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Flow resistance and hydraulic capacity of water courses with aquatic weed growth. Part 2

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Abstract. The flow resistance is generally derived from field measurements, using the total wetted area of the cross-section. Less attention has been paid to the aquatic weed growth stage and often different resistance have been derived. In this paper the flow resistance required in the Manning formula was calculated from laboratory experiments and field data. A good solution appeared to be using the unobstructed part of the cross-section only and excluding the part covered by weeds. A practical solution was found using the relative weed obstruction in the water courses to represent the weed growth. Weed obstruction was measured throughout the growing season. The data were obtained from water courses without any weed control and also in sections where weeds were cleared twice during the growing season.

Key words: flow resistance, laboratory experiments, unobstructed part, weed growth, hydraulic radius, drainage canal

Introduction

Vegetation in an open channel retards the flow of water by causing a loss of energy through turbulence and by exerting additional drag forces on the moving fluid. Because of the complex nature of the flow system and the variety of conditions present, it is nearly impossible to develop an analytical equation to estimate the hydraulic capacity of a water course based entirely on local theoretical considerations. Therefore, much of the work done in the past has been empirical or semi-empirical.

The flow resistance (or roughness coefficient) for a certain aquatic weed growth is a function of many variables including flow velocity, vertical distribution of the weeds, roughness of the solid boundary and structural properties associated with the stems and leaves of the plants. Generally the roughness coefficient used in flow formulae such as Manning or Chézy, is derived from field measurements using the total wetted area of the cross-section. Less attention has been paid to the aquatic weed growth stage.

Excessive aquatic weed growth during the growing season affects the capacity of the water courses to transport water. Weed control is then necessary to maintain an adequate capacity (Querner 1997). To minimize weed control, it is important to quantify the transport capacity in relation to the growth of weeds in the water course.

In this paper a procedure is outlined to calculate the hydraulic capacity of a water course using data on aquatic weed growth. In the following section the procedure is described using the Manning equation, but any other flow formulae could be used as well. Based on the division of a cross-section in an unobstructed part and the part covered by weeds, the procedure requires information on the roughness coefficient of the unobstructed part and the measurement of the obstruction caused by the weeds. To verify the proposed concept, the roughness coefficient was derived from laboratory experiments and field measurements, also the obstruction was measured in the field. The procedure described in this paper has been incorporated in the model MWW (Querner 1997) to estimate the timing of aquatic weed control.

Flow resistance

Theory

In the past an appropriate flow resistance value is always obtained from field measurements. For a specific flow rate, wetted area and fall in head over a certain distance, the resistance is commonly calculated by one of the flow formulae such as Manning or Chézy. Using Manning formula the roughness coefficient k_M is estimated as (Chow 1959):

$$k_M = \frac{Q}{A\ R^{2/3} S^{1/2}} \tag{1}$$

where:

k_M	=	boundary roughness coefficient ($m^{1/3} \cdot s^{-1}$)
Q	=	flow rate ($m^3 \cdot s^{-1}$)
A	=	wetted cross-sectional area (m^2)
R	=	hydraulic radius (m)
S	=	hydraulic gradient (–)

The net cross-section is used for the wetted area and the hydraulic radius. The result is a roughness coefficient, such as k_M, which basically represents the roughness on the wetted perimeter. The flow formulae were originally derived for sections with little to no obstruction elements present, such as concrete lining or large alluvial channels.

