LABORATORY EXPERIMENTS ON THE FLOW RESISTANCE OF AQUATIC WEEDS

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1. INTRODUCTION

In the early seventies interest was created for other methods of maintenance of ditches than traditional ones in order to decrease costs and to fulfil requirements with respect to environmental and recreational demands. Investigations were carried out to explore the possibility of restricting or preventing the growth of weeds by means of light interception effectuated by floating leaves of certain species (Pitlo, 1978 and 1982). The design and management of vegetated channels require a procedure for predicting flow resistance due to aquatic weeds. A survey of the various research done in the past to accomplish such a procedure is very well embodied by Lindner (1982). A relatively simple flow model based on the drag force on vegetation in flow was described by Petryk & Bosmajian (1975). For a further development of this model flow resistance due to aquatic weeds was studied on monocultures of white water-lily (Nymphaea alba), broad pond-weed (Potamogeton natans) and reed (Phragmites australis) at the Agricultural University of Wageningen during the period 1983-1985. The aquatic weeds were also investigated, using a new technique in order to make a more profound estimation of plant biomass.
This paper describes the measurements and discusses the results.

2. BASIC EQUATIONS

In general flow resistance in an open channel is described by using Manning's coefficient as a friction factor:

$$\bar{u} = \frac{Q}{A} = \frac{1}{n} R^{2/3} S_H^{1/2} \qquad (1)$$

where $\bar{u}$ = mean velocity; Q = discharge; A = cross-sectional area; n = Manning's coefficient; R = hydraulic radius; S_H = energy gradient.

The coefficient of Manning represents the influence of the boundary roughness. In case of vegetated channels the model of Petryk & Bosmajian (1975) gives a description of the flow resistance through a vegetated channel in which both the influence of boundary roughness and aquatic weed are represented. From momentum considerations they obtained the following result:

$$S_H = \left\{\frac{C_d \Sigma A_i}{2g\ AL} + \frac{n^2}{R^{4/3}}\right\} \bar{u}^2 \tag{2}$$

where C_d = the drag coefficient for the vegetation; A_i = the projected area of the *i* th plant in the streamwise direction; g = the gravitational constant; L = the length of the channel reach being considered.

Several steps can be taken to refine this model and to make it more suitable for the analysis of actual measurements involving aquatic weed and flow resistance. The numerator of the first term between brackets refers, in case of the monocultures mentioned above, to the total projected area of the stems and its drag coefficient. The length of the stems can be related to the initial or the actual waterdepth in case of water-lily and pond-weed or reed respectively. Then $C_d \Sigma A_i$ in Equation 2 can be written as:

$$C_d \Sigma A_i = \mu\ dD \tag{3}$$

where μ = aquatic weed resistance; d = initial or actual waterdepth; D = diameter of the stems.

Note that the number of stems is unknown in the right hand side of Equation 3, and that the sum is omitted. In case detailed information about the stems does exist, then it is possible to calculate the sum of the projected area. However, it seems more realistic to take the mean values of stem length and diameter allowing a better reproduction in case of estimations. In this case the numerator can be written as:

$$C_d \Sigma A_i = \xi\ m\ \bar{l}\ \bar{D} \tag{4}$$

where ξ = drag coefficient of stems; m = number of stems; $\bar{l}$ = mean length of stems; $\bar{D}$ = mean diameter of stems. Both the coefficients μ and ξ depend on the Reynolds number and represent not only a drag coefficient but also the deficiency due to the simplicity of the model.

The influence of boundary roughness represented by the second term between brackets of Equation 2, can also be described with a non-dimensional roughness parameter. Analogous to the flow resistance in closed conduits the energy gradient without aquatic weed becomes:

$$S_H = \frac{\Delta H}{L} = \frac{\lambda}{R}\frac{\bar{u}^2}{2g} \qquad (5)$$

where ΔH = difference in total head; λ = wall roughness coefficient. Now, from Equation 2, 3 and 4 it can be derived that:

$$S_H = \left\{\frac{\mu}{A}\frac{dD}{L} + \frac{\lambda}{R}\right\}\frac{\bar{u}^2}{2g} \qquad (6)$$

Using Equation 4 instead of Equation 3, one obtains:

$$S_H = \left\{\frac{\xi\ m\ \bar{l}\ \bar{D}}{A\ L} + \frac{\lambda}{R}\right\}\frac{\bar{u}^2}{2g} \qquad (7)$$

This formula uses only dimensionless coefficients and consistently describes the influence of aquatic weed and wall roughness on the flow resistance. These coefficients can be related to the Reynolds number (μ or ξ) or to the relative wall roughness (λ) i.e. the ratio between the hydraulic radius and the equivalent roughness (R/k)

3. EXPERIMENTAL DESIGN

3.1 General

The model described above can be evaluated by taking measurements with the objective (i) to study the resistance at different flow conditions but at equal amount of aquatic weed, and (ii) to determine the relation between the resistance and the time dependent biomass. The measurements were taken in the period 1983-1985. Because of the fact that the three variables discharge, waterdepth and aquatic weed are independent variables (corresponding to Equation 7), in each year the experiment focussed on one of these variables.

All measurements were carried out in an outdoor laboratory from which a plan view is shown in Figure 3.1.

