, since new leaves of an

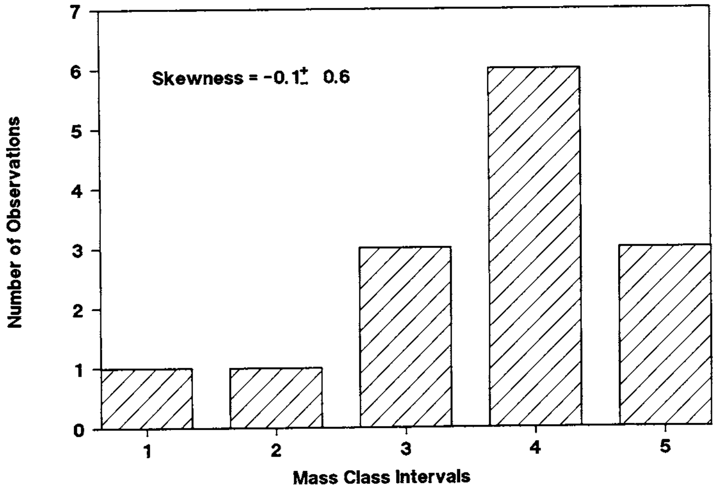

Figure 2. Water hyacinth mass classes in a well-established mat growing in Bivan's Arm. Plants were larger and probably older than those growing in Lake Alice, and class 4 predominated.

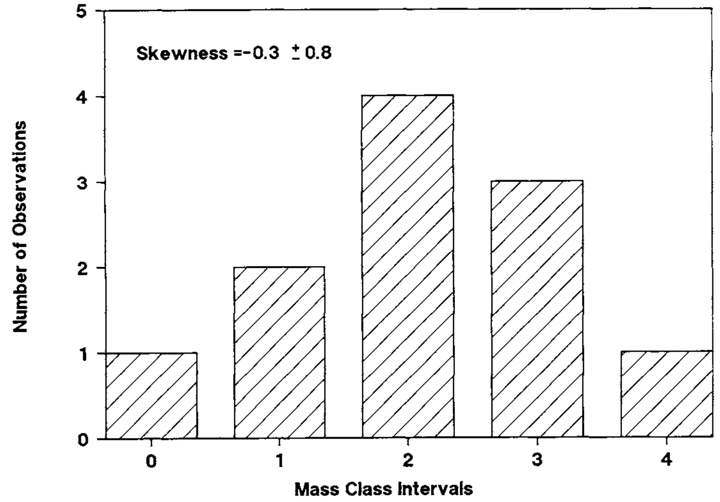

Figure 3. Water hyacinth mass classes in a well-established mat growing in a pond receiving agricultural waste water. Plants tended to be smaller than those from Lake Alice and Bivan's Arm, and class 2 predominated.

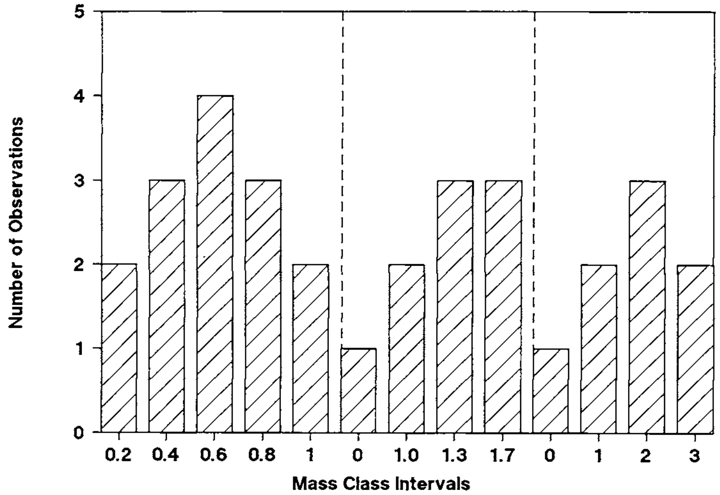

Figure 5. Mass data used in Figure 4 redistributed to show that a young, newly-formed population could consist of many subpopulations segregated by average size.

offspring produced from a stolon quickly reach the height of the mother plant in order to obtain adequate light for growth. More time is, however, required for offspring mass reflected principally in rhizome mass to approach the mass of the mother plant.