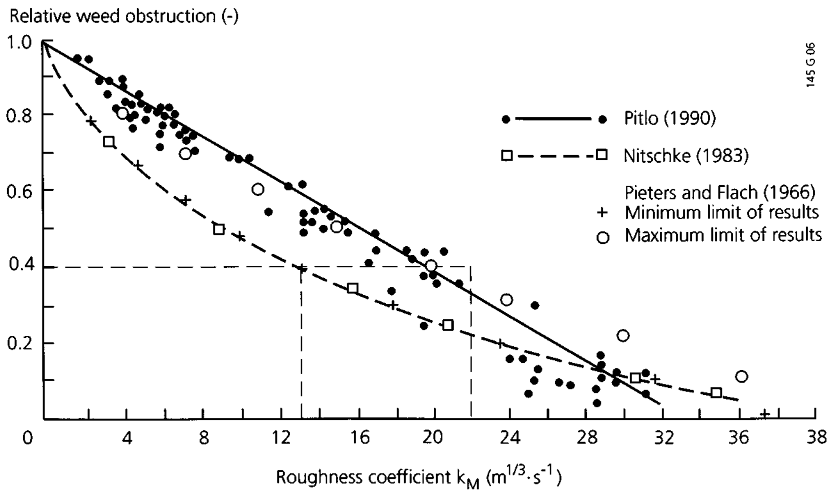

Figure 1. Relation between the roughness coefficient k_M and the relative weed obstruction (area weeds divided by wetted area) obtained by different authors (Querner 1993).

Different authors (Pieters & Flach 1966; Nitsche 1983; Pitlo 1990) have presented the relation between the weed growth and the roughness coefficient as compiled in Figure 1. The measured extent of weed growth, as the obstruction of the wetted area, was used. All the results as shown in Figure 1 give quite a range of roughness coefficients. According to these data, taking 40% obstruction would give a k_M between 13 and 22 $m^{1/3} \cdot s^{-1}$. It would mean a difference of about 40% in the capacity of the water course. This large variation is unacceptable.

Severe weed growth reduces the effective flow area considerably and the flow velocity within the vegetated part is often negligible. Figure 2 shows velocities in a cross-section of a water course which is obstructed by weeds in about 50% of its cross-section. The velocity within the obstructed part is less than 10% of the velocity in the open part. Therefore the obstructed part has little or no effect on the discharge capacity of the water course. Relating the resistance to the original net cross-section will always result in different k_M values, as shown in Figure 3. The flow area for both sections was the same, but the relative weed obstruction was different (section 1 = 0.47, section 2 = 0.68). This would lead to different k_M values if, for instance, the results shown in Figure 1 are used. The k_M value would be larger for section 1 than that for section 2 (Fig. 3). These effects associated with the relationship between obstruction and roughness coefficient may partly explain the large differences in the results shown in Figure 1. Therefore it is not advisable to use such a relation between relative weed obstruction and roughness coefficient.

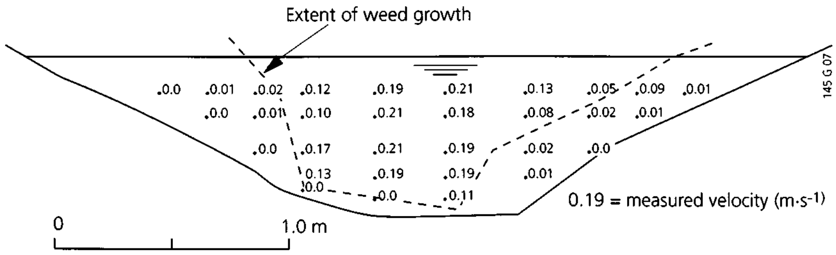

Figure 2. Velocity measured in a cross-section of a water course where weed growth consisted mainly of Glyceria maxima (reed sweet-grass). The relative weed obstruction is about 50% (Querner 1993).

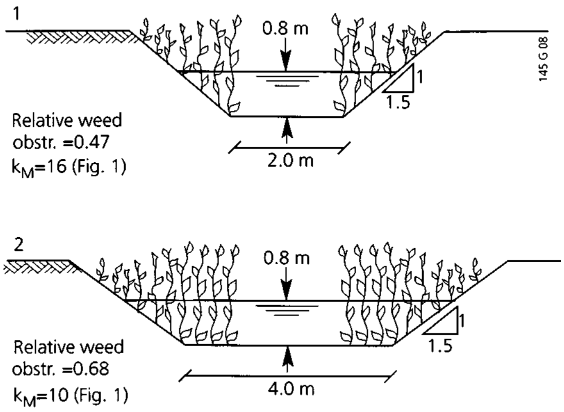

Figure 3. Two different hypothetical cross-sections with an equal unobstructed wetted area. The relation between relative weed obstruction and roughness coefficient (Figure 1) gives the roughness coefficients as shown.

