

# An improved method for roughening floodplains on physical river models

## Une méthode améliorée de représentation de la rugosité des plaines d'inondation dans les modèles physiques de rivière.

ROBERT H. J. SELLIN, *Emeritus Professor, Dept of Civil Engineering, University of Bristol, BS8 1TR, UK*

THOMAS B. BRYANT, *formerly Research Assistant, Dept of Civil Engineering, University of Bristol, BS8 1TR, UK*

JOHN H. LOVELESS, *Snr Lecturer, Dept of Civil Engineering, University of Bristol, BS8 1TR, UK*

### ABSTRACT

Physical (hydraulic) modelling of river systems subject to overbank flow require the simulation of floodplain roughness. Significant full and reduced scale experiments have now been carried out to establish the flow resistance of a range of real and simulated floodplain vegetation. One use for this improved knowledge of floodplain hydraulics is to provide a basis for an improved method for overbank roughening in hydraulic models. It can also be of value in multi-dimensional numerical models. The first part of this paper reviews briefly this work on floodplain vegetation resistance, leading to both empirical and theoretical relationships to describe floodplain roughness, and assesses the appropriate use of these methods. The second and greater part of the paper examines in more detail two methods used recently to roughen floodplains in large scale hydraulic models: non-submerging vertical rods, and a method based on expanded aluminium mesh units. A comparison is made between these two methods by reference to recent tests in the UK Flood Channel Facility at HR Wallingford. Practical recommendations are made for designing a roughness system appropriate for use in future river model tests.

### RÉSUMÉ

Modéliser physiquement des systèmes fluviaux sujets à débordement exige de simuler la rugosité des plaines d'inondation. Des expériences à échelles un et réduites significatives ont déjà été effectuées pour établir la résistance à l'écoulement d'une gamme de végétation réelle et simulée dans les plaines d'inondation. Une utilisation de cette connaissance approfondie de l'hydraulique des plaines d'inondation doit fournir une base pour une méthode améliorée de représentation de la rugosité en débordement dans les modèles hydrauliques. Cela peut également être utile dans les modèles numériques multidimensionnels. La première partie de cet article passe en revue brièvement ce travail sur la résistance de végétation des plaines d'inondation, menant aux relations empiriques et théoriques pour en représenter la rugosité, et évaluer l'utilisation appropriée de ces méthodes. La deuxième et majeure partie du papier examine plus en détail deux méthodes employées récemment pour représenter la rugosité des plaines d'inondation dans les modèles hydrauliques à grande échelle: des tiges verticales émergentes, et une méthode basée sur des grilles d'aluminium. Une comparaison est faite entre ces deux méthodes en se référant aux essais récents dans le service britannique d'expérimentation des inondations à HR Wallingford. Des recommandations pratiques sont faites pour concevoir un système de rugosités appropriées à l'usage de futurs essais sur maquette de fleuves.

## 1 Introduction

Recent events have indicated that storm generated river peaks are increasing in magnitude and frequency. This emphasises the need for more reliable predictions of river flood levels, which in turn calls for more accurate estimations of flow resistance caused by floodplain vegetation. This paper sets out to consider the problem of floodplain roughening in physical models, and in so doing presents original work on the design and use of artificial roughness elements representing model-scale vegetation and used in a recent large scale physical model. However it first reviews briefly a number of studies which have already been carried out to establish the flow resistance of different types and conditions of floodplain vegetation. Results from these are used to initiate the design process for the model floodplain roughening units.

The main objective of the paper is to demonstrate how floodplain roughness appropriate to heavy vegetation may be represented in a physical model in a consistent and determinate manner.

## 2 Selection of a measure of roughness

The question of which measure of hydraulic roughness is most

appropriate for free-surface flow has been widely debated. Whilst there are good theoretical reasons for the adoption of a non-dimensional resistance factor, such as used in the Darcy-Weisbach formula, the widespread use of the dimensional Manning/Strickler roughness coefficient  $n$  in numerical models has to be recognised. Therefore, while Manning's  $n$  will be used in the following discussion where prototype conditions are being considered, the Darcy-Weisbach formula will be used in the section relating to physical models for the following reasons.

Fluid mechanics distinguishes between turbulent flow in which the wall roughness elements are submerged within a laminar sub-layer of the flow close to the wall (*smooth turbulent flow*), and flow at higher Reynolds numbers in which the roughness elements protrude through the much reduced laminar sub-layer to interact directly with the turbulent core flow (*fully rough turbulent flow*). Friction factor values follow different relationships in these two cases; the Darcy-Weisbach factor  $f$  recognises this distinction (varies with Reynolds number) while the simpler Manning relationship is only true for fully rough turbulent (high Reynolds number) flow. There is therefore sound physical reasoning in preferring the Darcy-Weisbach  $f$  for hydraulic models as the flow is mostly *smooth turbulent* or *laminar* on the

Revision received June 7, 2002. Open for discussion till June 30, 2003.

floodplains, whereas Manning's  $n$ , being based on *fully rough turbulent* flow, is more appropriate at the prototype or field scale, to which numerical models relate.

In order that the model behaviour matches more closely that of the prototype, model floodplains almost invariably have to be roughened regardless of the surface nature of the actual floodplain. This is in an endeavour to trigger fully rough turbulent flow at the low Reynolds numbers inherent on model floodplains. Confidence can only be placed in the results of physical models if they are 'calibrated', after construction, against at least one measured set of data taken from the prototype.

The presence of heavy vegetation on the floodplain further complicates the situation, and it is this condition which will be mainly considered here. For the case of non-submerging vegetation, such as hedges, bushes and timber, the area of roughness elements presented to the flow changes with the flow depth and the value of any roughness coefficient must mirror this. As both the Manning and Darcy-Weisbach models were formulated on the basis of boundary (i.e. surface) roughness neither is directly applicable as they stand to a vegetated ground surface. Therefore, any roughness factors used will have to take account of this, both for numerical computations as well as in physical models. Section 3 reviews methods for evaluating full-scale floodplain roughness, which information is needed for the proposed new method for roughening floodplains in hydraulic models. This method is based on the use of discrete floodplain roughness elements which can operate either submerged or non-submerged as required.

### 3 A review of available methods for evaluating floodplain roughness values

This section gives an outline of previous work concerned with evaluating floodplain roughness, caused principally by vegetation. Some of these methods are used in developing the proposed new system for roughening the floodplains of hydraulic river models, presented in section 4.