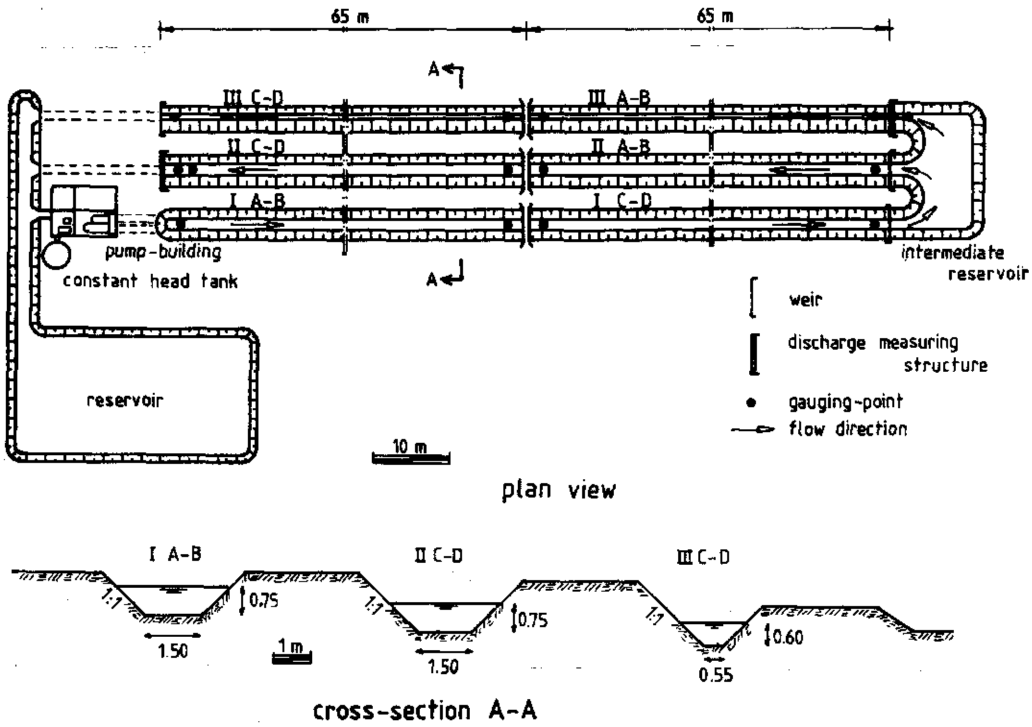

Figure 3.1 Diagram of the experimental ditches

Ditch section I-CD was planted with white water-lily, ditch section II-AB with broad pond-weed and ditch section III-AB with reed.

3.2 Flow resistance measurements

The cross-sectional area and wetted perimeter of the ditch section were obtained by levelling cross-sections every 5 meter with a 0.25 meter distance between measuring points. After calculating the cross-sectional area and wetted perimeter for each cross-section their averages were calculated. The levelling has been carried out in 1983 and was repeated in 1985.
The discharge was measured with two volumetrically calibrated V-notches at the end of intake flumes (Van Ieperen & Herfst, 1985). The waterheight was obtained using point gauges above a stilling well at the side of the flume.
A pressure transducer attached to an amplifier, data-logger and mini-computer was used to registrate the difference in waterheight between the gauging points in the ditch sections. This system was calibrated each year and regularly checked during the measurements by means of additional point gauge readings at stilling wells.

Concerning the flow resistance measurements, in 1983 the waterdepth was taken at a low, medium or high level with the discharge increasing from 0.030 to 0.130 m^3/s, with intervals of 0.020 m^3/s. The measurements were repeated 6 times during the season and each measurement lasted approximately 6 days. In 1984 also 6 repetitions took place but only at medium waterdepth and discharge increasing with an interval of 0.005 m^3/s, each measurement lasting 2 days. In 1985 measurements were performed weekly. In one day the discharge was increased from 0.040 to 0.115 m^3/s with intervals of 0.015 m^3/s at medium waterdepth. In this year ditch section III-AB was left out of consideration.

3.3 Estimation of plant biomass

Being a standard measure for plant biomass, the estimation of the percentage of cover by a vegetation when projected perpendicular on a horizontal plane has been used (Hoogers, 1963). In case of a high cover of floating leaves, it is hardly possible to make an estimation of the submerged parts of the vegetation. This and subjectivity of the observer make this method less suitable for research on dense vegetation in ditches.

In 1983 a start was made with collecting additional data on the vegetation next to the estimation of cover. Length and diameter of stems and area of leaves were measured once or twice.

In 1984 reed stems in ditch section III-AB have been counted monthly. On behalf of the vegetation in the other two ditches several experiments have been carried out to develop a better method for estimating biomass. Sampling the vegetation by harvesting a 0.50 m strip of the cross-section was very labour intensive but gave the best results. It was further developed to the method described below which has been used for ditch section II-AB in 1985.

During the growing season (April-October) a weekly sample of the vegetation was taken by cutting of the stems at the bottom of the ditch within a 0.30 x 0.40 m area. For this purpose in early spring two rows of 0.30 x 0.40 m rectangular frames were placed at the bottom of the ditch at a 0.40 m distance (Figure 3.2). These frames existed of 0.15 m long parts of a PVC ventilation shaft, around which polythene bags were folded, and were pushed into the mud untill they leveled the ditch bottom. Strings were attached to the polythene bags to pull them up in order to prefend the vegetation from floating away while cutting.

From the obtained vegetation samples the composition was noted. This consisted of broad pond-weed, water-thyme and other species (remainder). The number, length and diameter of stems and the number and area of leaves of pond-weed were obtained. Also the volume, fresh weight and dry weight of stems and leaves of pond-weed, water-thyme and remainder were measured.