The flow rate primarily depends on the unobstructed area, the hydraulic radius and the roughness on the edge of the unobstructed part of the water course. This is in fact a logical way of using the flow resistance: *considering only the unobstructed part and not any additional weed-covered area.*

Considering only the unobstructed part of the cross-section in water courses with aquatic weed growth, the roughness coefficient can be calculated as:

$$k_M^o = \frac{Q}{A_o\, R_o^{2/3}\, S^{1/2}} \tag{2}$$

where:

k_M^o = roughness coefficient for unobstructed part ($m^{1/3} \cdot s^{-1}$)

A_o = area of unobstructed part (m^2)

R_o = hydraulic radius for unobstructed part (m).

Table 1. Difference in flow rate obtained by using the hydraulic radius for the total wetted area (R) compared with that for the unobstructed part only (R_o). The two hypothetical sections are shown in Figure 3.

Section	Hydraulic radius				Relative difference in flow rate
	R (m)	R_o (m)	$R^{2/3}$ ($m^{2/3}$)	$R_o^{2/3}$ ($m^{2/3}$)	$\{(R^{2/3} - R_o^{2/3}\}/R_o^{2/3} \cdot 100$ (%)
1	0.52	0.41	0.65	0.55	18
2	0.60	0.41	0.71	0.55	29

The hydraulic radius is a parameter used to express the shape of the cross-section so that different geometries can be related to a certain change in flow rate. This means it is incorrect to use the hydraulic radius (R), calculated for the total cross-section and including parts covered by weeds. Instead the hydraulic radius should be calculated for the unobstructed part only (R_o). In Table 1 the hydraulic radius is calculated for the two hypothetical sections shown in Figure 3 in both ways. The difference in hydraulic radius between the two sections is pronounced when considering the net cross-section area, but their values are the same when only the unobstructed part is considered. Using the Manning formula (eq. 1) the flow rate depends on $R^{2/3}$. Whether the hydraulic radius is taken to be R or R_o will change the flow rate by about 18% for section 1 and 29% for section 2 (Table 1). These differences is estimated flow rate based on the two methods of using the hydraulic radius are appreciable and would also apply to the estimated roughness coefficient if the latter were estimated from field data.

The proposed calculation method given by Eq. (2) was evaluated by doing experiments in a laboratory flume using artificial weeds. These experiments and the results are discussed in the following paragraphs. To get some idea of the roughness coefficient for use in practice, Eq. (2) was used to estimate the roughness coefficient from some available field data. The flow resistances was also calculated by means of a numerical approach as described by Querner (1993). In such numerical approach a model was used to simulate the velocity distribution in a cross-section of a water course, using the finite element method and taking the weed growth into account. The calculated velocity distribution gives the transport capacity of the water course and that was used to derive a roughness coefficient for the unobstructed part (see Querner 1993).