#### 3.1 US Soil Conservation Service method, and other related methods

Cowan [1] developed a procedure for calculating open channel Manning's  $n$  values based on summing the resistance due to each of a number of global factors and multiplying the sum by a further factor to account for meandering. This formula was adopted by the Soil Conservation Service of the US Department of Agriculture [2] and a table of appropriate values given. The formula was further modified for use on floodplains by Aldridge and Garret [3], as shown below

$$n = (n_b + n_1 + n_2 + n_3 + n_4) m \quad (1)$$

where

- $n_b$  = a base value of  $n$  for the floodplain's natural bare soil surface,
- $n_1$  = a correction factor for the effect of the surface irregularities on the floodplain,
- $n_2$  = used to describe resistance due to the variation in the shape and size of a river channel and hence not applicable to the wide floodplain region – set to zero.
- $n_3$  = a value for obstructions on the floodplain
- $n_4$  = a value for vegetation on the floodplain, and
- $m$  = a correction factor for sinuosity of the floodplain outer boundaries, equal to 1.0 if flow over the floodplain is assumed to follow straight paths (parallel with the straight floodplain banks).

Values of  $n_b$  are given in Table 1 in Aldridge and Garret [3]; values of  $n_{1-3}$  can be found in Table 3 of the same source. Typical values of  $n_4$  for different floodplain types are available from a number of sources: natural channels – French [4], crops - Ree and Crow [5], Arizona vegetation - Aldridge and Garret [3], heavily vegetated floodplains - Arcement and Schneider [6]. The US Department of Agriculture report [2] gives fully worked examples of their method.

Table 1. Summary of methods for predicting vegetative resistance to flow.

Method	Data Required	Advantages	Disadvantages
Experience and intuition	Site visits Photographs	Quick	Requires experience open to errors of judgement
Photo Matching	Site visits Photographs	Quick and widely used - gives an approximate figure for any condition	No variation with water level.
Use of $n$ value tables	More detailed information on vegetation type density season etc	Systematic, familiar	Apparent accuracy is deceptive
Rigid roughness formula	Estimation of variation of plant density with depth, appropriate value of $C_d$	Gives variation with depth	Only applicable to limited conditions: low velocity i.e. no bending
Hedge roughness	$C_D$ value for hedge type	Accounts for flow through hedges	Calibration required
Flexible roughness formula	$C_D$ and $J$ for all plant types present estimation of density	The most accurate method for flexible vegetation in a high velocity flow	Only applicable to densely packed vegetation. Each new variety requires costly recalibration

Table 2. Scaling non-submerged vegetative roughness.

	Prototype	1:5 Model
h	= 0.28m $\longrightarrow$	= 0.056 (1)
f (Darcy)	= $8gn^2/R^{1/3} = 0.376$ (2) $\longrightarrow$	= $0.376(3)$
V	= $R^{2/3} S^{1/2}/n = 0.33 \text{ ms}^{-1}$ (4)	= $\sqrt{(Lm/Lp)} \cdot Vp = 0.150 \text{ ms}^{-1}$ (5)
Re	= $VL/\nu = 64166$ (6)	= 5833 (6)
$f_s$	not applicable	by equation (15) = 0.043 (7)
$\phi$	not applicable	by equation (29) = 0.52m (7)

Numbers in parentheses refer to the numbered steps in design procedure, suffices m and p refer to model and prototype.

Table 3. Summary of factors to be considered when selecting a method of physically modelling vegetation

Factor	Stones	Gravel or Enkamat cover	Rods (not suitable for "submerged" roughness)	"Expanded" metal strip roughening
Similarity to real vegetation:	Non- representational roughness	Models submerged vegetation	Discrete roughness elements (tree trunks, etc.)	Discrete lines (hedges, crops, vineyards etc.), or distributed roughness.
Cost:	Very cheap	Gravel low, Enkamat high, latter needs fixing	c.£20 / m <sup>2</sup> (high labour costs)	c.£4 / m <sup>2</sup>
Time to Build:	Low	High	High construction time for frames	Low, once units have been cut and bent
Ease of movement on model:	Easy	Need to take care	Difficult but can walk with care on units if built into a frame	Can step between lines of frames
Ease of varying roughness:	Simple, but only on an "ad-hoc" basis	Poor	Selective removal of rods can decrease roughness – time consuming	Decreasing or increasing row spacing changes roughness – inherently flexible

A more recent report, Phillips and Ingersoll [7], sets out the results of flow measurements carried out on 14 river and canal reaches in Arizona for which 37 roughness coefficients have been determined. Some of these streams, however, are ephemeral and vegetated and for these the relationships between vegetation density (cover) and the measured Manning's  $n_4$  values are plotted. It is intended by Phillips and Ingersoll that these results should be used in conjunction with current US guidelines that describe methods for assigning Manning's  $n$ .

### 3.2 Matching Photographs

A second method of determining Manning's  $n$  values for a channel, proposed by the U.S. Geological Survey, is based on the photographs presented in Barnes [8]. This method is set out in some detail in French [4]. Results suggest that, after training, engineers may be able to estimate the roughness of a channel to +/- 15% by comparing the channel in question with images of similar channels of known roughness, viewed through a three dimensional imager. The method has been extended to wooded floodplains by Arcement and Schneider [6] and is recommended as suitable if an approximate value of roughness is required for a particular floodplain.

### 3.3 Rigid non-submerged vegetation roughness

Petryk and Bosmajian [9] developed a relationship linking depth

with Manning's  $n$  for vegetation of known density. The analysis is based on the assumptions that the vegetation is non-submerged, that the velocities are sufficiently low to prevent plant bending and thereby changing the projected area, and that the plants are evenly spaced (crops).

Petryk and Bosmajian [9] use data sets provided by Ree [10] and Ramser [11] to verify their results. These consist of plots of Manning's  $n$  and vegetation density with depth. Entering the data for vegetation density into the equation gives good results for Manning's  $n$ . This method, which is developed primarily for use in the southern US, gives correlations for wheat, sorghum, cotton, and four vegetated channel conditions. The methods outlined in this section are all described in detail by Arcement and Schneider [6] where worked examples are given.

### 3.4 Rigid, non-submerged, incremental vegetation roughness

The assumption that the friction slopes are equal for the vegetation and the soil surface is reasonable if the vegetation is evenly distributed. In the case of fields and hedges this clearly is not the case as a large proportion of the head loss occurs when the flow passes through the hedge or fence. Klaassen and Zwaard [12] performed a two dimensional experimental study at full scale to investigate this condition. The method that they proposed for calculating roughness is based on the assumption that the energy gradient of a flow path crossing the hedges is composed of a gradient  $S_s$ , caused by the surface (soil) roughness, and a gradient  $S_e$ ,

caused by the equivalent distributed resistance of the hedges. Thus the total gradient  $S_t$  is given by

$$S_t = S_s + S_e \quad (2)$$

### 3.5 Rigid, submerged, incremental vegetation roughness

Klaassen and van Urk [13] expanded the work of Klaassen and Zwaard [12] to include the case of submerged hedges. They treated the hedge as a short crested weir, and derived an expression based on the normal weir equation for a shallow approach flow. This assumed that the flow over the hedge is not significantly affected by the flow through it and vice versa. Their experiments later showed that the flow through the hedges had minimal effect on the flow over them, thus confirming their initial assumption.