Rhizome Length. Data on rhizome length frcm all locations were aggregated and analyzed together. Rhizome length was found to correlate linearly with plant mass (Figure 6), and length varied from 1 to 21 cm. Two least square equations relating rhizome length to plant mass were evident: one for plants with considerable weevil/frost damage or mass concentrated in the rhizomes and another for healthy plants with ample foliage.

Areal Density. Biomass density in this study varied from 8 to 20 kg/m^2 (b), and population density varied from 40 to 300 plants/m^2. However, no accurate estimator of plant population could be obtained using only data of biomass density (Figure 7). One estimator of population density in a given aggregation is provided by the quotient of its biomass density (kg/m^2) and its average plant mass (average of 7 plants). This simple estimator functions well for population densities less than 100 plants/m^2, and it is very unreliable for aggregations of small or large population densities (Figure 8). Small plants usually indicate the population is not well established, in which case a reliable value for plant mass may be difficult to obtain. A more accurate estimator of plant population density was developed using observations by Tucker (1981) that biomass density increases with petiole length. The equation for this estimator (shown in Figure 9) is a nonlinear, least square relation involving the logarithm of average plant length and biomass density as independent variables. Both estimators were established for populations with short roots; hence, they should be used with caution for long-rooted plant systems.

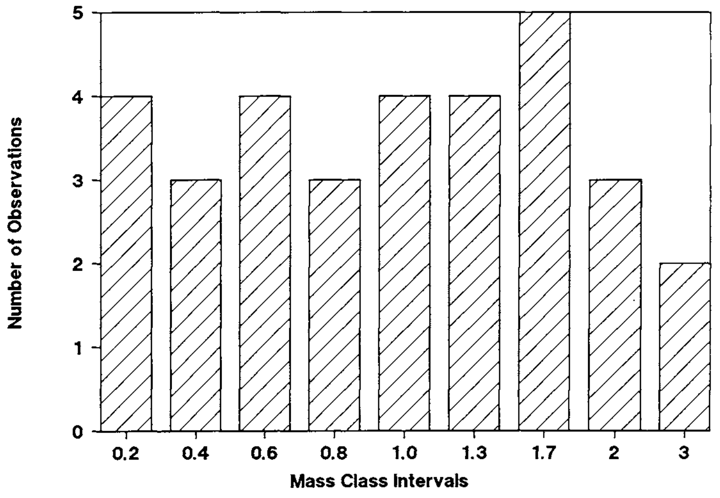

Figure 4. Water hyacinth mass classes in a population that had been frequently harvested. No predominant class size could be found.

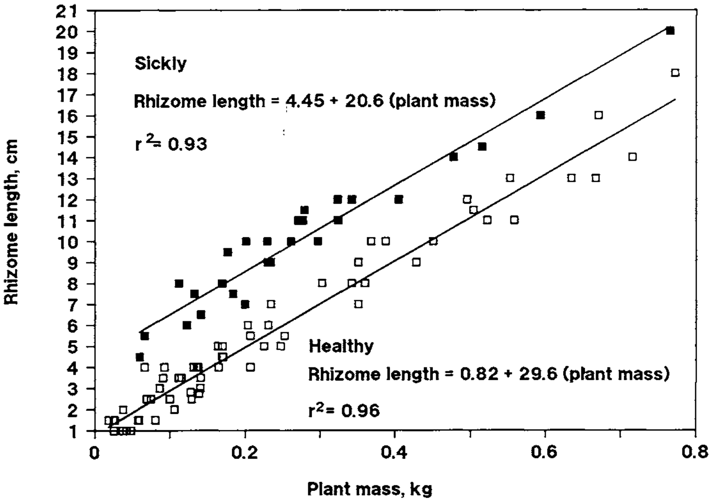

Figure 6. Rhizome length was found to be correlated to plant mass. Two equations are given here: one for plants that had been damaged by weevils or frost, causing foliage to be missing, the other for healthy plants with ample foliage.