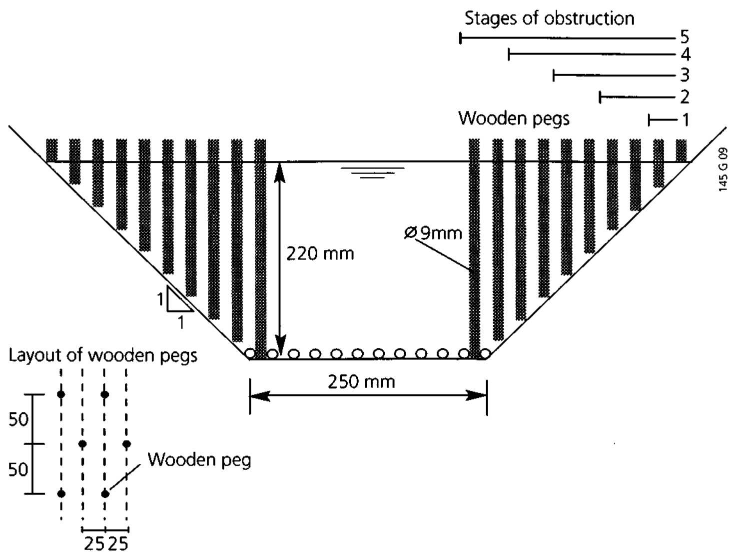

Figure 4. Cross-section and plan view of flume, showing the artificial weeds lay-our (wooden pegs) and the five obstruction stages.

Flow resistance derived from laboratory experiments

The proposed method of using the roughness coefficient for the effective flow area only was evaluated by doing laboratory experiments carried out in a flume 8 m long. The setup of the experiment is shown in Figure 4. Weed growth was simulated in the flume by wooden pegs of 9 mm in diameter arranged in the pattern shown in Figure 4. Measurements were taken at five stages of weed obstruction. The water depth was within the range of 0.18–0.22 m. Each run consisted of measurements for the five weed obstruction stages as shown in Figure 4 and two flow rates (15 and 20 $l \cdot s^{-1}$). The average velocity for all the runs varied between 0.15 and 0.4 $m \cdot s^{-1}$. In addition, the bottom of the plastic lining of the flume was covered with gravel, to increase the roughness. Furthermore the roughness of the pegs was increased by gluing wood-shavings to them.

The roughness coefficient evaluated with the Manning formula (eq. 1) gives the results shown in Figure 5a. The results showed very little difference between the two flow rates. The calculated roughness coefficients were of the same order of magnitude as field data (Fig. 1). The results of evaluating the roughness coefficient by Eq. (2) are shown in Figure 5b. For a relative obstruction of less than 0.2, the roughness coefficient k_M^o remained the same as the roughness coefficient k_M (see Figure 5a). If the obstruction was increased, the roughness coefficients (k_M^o) did not change much. For the largest relative

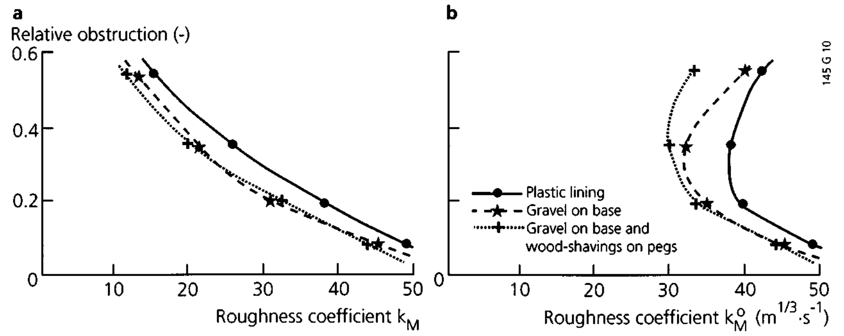

Figure 5. The roughness coefficient calculated for different obstructions and two flow rates (15 and 20 $l{\cdot}s^{-1}$), using measurements from a flume with wooden pegs (Figure 4).
(a) Conventional method of calculating roughness coefficient k_M, using total wetted area (Eq. 1); (b) Calculated roughness coefficient for the unobstructed part k_M^o (Eq. 2).

obstruction (Fig. 5b) the flow velocity through the obstructed area became higher and had the effect of increasing the roughness coefficient. This increase was more pronounced for runs in which there were no wood-shavings glued to the pegs, than when the pegs were smooth and caused less resistance to the flow velocity.

Flow resistance derived from field data

Table 2 shows roughness coefficients calculated from field measurements of flow rate, hydraulic gradient and wetted area. Field data from two water courses in Salland were obtained from the Advisory Group on Vegetation Management, in Wageningen, the Netherlands (Pitlo 1990). The first water course (Zijtak) has a base width of about 0.9 m, the second water course (Soestwetering) a based width of about 1.5 m. The roughness coefficient estimated for the unobstructed area (k_M^o) gives results in the order of 30 to 34 (Table 2). Given the large variation in relative obstruction, the variation of the estimated roughness coefficient (k_M^o) was very small.