### 3.6 Flexible roughness (non-submerged)

Fathi-Maghadam and Kouwen [14] considered the case of flexible trees in which, at the limit, the whole is just submerged. The trees therefore respond to the drag forces on their branches and canopy and only as the water depth becomes a fraction of the trees' height does their behaviour become that of an array of rigid cylinders. Experimental work was carried out in a flume using suitable saplings as models of full sized trees and bushes. Their experimental results are summarised in Figure 1 which shows measured values of Manning's  $n$  as a function of the relative depth and the mean water velocity.

An alternative approach taken by Rahmeyer [15] was to perform a regression analysis of the appropriate dimensionless groups, including the Reynolds number but omitting the Froude number since the flow is likely to be subcritical. The regression analysis was based on data from 21 test series. For submerged flow

$$C_d = 0.202 \left( \frac{A}{a'} \right)^{-0.631} \left( \frac{h'}{h} \right)^{0.328} \left( \frac{\rho V^2 A_t}{J} \right)^{-0.247} \left( \frac{\rho V h}{\mu} \right)^{-0.156} \quad (3)$$

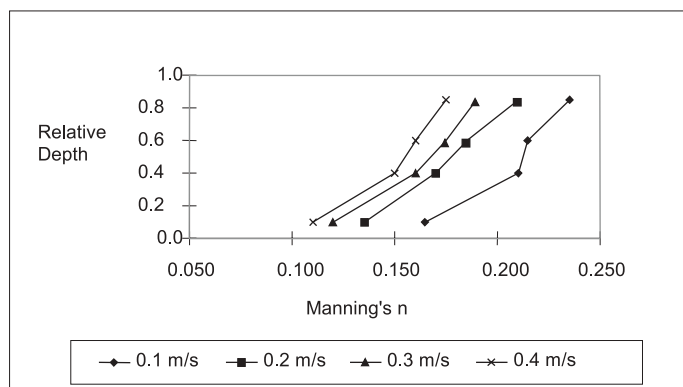


Fig. 1. Relationship between Manning's  $n$ , mean velocity and relative flow depth for a non-submerged pine stand (after Fathi-Maghadam and Kouwen, [14])

Both sets of research showed that flow resistance decreased with an increase in velocity and decreased with an increase in depth. Flow resistance also decreased with an increase in plant flexibility and a decrease in plant density.

Kutija and Hong [16] have developed a numerical model for flow over ground containing flexible vegetation, especially rushes. Their model was partially verified from data obtained in experiments with rigid vegetation. This work is only of relevance to numerical modelling.

### 3.7 Flume experiments

Many small scale flume experiments have been carried out on artificial grass and other materials representing floodplain vegetation. The most recent, and important of these is reported by Wu *et al.* [17], in which flow both submerged and unsubmerged tests were carried out in a tilting flume 1.2 m wide containing a length of a rubberised horsehair material to represent the plant growth. The results extend those of earlier workers but at the low Reynolds number end.

### 3.7 Summary of available methods for predicting floodplain roughness values

The methods so far considered are summarised in Table 1, ordered in terms of increasing complexity, accuracy and expense. Arcement and Schneider [6] recommend the use of the first two methods to give approximate values before further analysis is undertaken.

## 4 Representing vegetative roughness in physical models

For strength and practicality of modelling physical models are normally constructed with a trowelled mortar finish. This is durable and watertight but too smooth to model floodplain roughnesses found in nature. A specific river model of the two-stage channel on the River Blackwater in Hampshire, UK, (Sellin, Wilson and Naish [18]) had already shown that a large amount of roughening was required for a floodplain built to such a large scale (1/5 prototype size). A number of methods of roughening floodplains have been used in physical river models. Traditionally such models have had small stones or gravel placed on their floodplains at a density chosen to produce the required effect.

The criterion would be, where possible, the matching of the scaled water levels in the model against water level data taken from the river during some historic flood event. This validity of this procedure would depend on the accuracy of estimation of the prototype discharge, in turn used to set the discharge in the model. In moving away from a specific river reach model to a generic study of the hydraulics of the river-floodplain combination it is necessary to adopt a more systematic and reproducible method for roughening the floodplain. Rod roughening using an array of vertical cylinders held in a regular pattern has proved useful where non-submerged elements are required. below. In the present series of tests in the UK Flood Channel Facility greater flexibility in the roughening system was sought and shaped strips of



Fig. 2. View of UK Flood Channel Facility – Series C tests with metal floodplain roughness units in place.

expanded aluminium sheet were devised for use on this 50 m by 10 m area – see Figure 2 – constructed at HR Wallingford. The strengths and weaknesses of each method are considered.

#### 4.1 Rod Roughness

An early use of rods for roughening the floodplain, in a laboratory two-stage channel, is described by Pasche and Rouve [19]. A full analysis of rod roughening as used in the FCF is given by Ackers [20]. Ackers' main points are summarised as follows. Seven tests were performed in a straight 50 m x 1.5 m channel of simple cross-section at a bed slope of 1/1000 to provide calibration data for an empirical rod roughness formula. The tests were performed at flow depths in the range 44 mm to 119 mm. The rods were distributed in an equilateral triangular pattern (Figure 3). The pattern tested had a density of 12 rods per m<sup>2</sup>,  $\Delta_1/d = (310/25) = 12.4$  and  $\Delta_2/d = (268.5/25) = 10.7$ . Bed resistance was derived by experiment and may be expressed, in the form proposed by Keulegan [21], and modified for the smooth mortar channel bed of FCF from the Series A tests, as:

$$1/\sqrt{f_s} = 2.02 \log(\text{Re} \sqrt{f_s}) - 1.38 \quad (4)$$

Flow resistance due to the rods can be attributed to a number of physical processes, but predominantly form drag. The resistance force due to form drag is given by

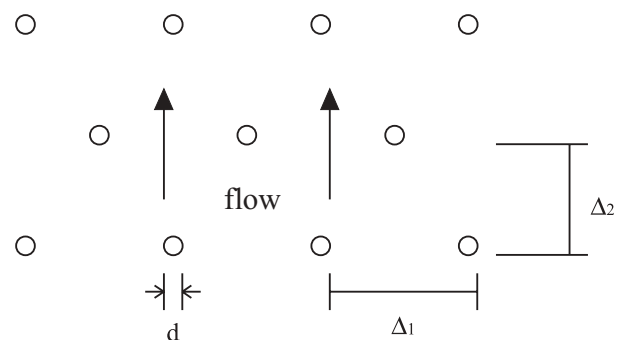


Fig. 3. Plan layout of roughening rods used in the Flood Channel Facility tests.

$$F_{ROD} = C_D \rho g d h \alpha \frac{\bar{u}^2}{2g} N \quad (5)$$

(adjusting all quantities to unit bed area), where

- $F_{ROD}$  = form drag of the rods per unit bed area
- $C_D$  = drag coefficient
- $N$  = number of rods per unit channel length
- $d$  = diameter of rods
- $h$  = flow depth
- $\alpha$  = velocity distribution coefficient
- $\bar{u}$  = the mean velocity between the rods (depth averaged).

