Hydraulic Characteristics of Vetiver Hedges: An Engineering Design Approach to Flood Mitigation on a Cropped Flood Plain

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Abstract

In this paper trials aimed at a quantitative description of the hydraulic characteristics of vetiver grass hedges are described. Three hedges were planted across a large outdoor flume, perpendicular to the flow. Trials were conducted at various discharges and depths and the discharge and depths upstream and downstream of each hedge were recorded. From this data an empirical hydraulic relationship was developed between the depths and the discharge. This relationship was used to calculate the maximum vetiver grass hedge spacing required to control soil erosion on a cropped flood plain of low slope subject to deep erosive overland flows. Finally an appropriate hedge spacing was calculated for a field site on the Darling Downs of Queensland, Australia. Hedges were planted at the appropriate spacing and flow retardance and sediment trapping were monitored for the validation of this theory.

Introduction

Although the Vetiver system has been extensively used for soil and water conservation and land stabilisation worldwide (Truong, 1993), few studies are known which describe the hydraulic characteristics of vetiver hedges in a quantitative sense. Rodriguez (1993) used simulated rainfall to determine empirical relationships between soil loss and slope length for hedges planted on steeply sloping land. Rao *et al.* (1992) and Rao *et al.* (1993) demonstrated the reduction in runoff and soil loss resulting from hedges planted along the contour on slopes of 2.8% and 0.6%. Of particular interest to the present flood plain project are the results for the lower slope. Here the vetiver hedges reduced the peak rate of runoff by approximately 64%.

On the agricultural flood plains of the Darling Downs of Queensland, Australia and on the north western slopes of New South Wales, an agricultural practice known as strip cropping is used to mitigate flood water and control soil erosion on low gradient lands subject to deep overland flooding. Strip cropping uses a similar "flow-through" technology as that of vetiver grass hedges. Crops are planted on the contour in a sequence of crop, stubble and fallow strips of uniform width arranged perpendicular to the flood flow direction with the aim of spreading the flood waters laterally thus reducing the depth, velocity and erosivity of flow. Successful protection of the cultivated flood plain using this method is limited during drought years when crop coverage is poor and little or no stubble remains from previous crops.

Smith *et al* (1991) presented an hydraulic analysis of flood flow through strip cropping for the purpose of determining optimum strip width guidelines in strip farming systems. The guidelines that were developed consider particular soil types, land slopes, flood discharges and crop rotations.

In the present paper the theory of flow through strip cropping presented by Smith is adapted for a quantitative description of the hydraulic characteristics of vetiver grass hedges. Hydraulic flume trials are described in developing this theory. From the quantified hydraulic description of the vetiver hedge a method for calculating the appropriate hedge design spacing is illustrated. The validation of this theory through field trials commenced in 1993 on a property near Mt Maria on the Darling Downs of Queensland, Australia.

Discharge Depth Equation

There is little precedent in the literature on which to base a hydraulic description of the flow through a dense hedge. The only study known to the authors (Klaassen and van der Zwaard, 1974) simply derived effective values of the Chezy C for a flood plain transected by hawthorn hedgerows.

A possible direction is provided by the literature on flow through more extensive vegetation, much of which was reviewed by Smith *et al*. (1990). The flow of water through a continuous stand of tall vegetation described by Turner *et al*. (1978), Turner and Chanmeesri (1984) and Smith (1982) is based on the Manning equation which gives an empirical equation for the flow of water through tall vegetation. Smith (1982) reviewed the Manning equation and the work done by Turner to describe deep overland flows through and over submerged vegetation using the following empirical equation:

$$q = A S_f^b y^c \qquad (1)$$

where q is the discharge per unit width; S_f is the slope of the energy line; and A, b and c are constants for the particular vegetation. This form of equation was subsequently used by Smith *et al*. (1990) to describe relatively deep flows through the broadacre crops typically used in strip cropping. For a vetiver grass hedge the stand of tall vegetation is discrete in nature and hence the equation described in this literature is not directly applicable. However an equation similar in form to equation 1 might be assumed to apply. In this case the energy slope, S_f might be replaced by the change in depth through the hedge, δy and the depth, y by the depth upstream of the hedge, y_1 giving:

$$q = a\, \delta y^b y_1^c \qquad (2)$$

Figure 1 illustrates the terms in equation 2. An equation of similar form can be developed assuming that the hedge behaves like a submerged orifice. While neither approach could be described as rigorous, the equations provide a vehicle for the analysis of experimental data.