Weed growth and obstruction

The maximum biomass attained by aquatic weeds at a particular site is the result of the combined effects of the growth conditions (light, inorganic nutrients and carbon, water temperature and water velocity) and the plant's physiological responses at its current state of growth (Dawson 1988). The complex interactions of a large number of variables make it very difficult to draw general conclusions about weed growth. Nutrients, especially nitrogen

Table 2. Roughness coefficient calculated from field data by the conventional method using total wetted area (k_M using eq. 1) and for the unobstructed area only (k_M^o using eq. 2)

Water course	Relative obstruction (–)	Roughness coefficient ($m^{1/3} \cdot s^{-1}$) k_M*	k_M^o
Zijtak	0.50	15	34
	0.80	5	30
	0.80	5	31
	0.85	3	32
Soestwetering	0.15	25	32
	0.29	26	34
	0.40	18	34

*After Pitlo (1990)

and phosphorus, are the most important growth factors. Instead of estimating the weed growth, measurements were carried out in the field. The extent of weed growth, such as shown in Figure 2, was measured in some cross-sections. The measured extent of weed growth gives the obstruction of the wetted area.

Classes of weed growth

In an aquatic environment the light available decreases down the water column. The attenuation of light (range 0.4–0.7 μm is photosynthetically active) is shown graphically in Figure 6. The extinction coefficient k_a used in Figure 6 expresses the light penetration and depends on the amount of suspended matter. For the average light intensities during summer in the Netherlands, it has been estimated that photosynthesis is not possible when the attenuation of light intensity exceeds about 93% (Vermaat & Van Viersen 1990). Figure 6 shows how the variation in water depth is used to define four weed growth categories, on the basis of the attenuation of light. Based on an extinction coefficient k_a = 2, the range for the attenuation of light intensity for category I is 0–50%, from 51–7576–88% for category III. These categories were used to present the field data of aquatic weed obstruction.

Field measurements of weed obstruction

For a water course the maximum discharge capacity is defined as the capacity with the maximum acceptable water level, also called high flow stage (Fig. 7). Such a high flow stage is reached only for short periods during the year.

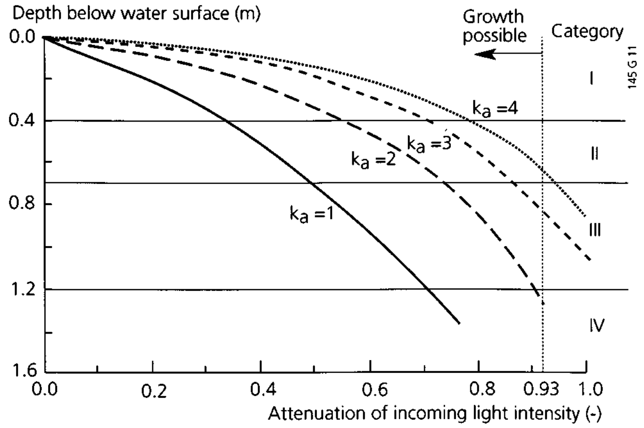

Figure 6. Attenuation of incoming light intensity dependent on water depth and extinction coefficient k_a. Water depth categories, based on k_a = 2, are defined for similar weed growth which reflects the reduction of incoming light intensity (Querner 1993).

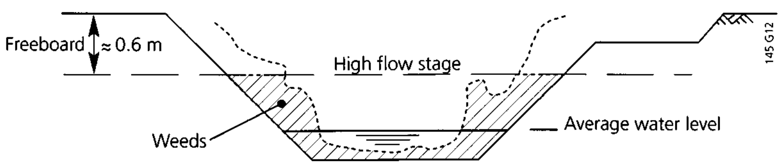

Figure 7. Cross-section of a water course showing the high flow stage for which the relative weed obstruction (area weeds divided by wetted area) was determined.