The velocity distribution coefficient allows for the variation of velocity over the length of the rod (the vertical velocity profile). The depth mean velocity per unit width  $\bar{u}$  is calculated allowing for the blockage caused by the transverse rows of rods:

$$\bar{u} = \frac{q}{(h - rhd)} \quad (6)$$

Where  $q$  = discharge per unit width and  $r$  = number of rods in each row. On this basis, a blockage coefficient,  $\beta$ , may be defined:

$$\beta = (\bar{u}/V)^2 = (1 - rd)^{-2} \quad (7)$$

where  $V$  = approach free stream velocity.

The total drag per unit length of channel is given by assuming that bed and rod roughness are additive, thus substituting equations (6) and (7) into equation (5) and using the roughness obtained for the smooth bed  $f_s$  we can write:

$$F_t = \beta \rho V^2 \left( \alpha d h \frac{C_D}{2} N + f_s P / 8 \right) \quad (8)$$

where  $P$  = wetted perimeter of channel, equal to 1 for unit channel width.

The drag equation can be converted into a conventional form of resistance equation using the force balance equation

$$F_t = \rho g A S = \rho g R S P \quad (9)$$

where

- $S$  = channel gradient,
- $R$  = hydraulic mean depth,  $A/P$ ,
- and

$$f_t = 8gRS / V = \beta [4(Ndh)\alpha C_D + f_s] \quad (10)$$

and where  $f_t$  = overall friction factor per unit area of bed.  $C_D$  is the only unknown and hence may be found by experiment. When using equation (10) in the reverse direction, with  $f_t$  or  $V$  unknown, iteration is required as  $f_t$  depends on the overall Reynolds number which, in turn, depends on  $V$ .

#### 4.2 Expanded metal strip roughness units

The particular tests for which this roughening method was devised involved overbank flow in a meandering channel with a mobile inner channel bed and a wide floodplain. A mixed grain size sediment was used, and the model arrangement in the Flood Channel Facility is illustrated in Figure 2. These tests constituted half of the Series-C programme. An overview of this investigation is given by Loveless and Sellin [22].

In the case of the earlier Blackwater model, also constructed in the Flood Channel Facility, dynamic similarity was only achieved after laying a close carpet of 10mm gravel over the floodplain, in addition to the rod units described above. Enkamat, an open weave plastic geotextile normally used for soil and turf reinforcement, was also used to roughen the top of the river banks to simulate the strong growth of shrubs and rushes in this area.

It was therefore decided at the outset of these Series-C tests that floodplain roughening would be required that provided a high degree of interaction with the flow there. An early test in Series C was run with an unroughened floodplain and under these conditions it was found that the floodplain flow totally dominated the inner channel flow, due to the latter's bed roughness and sinuosity. In the following analysis of the expanded metal strip roughness units the Darcy friction factor  $f$  is used since the flow is sometimes extremely slow on the floodplain in the Series C mobile bed tests, and thus dependent on the local Reynolds number. Expanded aluminium sheet was folded to form "tent" shaped roughness elements (metal strip roughness) 100mm high. These were placed on the floodplain at regular intervals perpendicular to the valley slope direction. In order to establish the basic resistance function for the individual units, calibration tests were conducted at the University of Bristol in a 300 mm wide glass walled



Fig. 4. View of tilting flume showing calibration tests on expanded metal roughness units in progress.

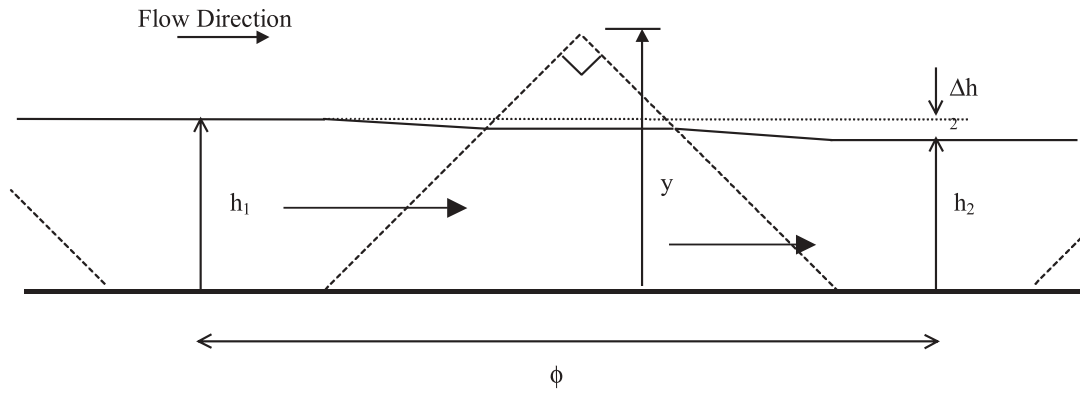


Fig. 5. Schematic diagram for flow through cross-section of unsubmerged metal strip roughness units.

flume, over a range of flow depths from 20 to 120 mm. Figure 4 shows the calibration tests in progress in a tilting glass-sided flume. The range of depths explored covered the flow depths to be used in the FCF tests. These tests also examined the effect of the spacing of the roughness elements ( $\phi$  in Figure 5) on flow resistance over the range  $\phi = 500$  to 200 mm; a 500 mm spacing was selected for the FCF.

Resistance to flow in these tests resulted from friction with the channel bed and walls as well as the action of the roughness elements. It is assumed in the analysis that the presence of the units does not seriously affect the roughness of the flume boundaries. Vertical variations in the velocity profile is allowed for by using a suitable distribution coefficient, in a similar way to that used for the rods. The aluminium mesh forming the roughness elements is structured as shown in Figure 6.  $A_0$ , the area of an individual opening, is given by

$$A_0 = 4(a_3 b_2) + 2(a_2 b_2) \quad (11)$$

#### 4.2.1 Analysis of the flow through the units: non-submerged vegetation

Our analysis of the flow through the roughness units is based on the Klaassen and Zwaard [12] and Klaassen and van Urk, [13] method for hedgerows. The flow conditions are as indicated in Figure 5.

Consider the inclined face of a single roughness unit. This may be considered as an array of orifices. For a single orifice Bernoulli gives,

$$h_1 + \frac{V_1^2}{2g} = h_c + \left( \frac{\alpha V_c^2}{2g} \right) \quad (12)$$

where subscript c indicates values at the *vena contracta* and  $\alpha$  is the velocity distribution coefficient (normally taken as unity for orifice flow).  $V_1$  and  $V_2$  are the velocities upstream and downstream of the orifice.

Rearranging this, and putting  $\alpha = 1$ , gives

$$V_c = \sqrt{2g \left( \Delta h + \frac{V_1^2}{2g} \right)} \quad (13)$$

also,

$$V_c = V_2 \frac{A_2}{A_c} = C_c V_2 \quad (14)$$

This defines the coefficient  $C_c$  that accounts for jet contraction as the flow passes through the orifice, including the effects of angle of attack and orifice shape.