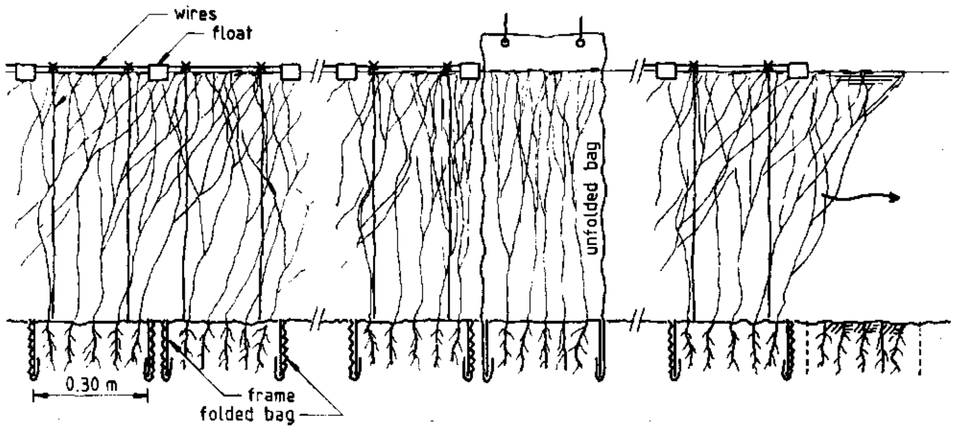

Figure 3.2 Sampling of the vegetation in ditch section II-AB

Vegetation sampling in ditch section I-CD existed of cutting off one water-lily plant. Number, length and diameter of leaf- and flowerstems, leaf area and fresh- and dry-weight were noted. In this section leaves of water-lily were counted on two fixed areas of 3 m^2 each.
From the hydraulic point of view number, length and diameter of the stems are important. The other parameters, as dry weights and leaf area, will be examined on their relation to the aquatic weed resistance coefficient and their suitability for working in the field in order to replace the method of estimating cover. They also can be used by the development of simulation models for the growth of water-lily and pond-weed.

4. RESULTS AND ANALYSIS

The measurements of 1983, when the variation of the waterdepth was emphasized, are to be considered as a first exploration of the influence of different flow conditions and the relation between the aquatic weed resistance μ and the Reynolds number (Re $= \bar{u}.D/\nu$, with ν = kinematic viscosity). A respresentative example of the results is given in Figure 4.1. There were no significant differences in aquatic weed resistance at different waterlevels.

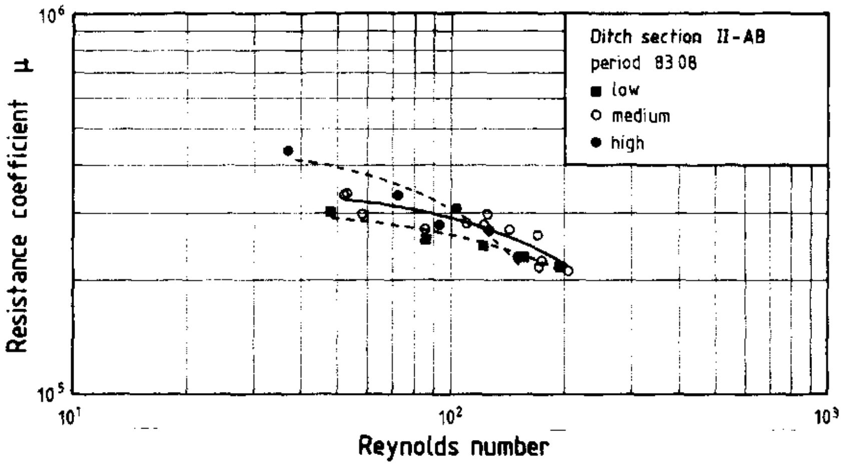

Figure 4.1 μ as function of Re, Ditch section II-AB, August 1983

In 1984, emphasizing the discharge, the relation between μ and Re was determined by a third degree polynomial regression on the approximately twenty data of each run. Table 4.1 shows the correlation coefficient r of the regression, the estimated standard deviation σ of the μ values, mean value of μ and the **ratio between σ and $\bar{\mu}$.**

Ditch section	Month	r	σ 10^3	$\bar{\mu}$ 10^4	$\sigma/\bar{\mu}$ 10^{-2}
I-CD	04	0.975	0.84	1.03	8.1
	05	0.954	0.80	1.50	5.3
	06	0.983	1.02	2.89	3.5
	07	0.962	2.05	3.58	5.7
	08	0.988	6.11	2.73	2.2
	09	0.980	5.71	2.30	2.5
II-AB	04	0.987	4.56	7.01	6.5
	05	0.973	18.50	17.64	10.6
	06	0.985	28.32	35.29	8.0
	07	0.988	19.30	28.45	6.8
	08	0.996	14.05	37.13	3.8
	09	0.993	22.98	42.75	5.4
III-AB	05	0.942	6.00	5.09	11.8
	06	0.995	1.71	6.52	2.6
	07	0.968	10.63	13.73	7.7
	08	0.953	5.68	12.77	4.5
	09	0.967	11.49	17.64	6.5

Table 4.1 Parameters from regression analysis

Notice that the mean value of μ gives no information about the actual resistance coefficient during the season because of change in range of the Reynolds number. It can be concluded from Table 4.1 that the regression is quite satisfactory. A remarkable feature however is the rather high ratio of $\sigma/\bar{\mu}$, despite the high correlation coefficient and high accuracy of the measurements. An error analysis showed that the relative error in μ is about 3 to 4% and in Re about 2%. So the phenomena itself causes the deviations to be rather high. The relation between μ and Re itself showed a decreasing value of μ at increasing Reynolds number. The order of magnitude of the negative gradient at the mean value of μ was 250, 3000 and 400 for ditch I, II and III respectively.

