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The Effect of Vegetation on Flood Levels

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SUMMARY: Stream rehabilitation often involves planting of vegetation, in the channel itself and on the adjacent floodplains. It is important to consider the effect that this vegetation will have on stream capacity, particularly the potential increase in water levels. This effect is especially significant in the event of high flows. To date, a substantial amount of research has been conducted regarding the issue of the effect of vegetation on streamflow. This paper presents a critical review of three methods considered to be most applicable to stream rehabilitation purposes. The first of these is the traditional use of Manning's formula. The second is the Relative Roughness Method, developed specifically for submerged grass-lined streams. The third is a comprehensive model, allowing for variation in the vegetation characteristics across the cross section. The limitations of each of these models reflect the enormous diversity of vegetation. It is apparent that no simple rule of thumb can be adopted to gauge the effect that vegetation will have a stream stage.
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MAIN POINTS OF THIS PAPER

- Vegetation increases the hydraulic roughness of a stream's bed, banks and floodplains.
- An increase in roughness will result in a decreased channel capacity and, thus, a higher water level.
- Predicting the magnitude of this increase is a very complex issue.
- Consideration must be given to these higher water levels when planning stream rehabilitation projects.

1 INTRODUCTION

Rehabilitation of streams and rivers may involve planting vegetation in either the channel itself or on the floodplain. Thus, consideration must be given to the effect of vegetation on the hydraulic roughness of the surface. An increase in roughness will result in a reduction of discharge capacity and consequently increased water levels. In times of flood such increase in stage may be disastrous. For this reason, specific knowledge of the effect of vegetation on the flood levels is vital. A substantial amount of research has been conducted into this issue, resulting in the development of several different models. Three of these models have been presented in this paper as having the potential to aid in effective planning of stream rehabilitation.

For a typical stream system, the diversity of vegetation is potentially enormous. Thus, a number of parameters must be considered when looking at the effect of plants on flood levels. These parameters include:

- The stiffness of the plant. This can range from a very flexible blade of grass to a stiff tree trunk.
- The shape of the plant.
- The distribution of the vegetation both longitudinally and transversely within the stream.
- The height of the vegetation relative to water level.
- The effect of the flow duration on the condition of the vegetation and, thus, the effect on the above mentioned parameters.
- Slope and cross-sectional dimensions of the channel.

In order to simplify their investigations, most researchers allowed for a variation of only a few of these parameters. As a result the available models range from those that deal with grass-lined channels only, to those that incorporate many of the parameters to allow for a variety of plant types and configurations.

2 EXISTING MODELS FOR GAUGING THE EFFECT OF VEGETATION ON WATER LEVELS

2.1 Traditional Model

Traditional channel design utilises the popular flow formula developed in the late nineteenth century, known as Manning's Formula (Henderson, 1966).

$$Q = \frac{AR^{2/3}S^{1/2}}{n} \qquad (1)$$

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Q is the discharge, *A* is the cross-sectional area of the channel flow, *R* is the hydraulic radius of the stream, *S* is the longitudinal slope, and *n* is known as Manning's roughness coefficient. This coefficient characterises the surface roughness, and hence is strongly influenced by the type and quantity of vegetation present.

The method adopted by the Soil Conservation Service of the United States (SCS) in the 1960s for establishing the value of Manning's *n* for a channel was to select a basic *n* value assuming a straight, uniform channel and then modify this value by adding correction factors (French, 1985). These correction factors allowed for the effects of vegetation, channel irregularity, obstruction and channel alignment. This method is used in the example below to illustrate the significant effect vegetation can have on the stage.

Example -

Consider a straight, smooth, uniform channel in earth with:

$$S = 0.001 \ \ and \ \ q = 10m^3/s/m$$

The basic value of *n* suggested for such a channel, without vegetation, is 0.020.