Considering the total flow through a frame per unit width,  $q$

$$q = A_1 V_1 = (\text{reduced flow area}) \cdot V_c = \frac{h \cdot 1}{ab} A_0 C_c \sqrt{2g \left( \Delta h + \frac{V_1^2}{2g} \right)} \quad (15)$$

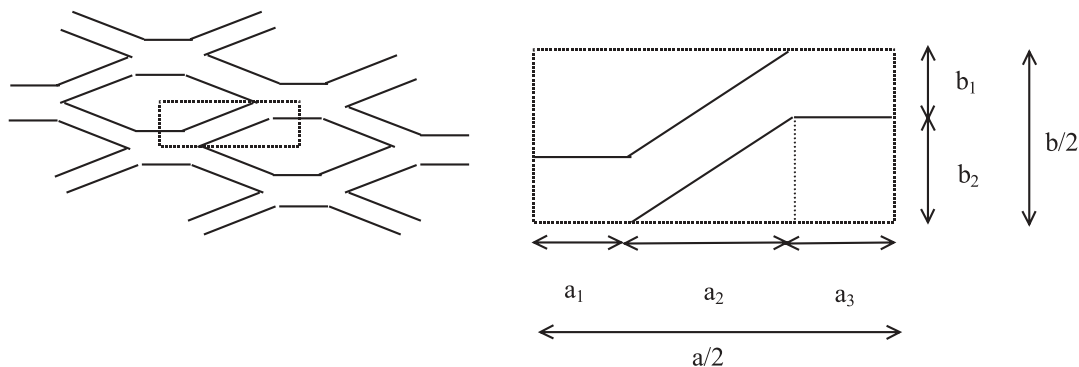


Fig. 6. Geometry of the expanded aluminium strip roughness material.

as the number of orifices increases with increasing flow depth it would seem likely that

$C_c$  is a function of the relative size of the orifice compared with the depth of flow;  $a$  and  $b$  are defined in Figure 6. Replacing  $(h/ba)A_o$  by  $pA_1$ , and rearranging equation (15), gives

$$C_d p = \sqrt{1 + \left( \frac{2g\Delta h}{V_1^2} \right)} \quad (16)$$

where  $\Delta h$  is the head drop across the units, and  $C_d$  includes  $C_c$ , as well as other associated losses.

In order to isolate the effects of the roughness units, the resistance caused by the bed and walls of the flume must be determined separately. The effect of the walls is accounted for by using the Vanoni and Brookes method, as in French [4], page 179. The bed roughness has been accounted for using a combination of experimental and theoretical techniques. Figure 7 shows the  $C_{dp}$  results after adjustment for these effects.

It can be seen from Figure 7 that the value of  $C_{dp}$  increases regularly up to a relative flow depth  $h/y$  of about 0.7. From observation it appears that this is due to the progressive interference between the flow through the two inclined legs of the metal strip units; the separation decreasing as the flow depth increases.

For relative flow depths below 0.75, writing  $R = h$  for a wide floodplain,  $S_e = \Delta h/\phi$  and substituting equation (16) into the Darcy Weisbach friction formula gives a value of the metal unit friction factor

$$f_e = \frac{8gRS_e}{V_1} = \frac{4V_1 h}{\phi} \left( \frac{1 - p^2 C_d^2}{p^2 C_d^2} \right) \quad (17)$$

where  $C_{dp}$  is given by  $[0.35 + 0.13(h/y)]$  or, if greater accuracy is justified, may be read from Figure 7. The overall friction factor  $f_t$  corresponds to the scaled Darcy Weisbach friction factor.

$$f_t = \frac{4V_1 h}{\phi} \left( \frac{1 - p^2 C_d^2}{p^2 C_d^2} \right) + f_s \quad (18)$$

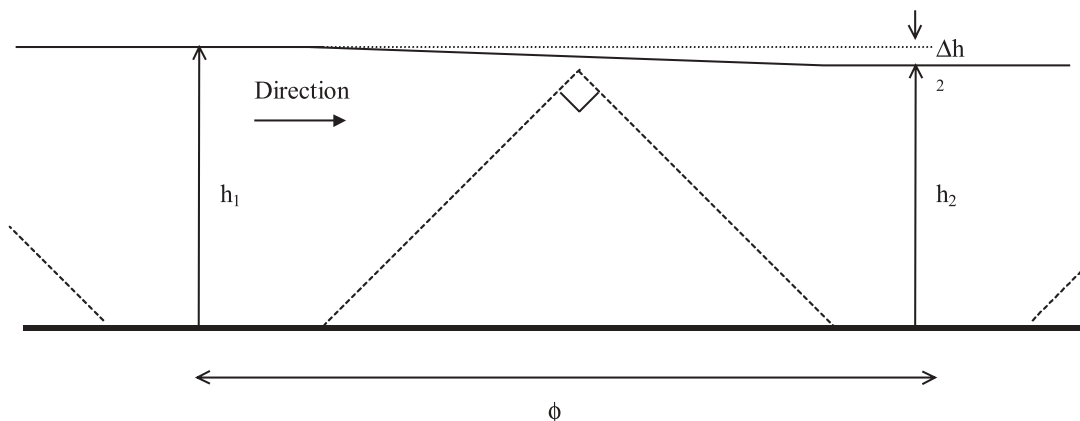


Fig. 8. Flow through and over submerged metal strip roughness units, shown in cross-section.

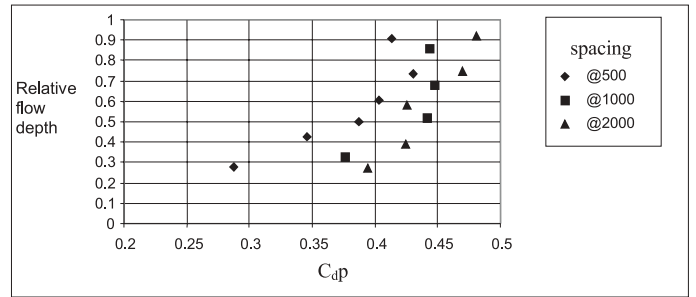


Fig. 7. Variation of discharge coefficient with relative depth for metal strip units (three values of spacing  $\phi$  shown).

which represents: -  $f_t = f_e + f_s = (f_e \text{ equation (17) as it stands}) + f_s$ , where  $f_s$  is the bed surface roughness factor evaluated using equation (4) and  $f_e$  is the element roughness given in equation (17) above.

### Design procedure: Non-submerged vegetation

#### The design of non-submerged floodplain vegetation units for physical models

This section explains how to use the roughness elements described above to model vegetation. An example is presented for a 1:5 scale physical model based on flow through the floodplain crop Redlan Kafir, a variety of sorghum (tropical cereal grasses), or similar, taken from the stage-roughness curve shown in Figure 9 (which is taken from Figure 3 in Petryk and Borsmajian [9]). Table 2 shows the results of the calculations set out below at each stage.