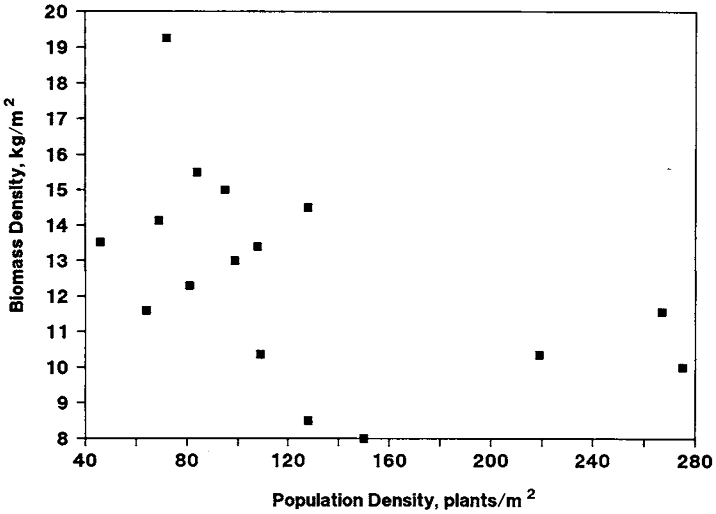

Figure 7. Scatter diagram of biomass and population densities shows only a slight relationship existing between the two variables for water hyacinths.

Connectivity and Buoyancy. Mat buoyancy in this study varied from 20 to 240 Pa and connectivity from 20 to 180 Pa (Table 2). Penfound and Earle (1948), on the other hand, found that load capacity varied from 177 to 430 Pa, where the larger value probably represented an extremely dense aggregation.

Mat buoyancy did not correlate well with population density, although buoyancy appeared to increase somewhat with biomass density. A relation between mat buoyancy and biomass density became evident when the data were parameterized by the ratio of connectivity to mat buoyancy (Figure 10), which is logical since the ratio appears to reflect the mechanics of vertical plant support in a mat. That ratio was termed connectivity ratio (%), and the least square relations are presented in Table 3. The largest buoyancy at any standing mass density occurred when connectivity ratio was less than 40% and mats were comprised of plants with many floated petioles. The smallest mat buoyancy occurred when the connectivity ratio was greater than 70% and petiole entanglement was highest. A large connectivity ratio indicates that plants are ver-

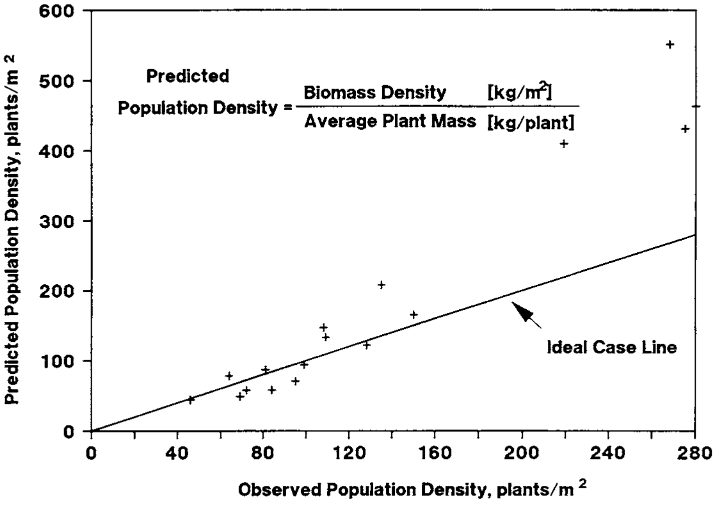

Figure 8. An estimator of water hyacinth population density based on biomass density and average mass of seven plants is effective for small standing populations. The straight line represents theoretically perfect correlation between predicted and actual responses.

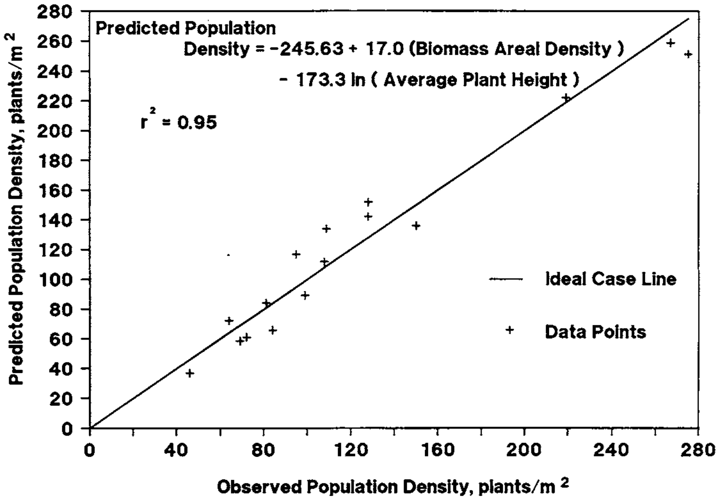

Figure 9. An accurate estimator of water hyacinth population density based on standing biomass density and plant length. The straight line represents theoretically perfect correlation between predicted and actual responses.