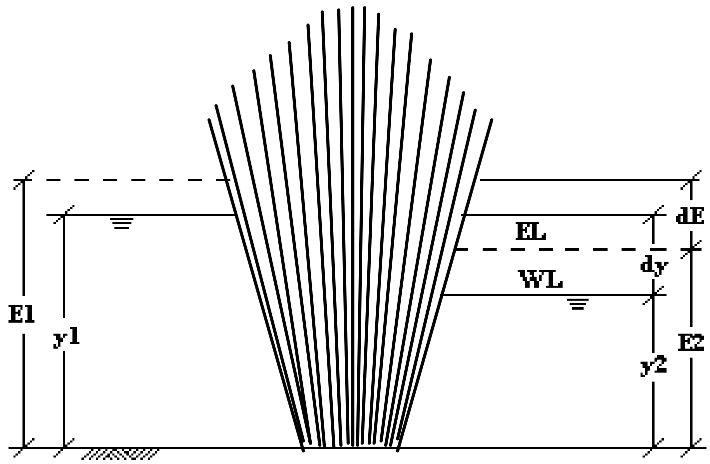

Figure 1: System of flow through a vetiver grass hedge and definition of terms in the discharge-depth equation

Experimental

The Flume Facility

The channel of the outdoor flume facility is 20 m long, 2 m wide and has a bed slope of 0.25%. Discharges of up to 300 Ls^{-1} are supplied by a 350 mm diameter axial flow pump and measured using a 300 mm diameter McCrometer in-line propeller flow meter. A drop board weir at the downstream end of the channel allows control over the depth and velocity of flow for any given discharge. Depths up to 0.6 m can be obtained in this manner. Longitudinal depth profiles can be monitored to a discrimination of 1 mm by a series of manometers located at 1 m intervals along the centre line of the channel.

Experimental Method

The vetiver grass hedges were planted across the flume in October 1992. Each hedge comprised 15 plants spaced 125 mm apart. Three hedges were planted to speed up the rate of data collection. The upstream hedges were under the influence of the backwater from the hedge downstream. Hence for any discharge and downstream drop board setting each hedge had a different combination of upstream and downstream depth and thus three data points would be obtained.

Trials were performed in March, July, September and December 1993 and July 1994. Each trial consisted of measurements of the depths upstream and downstream of each hedge for a range of discharges up to 125 Ls^{-1} and for various drop board settings (that is, depths at the downstream end of the flume). A detailed description of the experimental procedure is to be found in Dalton (1993).

The vetiver grass remained unsubmerged in all trials, the maximum depth of flow being 0.6 m. Whilst there was a substantial difference in the water levels either side of a hedge, the plants showed little tendency to flex and remained upright throughout the tests. Figure 2 shows one hedge during a trial.

Figure 2: Flow through a hedge in the July 1993 trial

Evaluating the Constants in the Discharge E-Depth Equation

Equation 2 suggests a form for a discharge-depth equation to describe the hydraulic characteristics of a vetiver grass hedge. Multi-variate non-linear regressions were attempted using the measured values from the first trial of the variables q, y_1, y_2, δy and δE in various combinations, with that described by Equation 2 giving the best fit. For the subsequent trials only that form of equation was used. The results for the five trials are presented in Table 1.

Table 1: Constants in the discharge-depth equation and regression fits for the flume trials

Trial	a	b	c	r^2
March 93	1.65	0.57	2.16	0.900
July 93	0.96	0.54	1.85	0.957
Sept 93	0.74	0.48	1.81	0.968
Dec 93	0.66	0.62	1.78	0.969
July 94	0.51	0.46	2.44	0.963

From these results it appears that Equation 2 provides an adequate description of the hydraulic characteristics of the vetiver hedge. As the hedges established the fit improved, as evidenced by greater r^2 values, suggesting that minor differences in initial hedge geometry become insignificant with age. The remainder of the variability in the discharge, q, not predicted by the regression equation, must be due to differences between the hedges. As an illustration, Figure 3 compares the discharges measured in the final trial with those predicted using Equation 2 and the corresponding parameter values for the July 1994 flume trial.