1. Scale the roughness from prototype to model in accordance with the selected scale.
2. Obtain values for the prototype floodplain roughness in terms of Darcy  $f$  and average velocity over the anticipated range of flow depths. This can be done using the Darcy-Weisbach equation and field data from two appropriate cross-sections (use the Phillips and Ingersoll [7] method referenced in 3.1, or one of the other methods referred to elsewhere in section 3).
3. Set the model dimensionless roughness ( $f_t$ ) equal to the proto-

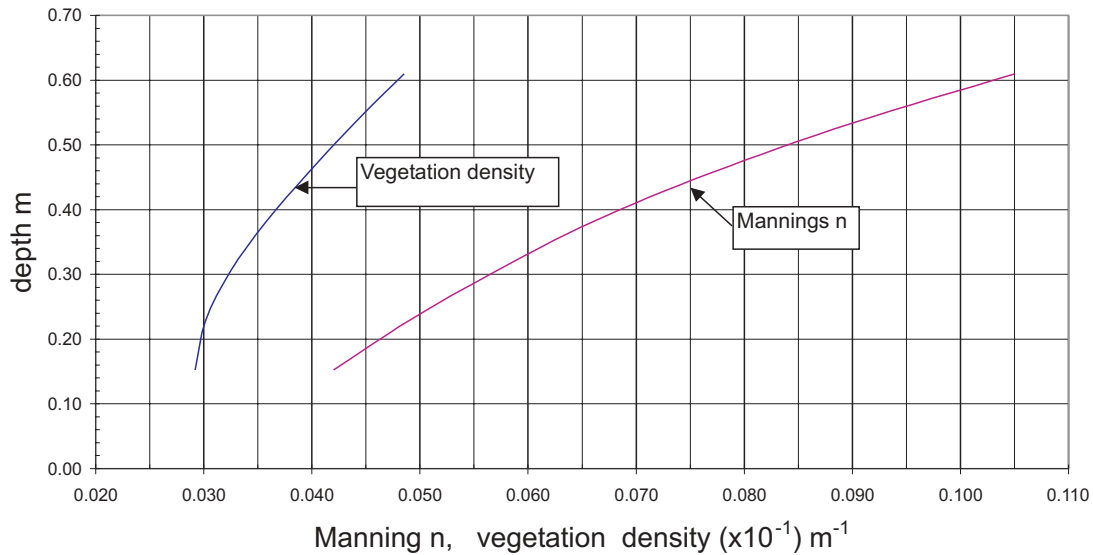


Fig. 9. Graph showing relationship between vegetation density, water depth and Mannings n for floodplain units (after Petryk and Bosmajian [9])

type value.

4. Calculate the flow velocity for the prototype using either the Manning or the Darcy-Weisbach formula depending on the measure of roughness selected above. In this example a wide floodplain has been assumed.
5. Calculate the flow velocity for the model using Froudian scaling laws
6. At this stage the Reynolds number for both prototype and model should be calculated to ensure that both lie in the fully rough flow range.
7. The variables calculated above can now be used to find the surface roughness  $f_s$  using equation (15).
8. The element spacing  $\phi$  can now be obtained from equation (17) to model the prototype roughness.

The graph shown as Figure 9 (from Petryk and Borsmajian [9]) is based on data collected by Ramser [11], and plots the stage-roughness curve for flow through the crop specified. Table 2 uses the values from one point on this stage-roughness curve. This analysis may be extended to modelling hedges crossing the floodplain.

#### 4.2.2 Modelling submerged vegetation

If flow occurs above the frames, as indicated in Figure 8, then the flow equations appropriate to submerged hedges are used, as set out below. The short crested weir equation

$$q = C'_d (h - H) \sqrt{2g(h + V^2 / 2g)} \quad (19)$$

is used to compute the flow over the top of the units,  $q_w$ . The total discharge per unit width is then given by

$$q = q_{o(h=H)} + q_w = M.h \sqrt{2g(h + V^2 / 2g)}, \quad (20)$$

in which  $q_{o(h=H)}$  is the discharge passing through the submerged hedge; the appropriate value of M being obtained using

$$M = \left[ (C_d P)_{h=H} \cdot \frac{H}{h} + C'_d \cdot \left( \frac{h - H}{h} \right) \right] \quad (21)$$

The necessary steps are set out in the following procedure:

#### Design procedure: Submerged vegetation

*The design of a physical model representing submerged floodplain vegetation*

1. Follow the steps 1-6 as for the non-submerged roughness frames (shown above).
2. Equations (19) to (21) should then be used to design an equivalent element roughness ( $f_e$ ) expression for submerged frames to that developed for non-submerged frames and given in equation (17). This must then be calibrated by experiment to obtain the appropriate roughness relationship.

#### 5 Flow distribution on the roughened model floodplain using the new units

The metal roughening units were designed for use in a generic study into floodplain flow in the presence of a mixed grain mobile bed in the deep channel – see Loveless et al. [22]. The only assessment that can therefore be made of their performance at this stage is whether or not they met the needs of this study. The most detailed information that was obtained in this study into flow conditions on the floodplain resulted from comprehensive video filming of dye plumes released into the flow. Near-surface velocity vectors were constructed from these records and a selection from the resulting diagrams are shown here. Figure 10 shows the vector flow pattern for the test HORW (*High Overbank depth, Rough Wide floodplain*). The grid shown indicates a 1 m grid on the model. Figure 11 shows the same information for test HORS in which conditions are similar to test HORW except that the outer limit to the flood channel is given a sinuosity in phase with that

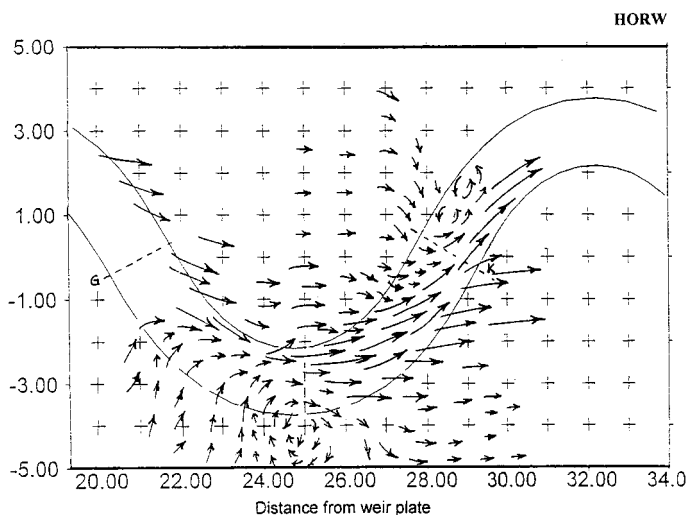


Fig. 10. Surface vector flow pattern for test HORW in Flood Channel Facility Series C programme, showing influence of roughened floodplain on recirculation and low flow areas of floodplain.

of the deep channel, but only half the value (1.15 compared with 1.38).