TABLE 2. VALUES OF MAT BOUYANCY, CONNECTIVITY AND CONNECTIVITY RATIO.

Buoyancy Pa	Connectivity Pa	Connectivity ratio %	Areal density kg/m	Average plant length cm
165	22.8	14	10.4	18.6
169	47.7	28	11.6	17.0
203	62.9	31	13.4	47.0
238	90.6	38	19.0	27.1
105	42.0	40	10.0	15.2
140	56.4	40	12.3	50.0
167	76.5	46	15.6	53.8
178	70.6	42	13.0	52.0
177	76.2	42	15.5	76.0
193	76.2	40	18.0	18.5
67	38.2	57	8.5	24.6
118	59.0	50	13.5	74.1
135	76.1	56	14.0	69.4
143	71.5	50	15.0	54.0
133	71.9	54	17.0	46.7
177	95.6	54	20.0	42.9
202	119.2	59	21.5	52.7
45	39.4	88	8.0	24.3
66	50.8	77	10.4	31.0
93	68.8	74	11.6	50.0
119	102.9	86	13.4	21.0
117	89.5	76	14.5	42.0
170	119.0	70	19.4	38.0
102[1]	78.5	77	16.7	57.9
922[1]	181.6	197	22.7	59.0

[1] The last two entries are from long-rooted plants.

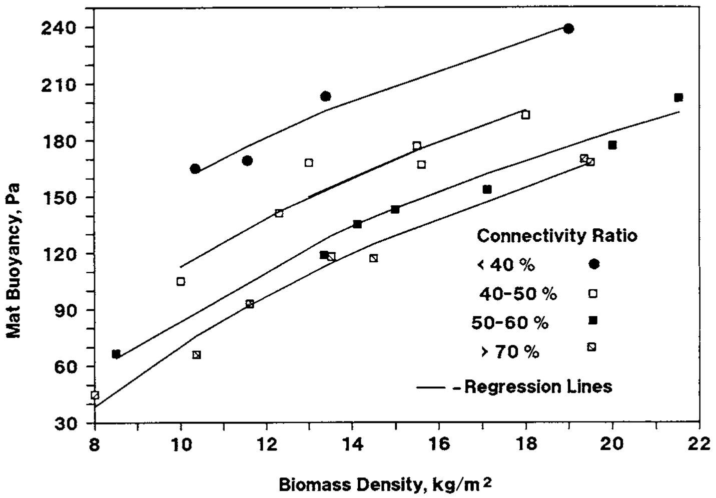

Figure 10. Mat buoyancy as a function of standing biomass density and parameterized by the ratio of connectivity to mat buoyancy.

tically supported mostly by petiole entanglement, while a small ratio indicates that plants are vertically supported by many float-like petioles and are free floating. Floated petioles are common when a mat is periodically harvested because open conditions lead to float formation in plants of any size (Roa, 1920). Floats increase mat buoyancy, because the specific gravity of a float is one-fifth that of an elongate petiole (Penfound and Earle, 1948).

Two values of buoyancy were determined for long-rooted plants, and they were smaller than values for short-rooted plants with similar connectivity and standing density. This is explained by long-rooted plants having approximately 25% more biomass underneath the water than short-rooted systems (Reddy, 1988).

To summarize, rhizome length and population density are needed to determine the drag properties of water hyacinths. Rhizome length in this study ranged from 1 to 20 cm and correlated linearly with plant mass. Population density is a function of plant length and biomass density. Mat buoyancy, a determinant of mat behaviour during towing and compaction, increases with biomass density, and it is more important for plant vertical support when plants are floated. Connectivity is a new property that reflects petiole entanglement, and is usually small in value as compared to buoyancy in mats comprised of plants with many floated petioles. Plant mass within established populations was normally distributed. A classification system based on plant mass was developed to be used when comparing different hyacinth mats.

TABLE 3. RELATION BETWEEN MAT BUOYANCY (MB) AND BIOMASS DENSITY (BD).

Connectivity ratio	Equation	r^2
70	MB = –262.0 + 144.5 ln (BD)	0.98
50-60	MB = –235.8 + 139.2 ln (BD)	0.98
40-50	MB = –212.3 + 141.2 ln (BD)	0.90
40	MB = –135.0 + 127.4 ln (BD)	0.96

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