As expected nearly all the 1985 harvesting data showed a large scattering, especially those of pond-weed. For this species Table 4.2 shows the correlation coefficient of a fifth degree polynomial regression on the various plant parameters, estimated standard deviation σ, the mean values $\overline{y}$ and the ratio between σ and $\overline{y}$.

	r	$\sigma/\overline{y}$ 10^{-2}
Stems		
number	0.499	53.7
mean length	0.704	15.3
mean diameter	0.855	53.8
fresh weight	0.411	51.8
dry weight	0.429	54.0
Leaves		
number	0.730	45.7
area	0.728	52.8
fresh weight	0.747	52.2
dry weight	0.699	57.7
Total		
fresh weight	0.461	43.0
dry weight	0.494	52.1
volume	0.505	49.0
$\Sigma A_i/L$	0.436	52.8

Table 4.2 Parameters from regression analysis

The method of taking one sample each week together with the very small sample area explains the high ratio between σ and $\overline{y}$. The low ratios for stem length and diameter promise a better result when sufficient repetitions can be done.

The calculated values of the area of stems are shown in Figure 4.2. The drag coefficient ξ can be calculated by Equation 7 using the predicted values of $\Sigma A_i/L$. A value of 0.045 was taken for λ, this being the wall resistance coefficient at the begin of the season. Without this the value of ξ would have been extremely high in case of small areas of stems. In comparison to the drag coefficient of a cylinder the values of ξ are rather high. However, the decrease of ξ at increasing Reynolds number is similar to the decrease of the drag coeffi-

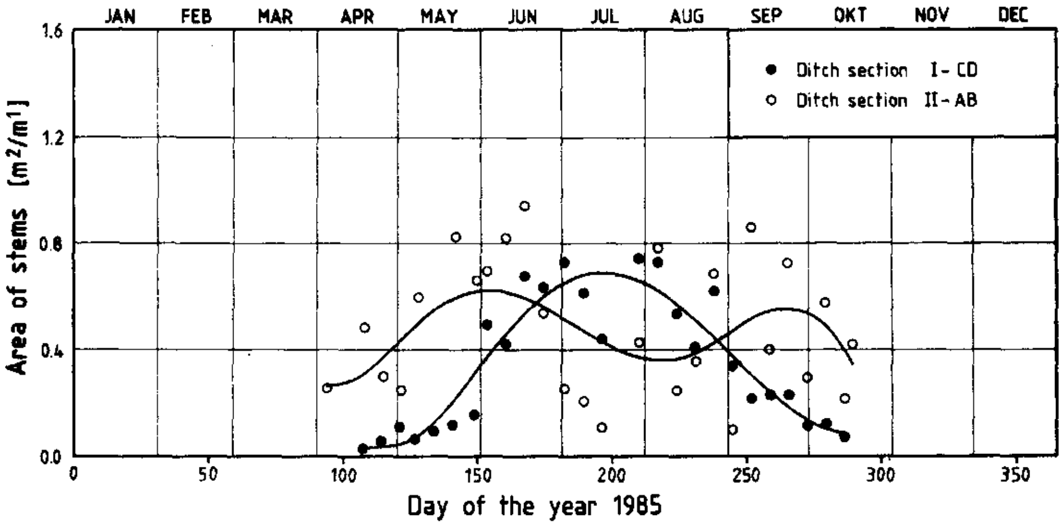

Figure 4.2 Area of stems per unit length $\Sigma A_i/L$

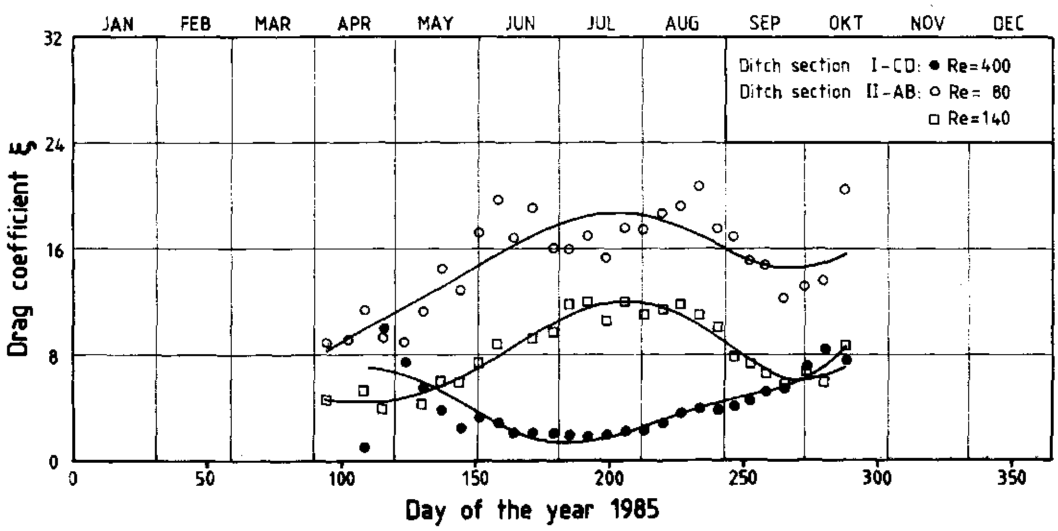

Figure 4.3 Drag coefficient of stems ξ

cient of a cylinder at increasing Reynolds number (Figure 4.3). Despite the difference in structure of the aquatic weed in ditch section I-CD (single stems with a 10 mm diameter) and II-AB (branched stems with a 2.5 mm diameter) the drag coefficients of stems link up nicely with each other. The regression-analysis resulted in a value for $\sigma/\overline{\xi}$ of 30% in case of ditch I-CD and 10% in case of ditch II-AB.