This means that the wetted area often consists not only of aquatic plants, but also of plants at the water edge, plus terrestrial vegetation. In the Netherlands the high flow stage for farming is about 0.50 to 0.60 m below soil surface and is expected to be exceeded once a year. The relative weed obstruction is defined as the area covered by weeds divided by the wetted area.

In the Poelsbeek and Bolscherbeek catchments the weed obstructions were measured during the growing season of 1990 and 1991. The nine locations in the catchment are shown on Figure 8. Using the average water depth the nine locations were grouped according to the categories shown in Figure 6. At each location no weed removal was carried out in one stretch of the water course. At the start of the growing season the measurements were frequent (once in 10–15 days); later in the year they were less frequent (once in 20–30 days). The major weed species encountered in the nine water courses are stinging nettle, common sorrel, reed sweet-grass, flote-grass, hornwort and elodea. Figure 9a gives the extent of weed growth on four dates during 1990 at location 7. As shown most of the weed growth was on the side slopes of

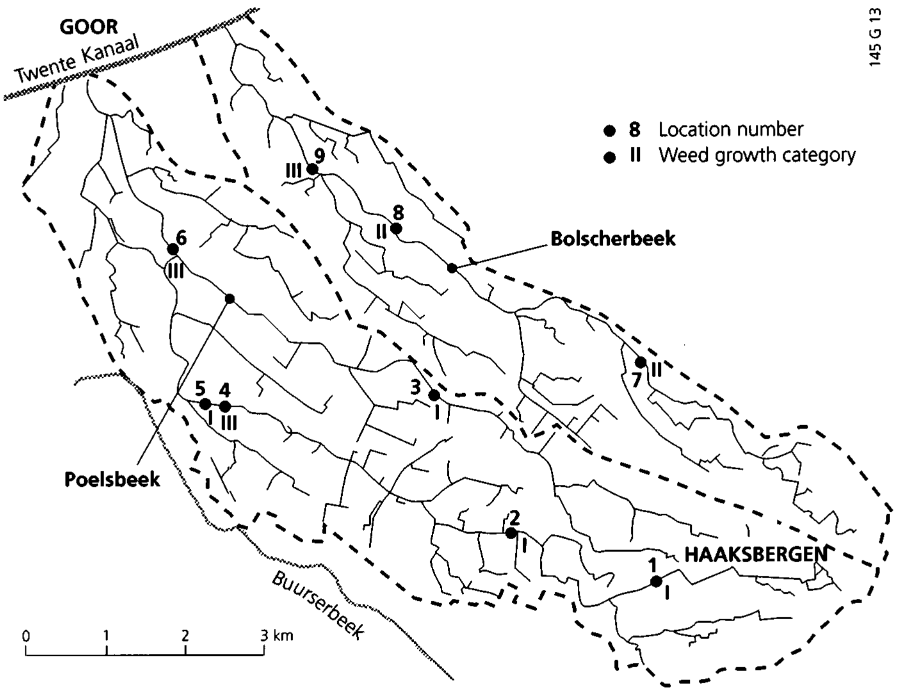

Figure 8. Location of water courses where weed obstruction was measured. The average water depth was used to define a category from Figure 6.