Manning's equation can be used to determine the water depth, *y*:

$$q = \frac{Q}{B} = \frac{yR^{2/3}S^{1/2}}{n}$$

Assuming the channel can be considered wide, $R = y$.

$$\therefore y^{5/3} = \frac{nq}{S^{1/2}}$$

$$= \frac{0.020x10}{(0.001)^{1/2}}$$

$$\therefore y = 3.0m$$

If the same channel were to be vegetated with, for example, dormant willows intergrown with some weeds and brush, and no significant growth on the channel bottom, then a value correction factor for *n* in the range 0.025-0.050 is suggested. Taking 0.04 gives:

$$n = 0.020 + 0.040 = 0.060.$$

Thus

$$y^{5/3} = \frac{0.060x10}{(0.001)^{1/2}}$$

$$\therefore y = 5.8m$$

It can be seen that the effect of the vegetation in this example is to nearly double the water level of the channel. Naturally, the magnitude of this effect in a given stream will vary depending upon the amount and type of vegetation present. In general, an increase in the volume of vegetation will correspond to an increase in the channel roughness. In addition, certain types of vegetation, such as bushes and tree canopies can be considered hydraulically "rougher", and will make a greater contribution to the surface roughness than hydraulically "smooth" vegetation such as grass and reeds.

Although the above example served to illustrate the importance of considering the effect of vegetation on stream levels, the traditional assignment of one Manning's *n* value for the roughness of a vegetated channel for all flows may not always be appropriate. Factors such as the deflection of flexible vegetation within the flow, and the variation of both the vegetation density and shape with depth, result in a roughness that varies with the flow. In addition, the type of vegetation will typically vary both along the stream length and across the cross section. Thus, alternative methods need to be developed in order to predict the stage of flow in a vegetated stream reliably.

2.2 Models for grass-lined channels

Investigations into flow in vegetated channels began in the United States in the 1940s, with the design of grass-lined irrigation channels. Generally, these irrigation channels will only carry water for a short time, with the grass fully submerged by the flow. Consequently, these early investigations concentrated on the effect of the density and flexibility of the grass blades, as well as the slope of the channel.

One of the most prominent models developed for flow in grass-lined channels was that of Kouwen along with a number of associates: Unny, Hill, Li and Simons. The model, referred to as the Relative Roughness Model, was developed and presented through a series of papers spanning from 1969 until 1992. The model is based upon the influence of the deflected height of the grass, *k*, and the grass stiffness.

Kouwen et al hypothesised that there was a relationship between the deflected height of the grass, *k*, the actual height of the grass, *h*, and the stiffness of the grass elements (Kouwen and Unny, 1973). Through experiments using flexible plastic strips to simulate grass in a flume they developed a relationship between *k* and *h*;

$$k = 0.14h\left[\frac{\left(\frac{mEI}{\gamma y_n S}\right)^{0.25}}{h}\right]^{1.59} \qquad (2)$$

In Equation (2), S is the friction slope of the channel, y_n is the flow depth, m is the density of the grass blades, and EI represents the stiffness of the grass. Since the variability of grass linings makes it impractical to determine m, E and I individually, mEI was treated as a single parameter that reflects the overall resistance to lining deformation resulting from flow passing over it. Thus, the relationship given by Equation (2) is suitable only for vegetation that has both a constant stiffness and density.

Kouwen and Li (1980) addressed the troublesome issue of determining the value of mEI for any type of grass, by setting up a table of mEI values for all the common grass linings. This was achieved using a large amount of data from previous experiments by other researchers.

Following the establishment of the reference table of mEI values, the Relative Roughness Method for the design of grass lined channels, was proposed formally by Kouwen and Li as the following procedure:

(i) Select the shape of the channel, trial values for the bottom width and the bank slope, and a grass type. The latter should be from the established reference table of grasses.

(ii) Select a trial depth, and subdivide the cross section. It was suggested that division should result in one centre section and three parts of equal width on the side slopes. More sophisticated means of subdivision could allow for the inclusion of floodplains in the analysis.

(iii) For each subdivision determine k from equation (2), where S is interpreted as channel slope.

(iv) The value of the Darcy-Weisbach f, an alternative roughness coefficient, can be determined from the following accepted semi-logarithmic relationship, based on the Colebrook-White equation (Henderson, 1966):

$$\frac{1}{\sqrt{f}} = a + b\ln\left(\frac{y_n}{k}\right) \qquad (3)$$

Manning's n can then be determined from:

$$n = \frac{f^{1/2} R^{1/6}}{\sqrt{8g}} \qquad (4)$$

(v) Manning's formula, given by Equation (1), can then be used to establish the discharge capacity of the trial channel.

(vi) The channel dimensions are modified until the desired discharge is achieved.

In summary, the Relative Roughness Method is a useful tool for the design of grass-lined channels. It considers the effect of the density of the grass elements, their stiffness, and the height of the grass in the flow. The method is restricted to submerged grasses, with only one species at a time. Although this is a common state for several man-made and managed channels, especially in agricultural areas, the model will not always be suitable for stream rehabilitation purposes. However, as is discussed in Section 2.3, the Relative Roughness Method can be combined with other models to allow the effect on flood levels of more complex and varied vegetation to be modeled.