5. CONCLUDING REMARKS

An attempt has been made to model the flow resistance of aquatic weeds using plant biomass related parameters. The

number, diameter and length of the stems are the most relevant from a hydraulic point of view. Three species of aquatic weeds were investigated within a limited range of Reynolds numbers. The results might be influenced by scatter in the data of the aquatic weeds. This scatter would not occur when the sample area could be enlarged. In this project the limited range of homogeneous vegetation restricted the sample size. Instead of harvesting a technique which allows sampling data more accurate would be preferable.
The drag coefficient used in the model shows a time dependent variation. This should not occur in case of the model being perfect. The question arises whether this is caused by neglecting the energy correction factor in the model. It is quite obvious that the velocity distribution in a vegetated ditch is different from a (nearly) clean ditch. Nevertheless the results are encouraging and a further development of the model could be accomplished by increasing the range of Reynolds number at one species and by observing different species with flow conditions causing an overlap in Reynolds number.

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LIST OF SYMBOLS

A	area	$[L^2]$
C_d	drag coefficient	[1]
D	diameter of stems	[L]
d	waterdepth	[L]
g	gravitational constant	$[L \cdot T^{-2}]$
H	total head	[L]
k	equivalent wall-roughness	[L]
L	length of channel reach	[L]
l	length of stems	[L]
m	number	[1]
n	Manning's coefficient	$[L^{-1/3} \cdot T]$
Q	discharge	$[L^3 \cdot T^{-1}]$
R	hydraulic radius	[L]
Re	Reynolds number	[1]
r	correlation coefficient	[1]
S_H	energy gradient	[1]
u	velocity	$[L \cdot T^{-1}]$
Δ	difference operator	
λ	wall roughness coefficient	[L]
μ	aquatic weed resistance	[1]
ν	kinematic viscosity	$[L^2 \cdot T^{-1}]$
ξ	drag coefficient of stems	[1]
σ	standard deviation	