These tests revealed areas of low flow and recirculation cells on the floodplain and, more conclusively, fine sediment was found deposited on the floodplain from the deep channel in comparable areas to that commonly observed in nature. This was particularly so in the test with straight flood walls shown in Figure 10.

Because of the generic nature of these Series C tests there is no prototype condition with which to compare result. However the earlier 1 to 5 scale model of the Blackwater had shown all these features, when roughened in a different way, as described above, and these were in agreement with measurements and observations made on the prototype – Sellin *et al.* [18].

## 6 Discussion of the merits of alternative roughening schemes

It is now possible to consider the relative merits of alternative

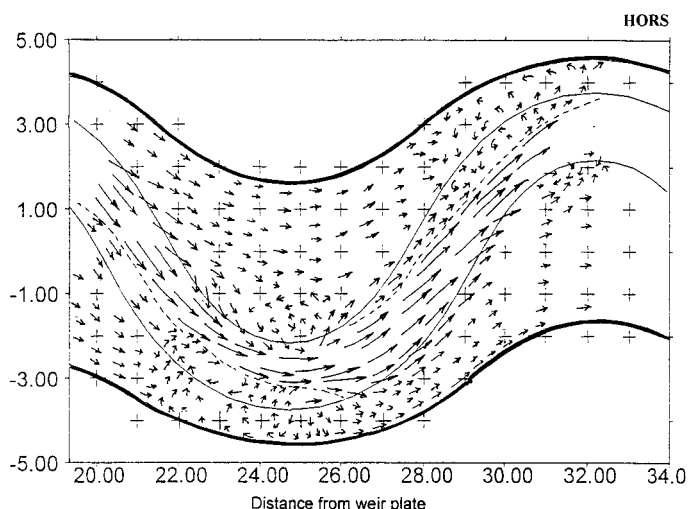


Fig. 11. Surface vector flow pattern for test HORS in Flood Channel Facility, Series C programme, showing influence of roughened floodplain on recirculation and low flow areas of floodplain.

roughening schemes suitable for use on model floodplains.

The use of randomly scattered gravel or small stones is cheap and appropriate for large scale models in which depths over the flood are usually limited to a few centimetres. With this material it is very difficult to model a previously determined roughness value for the floodplain; the behaviour of the model as a whole can only be verified against data obtained on the river during a past flood event, where available. As already stated it is difficult either to quantify or reconstruct this degree of roughening.

Greater roughening can be achieved on the floodplain by the use of some all over treatment; either plastic Enkamat sheeting or a contiguous single-sized gravel layer. There is a limit to the degree of roughness that can be achieved with either of these, especially when depths of 5 cm or more are required on the floodplain. Enkamat sheet floats so needs to be fastened in place with a suitable adhesive. With neither is it easy to adjust the floodplain roughness, and access can be a problem. The rubberised horsehair mats used by Wu *et al.* [17] would behave in a similar way to the plastic Enkamat but past experience with horsehair shows that the mats disintegrate eventually causing problems with measuring instruments.

Both the earlier fixed bed Series-B tests, and those Series-C tests which were based on a straight channel and single size sediment, used the rod roughening system. These were unable to represent submerged roughness elements. The frames holding the vertical rods were found to restrict mobility on the floodplain and also made the filming of die releases impossible. These frames, which had to be above the water level at all times, were expensive to build and modify and bulky to store. However their hydraulic roughness could be quantified and they could be used as often as was required.

The expanded metal tent units, constructed from aluminium alloy, were heavy enough not to be moved by the flowing water, could be rearranged quickly at a different pitch or ground pattern and were compact when stacked for storage. The height  $y$  of the units can be chosen to give either submerged or surface-penetrating use to suite the application. Smaller units can be constructed to fit either between or underneath larger ones to give a scaled response to flow depth. All this adds up to flexibility in use and reuse.

## 7 Conclusions and recommendations

1. The relative merits of different methods for expressing the roughness coefficients for vegetated floodplains are discussed. It is concluded that for reasons of simplicity and familiarity Mannings  $n$  is usually appropriate for high Reynolds number flows.
2. Manning's  $n$  for a floodplain is a complex function of flow depth and velocity, vegetation type, density, dimensions and flexibility, which in turn are functions of age and season. Hence a single value of Manning's  $n$  to cover all conditions in a particular case is inappropriate, if accurate results are desired.
3. It is possible to evaluate the roughness coefficient for vegetated floodplains based on the results obtained with full scale experiments on specific crops or timber stands.
4. However, resistance predictions based on simple tables and photographs are quicker and cost less than these more complex methods which require more data collection and analysis.
5. Available methods for roughening hydraulic model floodplains

are outlined and compared.

6. In order to represent floodplain vegetation correctly in a hydraulic model, the roughening materials used must give a correctly scaled stage-roughness relationship and operate under a similar flow regime. A method for scaling prototype floodplain roughness for use with the model is set out.
7. A new roughening method, using strips of expanded metal sheet folded in the form of "tents", is proposed. This has been used in the UK Flood Channel Facility and has achieved the above objectives whilst improving on previous methods in terms of: cost, accessibility, adjustability and ease of placement.
8. A design method for this type of floodplain roughness has been developed both for submerged and emergent vegetation.

It is important that further work should establish the sensitivity of flood flow packages to the accuracy of estimation of the floodplain roughness. In the long term a data base of applicable characteristics of a wider range of floodplain vegetation may be assembled in order to improve prediction. In the short term an awareness of the problems of vegetative resistance should help with defining safety margins when designing two-stage channels or channels with overbank flow.

Further investigation into the behaviour of metal strip would also be of value to aid the further development of the design methods; in particular the variation in roughness coefficient with mesh size, strip height and flow velocity. Its suitability for modelling hedgerows and bankside vegetation should also be explored.

### Acknowledgements

The authors wish to acknowledge the financial support of the UK EPSRC and the help given by the staff of HR Wallingford. They are also very grateful to Dr Peter Wormleaten of QMWC, University of London and Dr Richard Hey of the University of East Anglia who gave much valuable advice in relation to the Series C programme in the Flood Channel Facility, and to Mr Philip Leonard who built the excellent flume test rig at the University of Bristol. Mr Andrew Pepper of ATPEC Consultancy read the paper in draft and offered much useful advice, for which the authors are very grateful.