2.3 Models for complex cross sections

Many rivers and their floodplains support not only grasses but also discrete vegetation elements such as trees and bushes. A substantial amount of research has been conducted into the effect that such vegetation has on the water level of a stream. This research requires the consideration of a greater number of parameters than did the work with grass-lined channels. Since the degree of simplification varied among authors, several different models were developed.

The most comprehensive model developed to date is presented through a series of papers by Masterman and Thorne (1992) and (1994), Darby and Thorne (1996) and Darby (1997). This is an all encompassing model to determine the water level for streams with:

- Flexible and stiff vegetation;
- Emergent and submerged vegetation;
- A variation of vegetation characteristics across the cross section;
- Non uniform cross sectional geometry, allowing the inclusion of floodplains.

This comprehensive model combines several earlier models, one of which is the Relative Roughness Method. It has been implemented as a computer program, for which the user must input a substantial amount of data.

Within the model, the user-defined cross-section is divided into up to 200 computational nodes. Each of these nodes can be classed by the user as being composed of gravel, sand-bed material, flexible submerged vegetation, or emergent vegetation. Fifty possible water surface elevations for the cross section are then calculated, ranging from just above the lowest elevation of the streambed up to a specified maximum level.

For each of the elevations, equations from the relevant component models are applied at all 200 nodes, depending upon the classification of the node. This results in a value of the Darcy-Weisbach friction factor, *f,* for each node.

For nodes that are classified as having flexible vegetation, Equation (2) of the Relative Roughness Method is applied to determine *k*, the effective roughness height of the vegetation. This is then used to calculate *f* according to the Colebrook-White equation:

$$\frac{1}{\sqrt{f}} = a + c\log\left(\frac{R}{D}\right) \qquad (5)$$

In Equation (5) *D* is the roughness height, for which *k* can be substituted. *a* and *c* vary depending upon how prone the vegetation is.

For nodes that have been identified as gravel, Equation (5) was empirically calibrated by Hey (1979) to give:

$$\frac{1}{\sqrt{f}} = 2.03\log\left(\frac{a_s R}{3.5D_{84}}\right) \qquad (6)$$

with

$$a_s = 11.1\left(\frac{R}{D_{84}}\right)^{-0.314}$$

D_{84} represents the gravel diameter for which 84% of the bed material is finer or equal to and is determined by the particle size distribution.

For those nodes that are to be treated as being mainly composed of sand bed materials, a flow resistance relationship developed by van Rijn (1984) is applied:

$$k = 3.5d_{84} + 1.1\Delta\left(1 - e^{-25\Psi}\right) \qquad (7)$$

In Equation (7), ψ is the bedform steepness given by Δ/λ. Δ is the bedform height and λ is the bedform wavelength, $2\pi/D$. The value of *k* calculated from this equation is then used to calculate *f* according to the Colebrook – White equation, Equation (5).

For those nodes with discrete emergent roughness elements, the value of the friction factor, *f,* is calculated using a model developed by Thompson and Roberson (1976). This gives equations for the wake velocity correction downstream of the emergent vegetation, according to the pattern of the vegetation and the ratio of the spacing of the vegetation elements to their diameter. Only regular patterns, either staggered or parallel, are accounted for. The corrected velocities, u_w, for each node are then used to determine *f* according to:

$$f = \frac{8gRS}{u_w^2} \qquad (8)$$

The above is obtained by combining Manning’s formula, Equation (1), with Equation (4). Therefore, at each node with emergent vegetation, a representative element spacing and diameter needs to be estimated. Unfortunately, only regular spacing of the vegetation elements is provided for.

Once a value of the friction factor, *f,* has been calculated for each node, the following equation is applied to determine the corresponding unit discharges

$$gDS - \frac{B_s f q^2}{8D^2} + \frac{\partial}{\partial y}\left(\varepsilon\frac{\partial q}{\partial y}\right) = 0 \qquad (9)$$

Equation (9) is a simplified version of the flow momentum and continuity equations for the lateral distribution of local unit discharge. *D* is the flow depth, *y* is the lateral co-ordinate of the node, B_s is a factor relating the stress on an inclined surface to the stress on a horizontal plane, and ε is the local eddy viscosity.