For a given discharge, the flow depths for each hedge were different. At hedge 1, the furthest upstream, the flow was deepest and at hedge 3 shallowest. From Figure 3, it can be seen that the hydraulic behaviour of the three hedges differs slightly because of the difference in flow depths and/or velocity through each hedge.

Figure 4 shows the relationship between discharge and upstream depth for a given downstream depth for each set of parameter values. The increased flow retardance with hedge maturity or thickness is clearly evident.

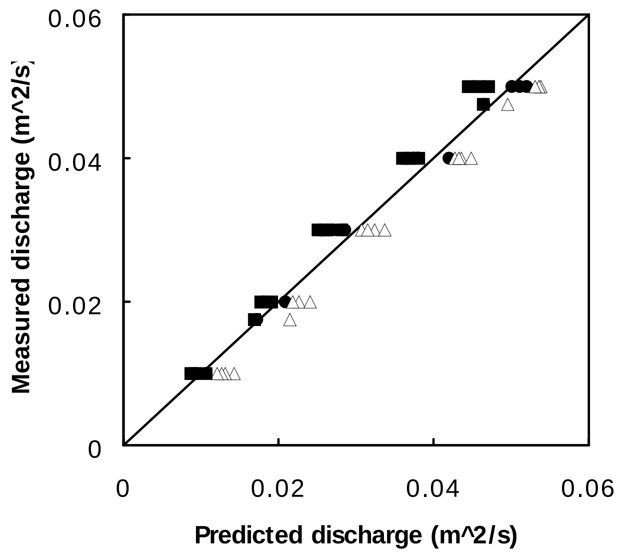

Figure 3: Predicted vs measured discharges for the July 1994 trial, $r^2 = 0.963$ (Δ Hedge 1; ● Hedge 2;■ Hedge 3)

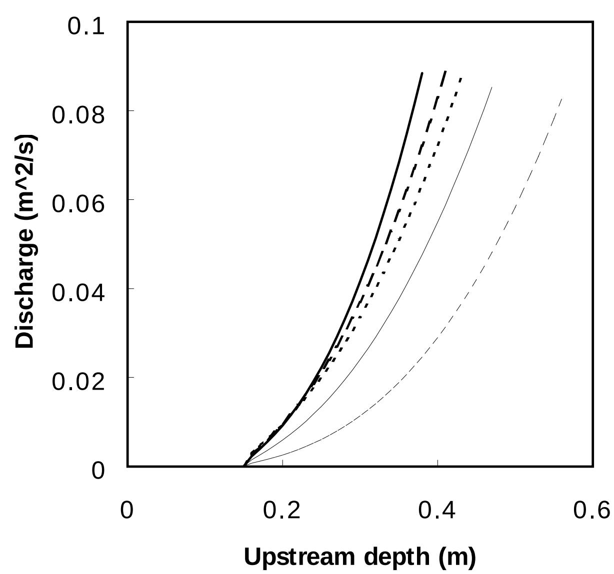

Figure 4: Plots of Equation 2 for each of the trials for a downstream depth y_2 of 0.15 m (▬March '93;▬ ▬ ▬ July '93; ▪ ▪ ▪Sept '93;▬ Dec '93;▪ ▪ ▪ July '94)

The hedges tested in July 1994 (which were then 20 months old) appeared to have sufficient retardance at least for effective use on the flood plains. The authors have no indication of what may constitute an optimum or desirable hedge age or thickness. However such a maximum may need to be nominated. It should be noted that the data and regressions described above are limited in their applicability, viz:

- the maximum depth of flow was 0.6 m and the regression coefficients would not be valid at greater depths; and

- the flow downstream of each hedge was not normal for the discharge but was subject to a backwater from a downstream control.