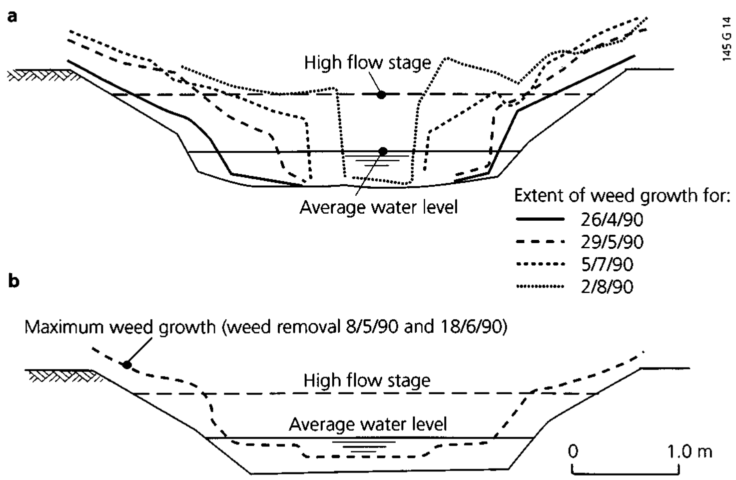

Figure 9. Weed growth at observation point 7 during summer 1990 (location shown in Figure 8). (a) Change in weed growth during the growing season (no weed clearance); (b) Maximum extent of weed growth when weed was removed twice during the growing season.

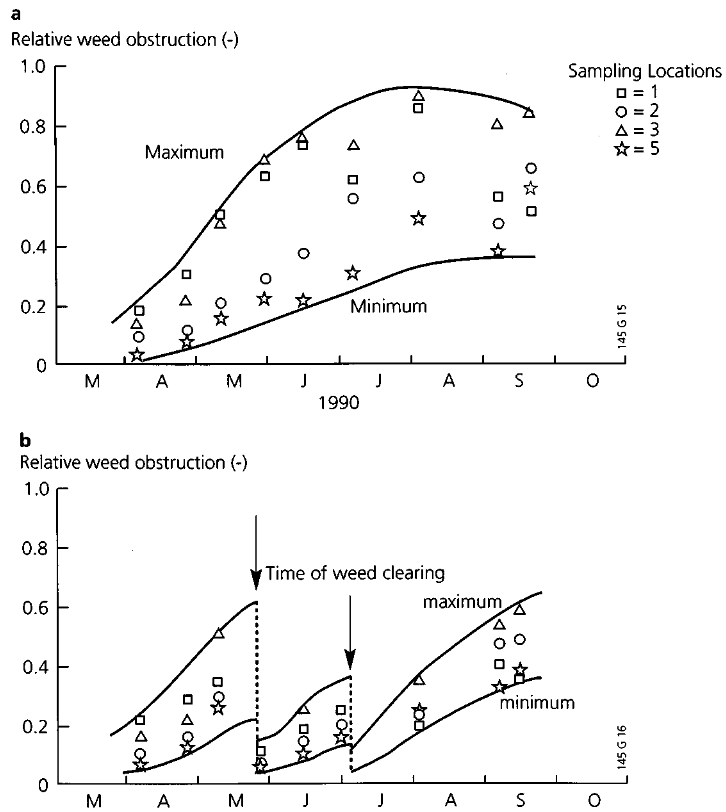

Figure 10. Temporal range in relative weed obstruction for the high flow stage (freeboard 0.6 m) in water depths of category I (average water depth < 0.4 m) during 1990 (sampling locations shown in Figure 8). (a) No clearance; (b) Weeds cleared twice during growing season.

the water course. Figure 9b showed the maximum weed obstruction during the growing season when weed was cleared by the water board. The upper ends of the weed were not included in the obstructed area, because they are easily bent over by the flowing water.

The relative weed obstruction obtained for the high flow stage is shown in Figure 10, together with the bandwidth of observed data. The data shown in Figure 10 were obtained in 1990, and very similar results were obtained for 1991. In Figure 10a the obstructions are given for the stretch of water course where no weed removal was carried out. In Figure 10b the data are for the stretch cleared twice during the growing season. The increase in obstruction, as much as 35% in the period mid April to mid May (Fig. 10a), can be noted. At some locations the adjacent land use, particularly heavily fertilized maize for a number of years, had a marked effect on this sudden increase