### Notation

- a, b, a<sub>1</sub>, a<sub>2</sub>, a<sub>3</sub>, b<sub>1</sub>, b<sub>2</sub> orifice dimensions in expanded metal mesh  
a' horizontal area of vegetation canopy  
A cross sectional area of flow  
A<sub>i</sub> the projected area of the i th plant in the streamwise direction.  
A<sub>0</sub> area of individual orifice in expanded metal mesh  
A<sub>1</sub>, A<sub>2</sub> cross-section flow area per unit channel width (approach channel)  
A<sub>c</sub> cross-section flow area at *Vena Contracta* (orifice flow)  
C<sub>c</sub> the orifice coefficient of contraction  
C<sub>d</sub> discharge coefficient for roughness units, hedges  
C'<sub>d</sub> discharge coefficient for weir equation  
C<sub>D</sub> the drag coefficient for vegetation  
d diameter of rods  
f Darcy-Weisbach friction factor

- f<sub>e</sub> friction factor due to action of metal strip roughness units  
f<sub>s</sub> surface friction factor (bare earth)  
f<sub>t</sub> overall friction factor  
F<sub>ROD</sub> the form drag of the rods per unit length of the channel  
F<sub>t</sub> total drag per unit length of channel  
g acceleration due to gravity  
h flow depth  
h<sub>c</sub> flow depth at *vena contracta*  
h<sub>1</sub> upstream flow depth  
h' average height of vegetation in canopy  
H hedge, roughness element height  
J flexural stiffness (EI)  
m channel sinuosity factor  
M submerged hedge discharge factor  
n (total) Manning's roughness coefficient  
n<sub>b</sub> Manning's roughness coefficient, bare earth value  
n<sub>i</sub> Manning's roughness coefficient pertaining to variable i  
N number of rods per unit channel length  
p the extent of openings in hedgerow/unit expressed as percentage of whole (porosity)  
P wetted perimeter of channel  
q the discharge per unit width  
q<sub>o(h=H)</sub> the discharge per unit width passing through submerged hedge  
q<sub>w</sub> the discharge per unit width above submerged hedge  
r number of rods in each row.  
R hydraulic mean depth, A/P  
Re Reynolds number  
S water surface slope, channel gradient  
S<sub>e</sub> slope caused by the equivalent distributed resistance of the hedges  
S<sub>s</sub> slope caused by the hydraulic resistance of the soil surface  
S<sub>t</sub> total slope  
ū mean velocity between rods per unit width  
V approach free stream velocity, mean velocity over the flow depth  
V<sub>1</sub> approach velocity in relation to orifice flow  
V<sub>2</sub> velocity downstream from orifice, after jet expansion  
V<sub>c</sub> velocity at orifice *vena contracta*  
V<sub>i</sub> average approach velocity to the i th plant  
y vertical height of metal roughness unit  
α velocity distribution coefficient  
β blockage coefficient  
Δ<sub>1</sub>, Δ<sub>2</sub> cross-stream, streamwise spacing of roughness rods  
Δh (h<sub>1</sub> - h<sub>2</sub>)  
μ viscosity coefficient  
ρ fluid density  
φ roughness strip spacing

### References

- 1 COWAN, W.L., (1956). Estimating hydraulic roughness coefficients: *Agricultural Engineering*, Vol. 37, no.7, pp.473-475.
- 2 ANONYMOUS, (1963b). Guide for selecting roughness coefficient 'n' values for channels, U.S.Department of Agriculture, Soil conservation service, Washington, December (see French 1985).
- 3 ALDRIDGE, B.N. and GARRET, J.M., (1973)., *Roughness co-*

- efficients for stream channels in Arizona: U.S. Geological Survey Open-File report, 87pp (see Arcement and Schneider 1989).
- 4 FRENCH, R.H., (1985), 'Open channel hydraulics', McGraw Hill.
  - 5 REE, W.O. and CROW, F.R., (1977), 'Friction factors for vegetated waterways of small slope', Agricultural Research Service, U.S. Department of Agriculture, ARS-S-151, 56 pp.
  - 6 ARCEMENT and SCHNEIDER (1989). 'Guide for selecting Manning's roughness coefficients for natural channels and floodplains.' US Geological survey, Water supply paper; 2339.
  - 7 PHILLIPS, J. V. and INGERSOLL, T. L. (1998), 'Verification of roughness coefficients for selected natural and reconstructed stream channels in Arizona', U. S. Geological Survey Professional Paper 1584, 1998, 77 pp.
  - 8 BARNES, H.H., (1967), 'Roughness Characteristics of Natural Channels.' US Geological Survey, Water supply paper; 1849 (see French 1985).
  - 9 PETRYK, S. and BOSMAJIAN, G., (1975). 'Analysis of flow through vegetation', Proceedings, ASCE, Journal of Hyd. Div., Vol.101, no. HY7, pp. 871-884.
  - 10 REE, W.O., (1958), 'Retardation Coefficients for row crops in diversion terraces', Trans. of Am. Soc. Agricultural Engineers, Vol. 1, 1958, pp.78-80.
  - 11 RAMSER, C.E., (1929), 'Flow of water in drainage channels,' Technical Bulletin No. 129, U.S. Department of Agriculture, Nov.,1929, 101 pp.
  - 12 KLAASSEN, G.J. and van der ZWAARD, J.J., (1974). 'Roughness coefficients of vegetated floodplains', Journal of Hydraulics Research, Vol.12, no.1, pp 43-63.
  - 13 KLAASSEN, G.J. and van URK, A., (1985), 'Resistance to Flow of floodplains with grasses and hedges', 21st IAHR congress, Melbourne, Australia.
  - 14 FATHI-MAGHADAM, M. and KOUWEN, N., (1997), 'Non-rigid, nonsubmerged, vegetative roughness on floodplains', Proceedings, ASCE, Journal of Hyd. Div., Vol.123, HY1, pp 51-57.
  - 15 RAHMEYER, W.(1998), 'Field determination of Manning's value for shrubs and woody vegetation.' in Engineering approaches to Ecosystem Restoration, Donald F. Hayes (ed.), pp 48-53.
  - 16 KUTIJA, V. and HONG, H.T.M. (1996), 'A numerical model for assessing the additional resistance to flow induced by flexible vegetation.' Journal of Hydraulics Research, Vol.34, no.1, pp 99-114.
  - 17 WU, F-C., SHEN, H. W. and CHOU, Y-J. (1999), 'Variation of roughness concepts for unsubmerged and submerged vegetation.' ASCE, J. of Hyd. Eng., Vol. 125, No 9, pp 934-942.
  - 18 SELLIN, R.H.J., WILSON, C.A.M.E. and NAISH, C.(2001), 'Model and prototype results for a sinuous two-stage river channel design.' Journal of CIWEM, Volume 15, No 3, July/August, pp 206-216.
  - 19 PASCHE, E. and ROUVE, G. (1985), 'Overbank flow with vegetatively roughened floodplains.' ASCE, J. of Hyd. Eng., Vol. 111, No 9, pp 1262-1278.
  - 20 ACKERS, P.(1989). Appendix 2, Resistance functions for the SERC-FCF at Wallingford.
  - 21 KEULEGAN (1938) 'Laws of turbulent flow in open channels', J. Res., Nat. Bureau of Standards, Vol.21(6), pp707-741.
  - 22 LOVELESS, J.H., SELLIN R.H.J., BRYANT, T.B., WORMLEATON, P., CATMUR, S. and HEY, R.D., (1999), 'Experiments with meandering mobile bed channels having overbank flow', IAHR Symposium on River and Coastal Engineering Morphology, Genova, Italy.