The values of the local unit discharges are then integrated laterally to give an estimation of the total stream discharge corresponding to a given water elevation. This information is used by the model to produce a stream-rating curve, giving an estimation of the water elevation for any discharge, and vice versa.

The model has been tested by comparing the predicted and observed stage-discharge curves for the River Severn in England. Figure 1 shows this comparison:

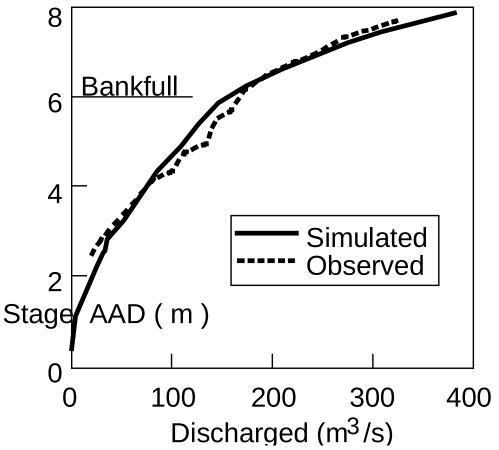

Figure 1 Predicted and observed stage-discharge curves for the River Severn (after Darby and Thorne, 1996)

Further verification of the model involved a comparison of simulated and gauged stage-discharge curves at three field sites, with the vegetation characteristics recorded during on-site surveys. The discrepancies ranged between 2% and 45%, with most less than 15%.

In summary, this model developed by Masterman, Thorne and Darby is a powerful tool, allowing for variation of vegetation characteristics across the cross section of a stream and its flood plains. One drawback of using the model is the large amount of data required, including the vegetation characteristics at 200 points across a stream. However, given the possible variability of vegetation, such information will always be necessary in order to produce more realistic estimates of the discharge corresponding to a given elevation. Unfortunately, the data required for the model as well as its complexity make the model, as it stands, impractical for application as a stream management tool. It may be possible to consider applying the model with a smaller number of computational nodes.

3 IMPLICATIONS FOR MANAGEMENT

Effective stream management requires an understanding of the influence that vegetation will have on water levels. In general, adding to the vegetation cover will lead to an increase in the hydraulic roughness of the surface, resulting in an increase of the water level for a given discharge. Knowledge of this will become especially important in times of flood, and for development of flood management strategies.

Due to the diversity of vegetation, determining the degree to which surface roughness is affected is an extremely complicated problem. This complication is a result of the numerous interacting parameters: the stiffness of the individual vegetation elements, the shape of the elements, the distribution of the elements, the deterioration of the vegetation under flow, and the cross sectional dimensions of the stream itself.

Three possible approaches have been highlighted in this paper. These are, in order of increasing complexity: the use of the traditional Manning’s formula, the Relative Roughness Model, and the model of Darby *et al.*

Unfortunately there are drawbacks with each of the three methods. The use of Manning’s equation, which assumes one value of *n* for all flows in a channel, was shown to be inadequate due to the variation of *n* with flow. The Relative Roughness Method allows for a variation of *n* with flow, yet is limited to grass lined channels only. The final model, that of Darby et al, is quite comprehensive, allowing for different types of vegetation as well as a variation across the cross section. This suggests it would be the most applicable for stream management purposes, yet its complexity renders it impractical.

Thus, there is no simple rule of thumb for stream management that can be adopted to gauge the effect of a particular revegetation project on the stream stage. If a very approximate estimate will suffice it is recommended that the traditional Manning’s formula be applied, according to the procedure adopted by the Soil Conservation Service of the United States, as described in Section 2.1.

4 CONCLUSIONS

Of the many models in current literature, three have been highlighted in this paper as being applicable for the purposes of stream rehabilitation: the traditional use of Manning’s formula (as proposed by the US Soil Conservation Service), the Relative Roughness Method, developed by Kouwen *et al*, and the comprehensive model of Darby, Thorne and Masterman.

The limitations associated with each of the three models reflect the fact that vegetation is enormously diverse and encompasses several important parameters whose effect on river stage cannot be predicted easily.

Since the effect of vegetation on flood levels is a complex issue, it must be accepted that there cannot be one general rule that may be applied to all revegetation programs.

A possibility of further work in this area would be to simplify the application procedures of the Darby et al model, making it more user friendly. This may involve including the effect of some additional parameters in the model, such as the spacing of vegetation elements.

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