Photo 1: White water-lily in ditch I

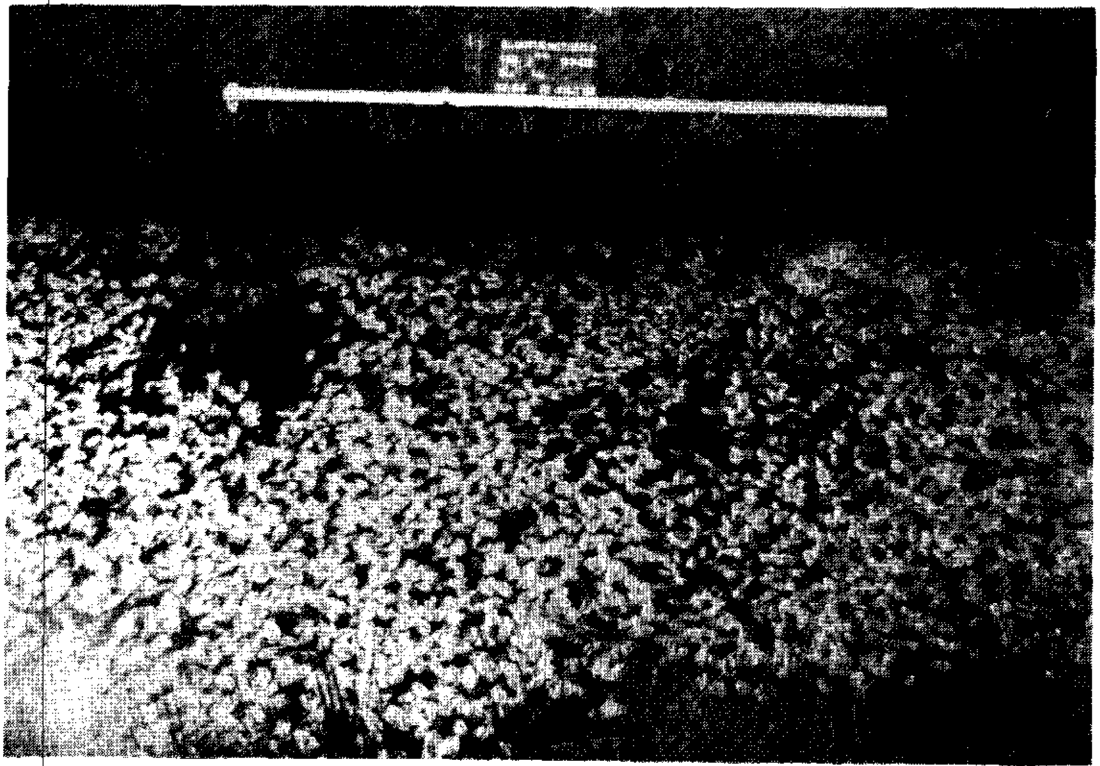

Photo 2: Broad pond-weed in ditch II

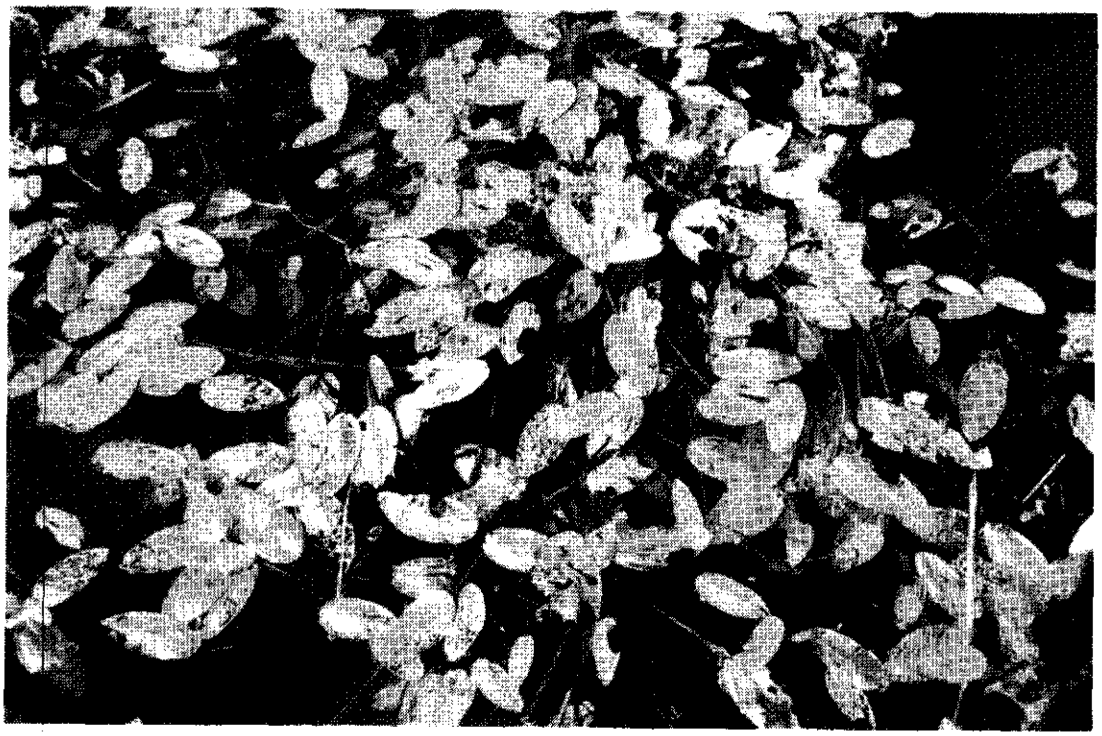

Photo 3: Detail of broad pond-weed

Photo 4: Reet in ditch III

Photo 5: Maintenance

Photo 6: Prevending this means research