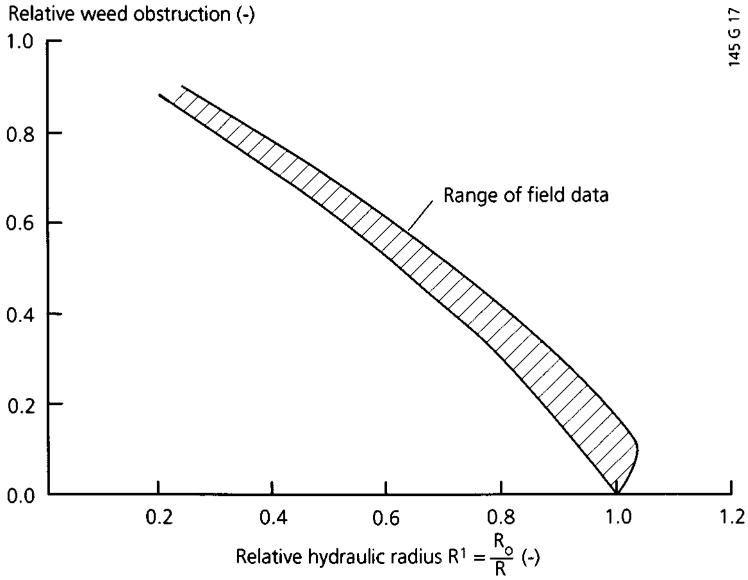

Figure 11. Relationship between relative hydraulic radius ($R_1 = R_0/R$) and relative weed obstruction measured in the Poelsbeek and Bolscherbeek areas. Given a relative weed obstruction, the hydraulic radius R_o for the unobstructed part can be estimated.

(e.g. location 3 of category I; Fig. 10a). A water course of category I reached a maximum relative weed obstruction of about 90%. After mid August the obstruction decreased, because the stems bend over and start to die off. Weed clearance had an effect on the relative obstruction; see Figure 10b. The weed clearance resulted in maximum obstruction of about 60% for water depths of category I.

The obstructions shown in Figure 10, are applicable for very low velocities, but they will be reduced when higher velocities occur. Little information on such changes in obstructed areas related to the velocity is available in literature. A rough estimate of the change in weed obstruction was carried out from some field measurements. The change in relative obstruction measured in the field, reduced the obstruction in the order of 5% for a velocity of 0.20 $m \cdot s^{-1}$ and by 10% for 0.30 $m \cdot s^{-1}$ (Querner 1993).

The hydraulic radius for the unobstructed part of the cross-section was derived from the field measurements of weed obstruction. A relationship was found between the relative obstruction and the relative hydraulic radius R^1 (Fig. 11), R^1 being the radius for the unobstructed part divided by the radius of the net cross-section. Approximately 95% of all the results came in the range shown in Figure 11.

Discussion and conclusions

In literature the roughness coefficient k_m is very often given as a single value. In reality, the value is very variable and depends on factors such as velocity and rate of obstruction. At present it is impossible to make a proper estimate of the flow resistance itself for these factors and different types of aquatic weeds.

The roughness coefficient has been estimated only for the unobstructed part of the cross-section. Measurements of velocities in two water courses showed that the flow rate through the obstructed part is generally very small and can be ignored when calculating the roughness coefficient. The roughness coefficient k_M^o for the unobstructed part derived from field data and laboratory experiments was found to vary between 30 and 34 $m^{1/3} \cdot s^{-1}$. For these calculations the hydraulic radius for the unobstructed part has been taken. The advantage of using the roughness coefficient in this manner is that it can be used in combination with data on relative weed obstruction.

The phenomenon of weed growth is very complicated, the dynamics of growth are to some extent unpredictable. It is never known exactly when and where a weed species will burgeon and in what quantity. Therefore weed growth situations cannot be modelled easily. A practical solution was found, using the relative weed obstruction in the water courses to represent the weed growth. The measurements were grouped into three classes according to the average water depth. At some locations the adjacent land use, particularly heavily fertilized maize for a number of years, results in excessive weed growth.

The amount of weed obstruction in a water course plays an important role in the conveyance capacity. The required capacity should be maintained during the growing season, which means doing a number of times weed clearing. The weed obstruction over the growing season is therefore very important and should be monitored. In that respect various hydrological conditions, such as seepage or leakage and the water quality, play an important role.

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