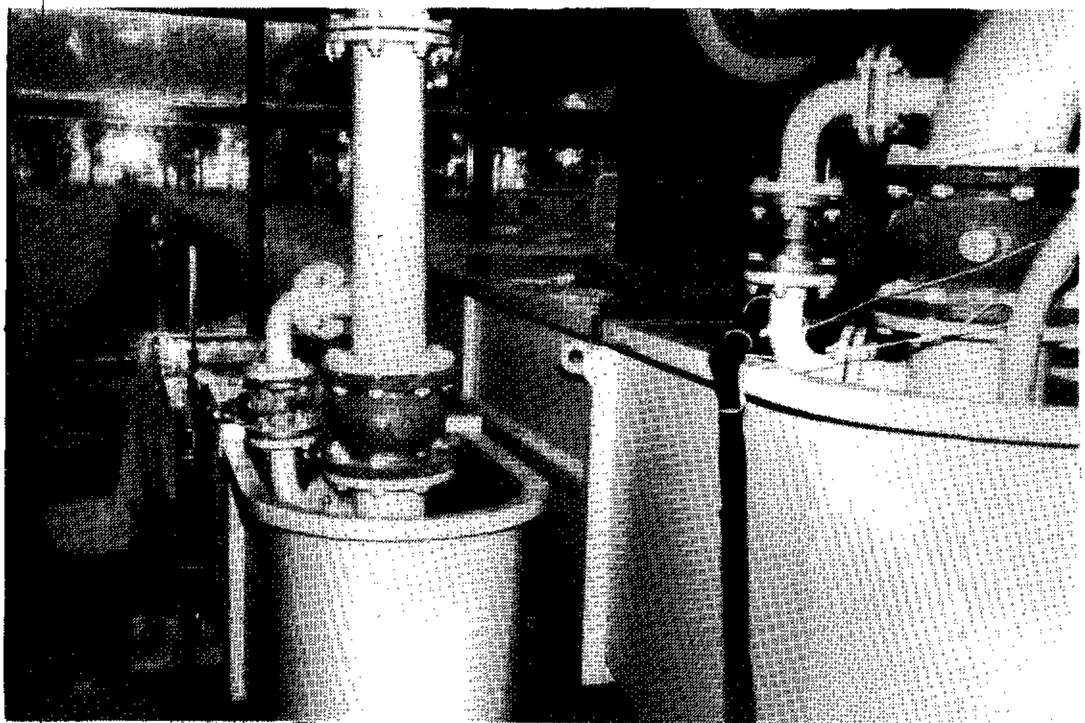

Photo 7: Intake tanks for measuring discharge

Photo 8: The equipment for measuring the pressure difference

Photo 9: Estimating the covering percentage

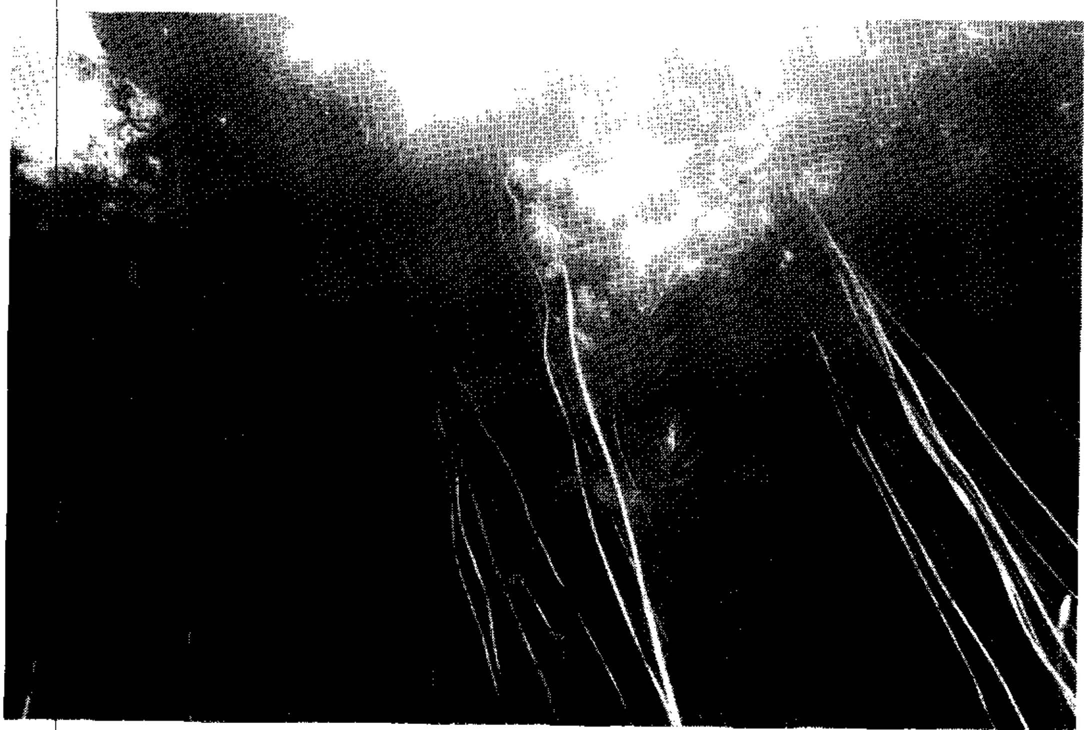

Photo 10: The fish-eye view is different

Photo 11: Sampling broad pond-weed

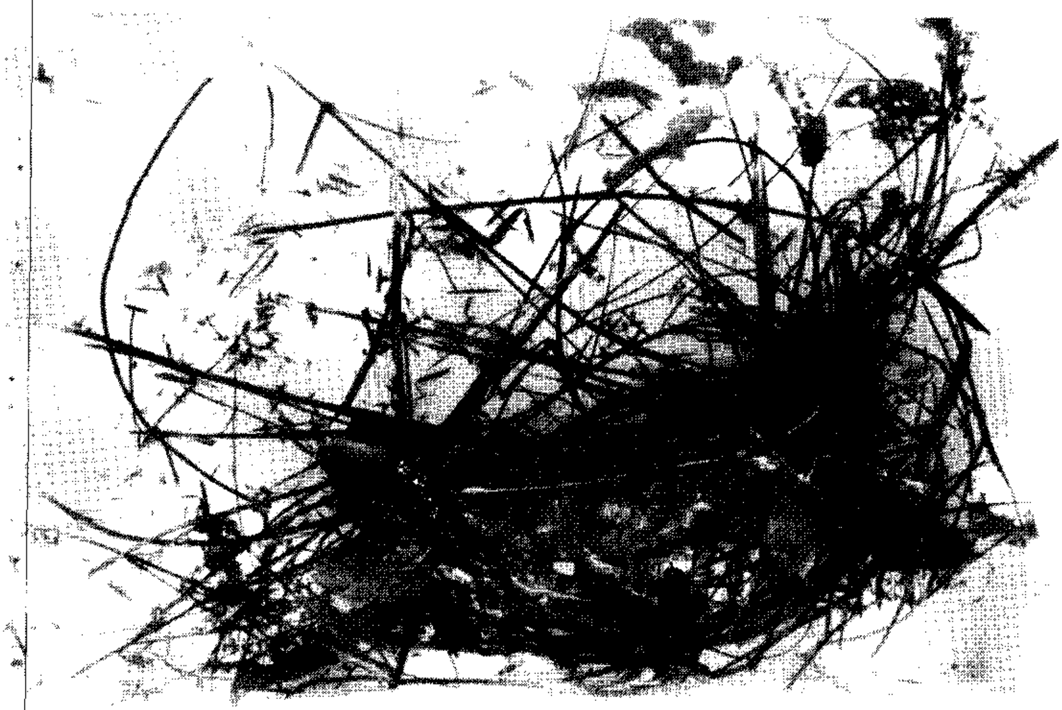

Photo 12: The result

Photo 13: It's much easier harvesting white water-lily

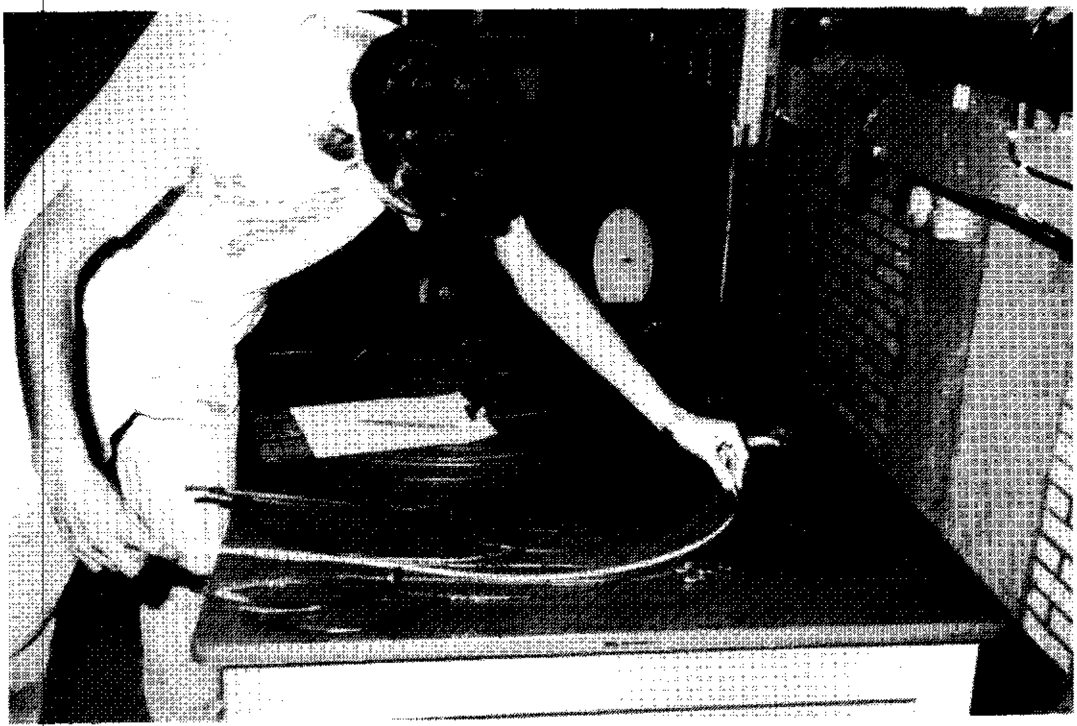

Photo 14: Measuring length of stems ...

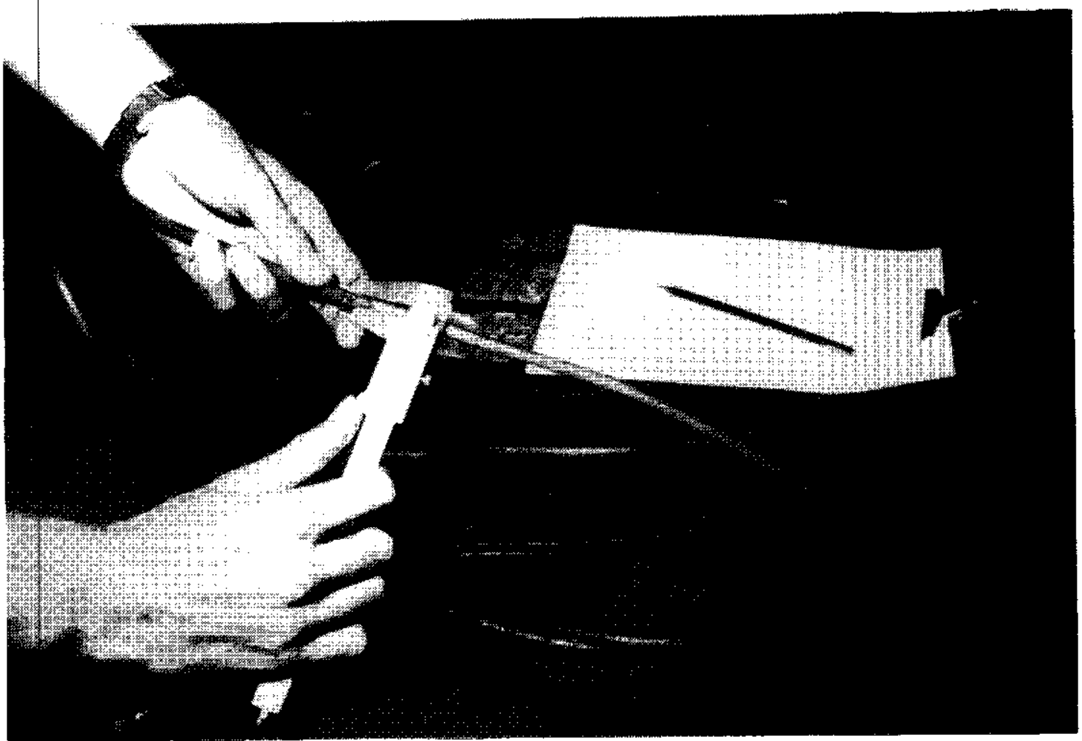

Photo 15: ... and diameter of stems