Application of Vetiver Hedges on a Cropped Flood Plain

The key feature in vetiver hedge design is the spacing between the hedges in the flow direction. The spacing of hedges depends principally on the anticipated discharge, the soil erodibility and the land surface slope. The design discharge can be estimated using an appropriate hydrologic procedure and the soil erodibility can be described in terms of a maximum permissible velocity V_{max}, which, from continuity implies a minimum depth. According to Smith *et al.*, (1991) the water surface profile through a strip cropping sequence is a series of drawdown or M2 curves (Chow, 1959) in the cropped or high retardance strips and backwater (M1) curves (Chow, 1959) in the fallow or low retardance strips. For vetiver hedge spacing calculation the drawdown profile is replaced by the change in depth (or energy difference) across the hedge (as defined by Equation 2) with a backwater curve occurring over the bare strip between the hedges. This curve is defined by the gradually varied flow equation:

$$\frac{dy}{dx} = \frac{S_o - S_f}{1 - N_F^2} \qquad (3)$$

where S_o is the land surface slope, S_f is the energy slope and N_F is the Froude number of the flow. The energy slope is determined from either the Manning equation or the discharge-depth equation (equation 2). The worst (or least protected) case will be that of bare soil between the hedges for which an appropriate value of the Manning *n* would be selected. The physical flow model is illustrated in Figure 5.

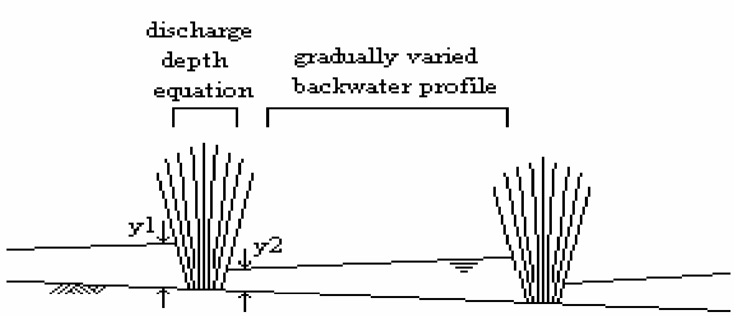

Figure 5: The physical model of flow over bare fallow and through vetiver hedges.

For given values of q, S_o and V_{max}, the hedge spacing required to minimise erosion can be calculated from Equations 2 and 3 if it is assumed that the maximum velocity occurs at the downstream side of the hedge. This point coincides with the upstream edge of the bare soil strip between the hedges. The form of the hedge spacing relationships calculated is shown graphically in Figures 6 and 7.

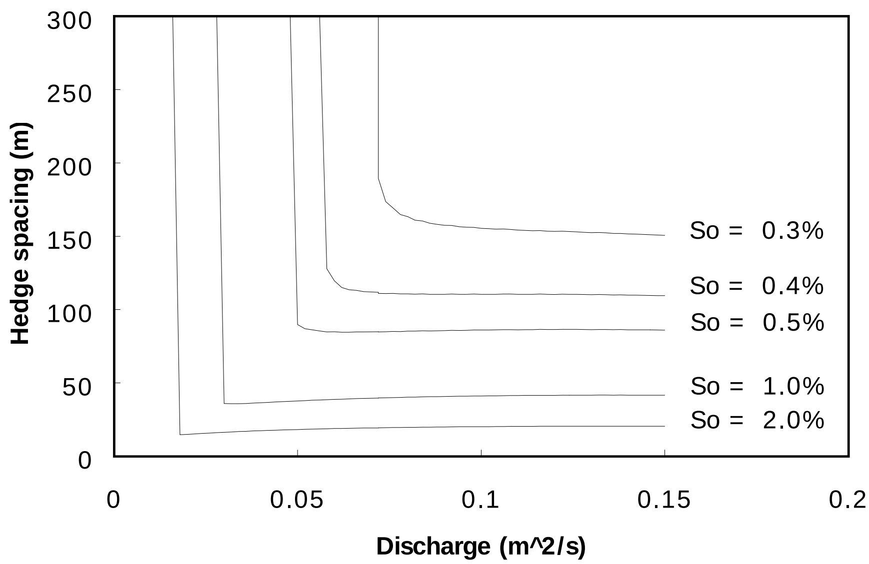

Figure 6: Effect of land surface slope, S_o on hedge spacing for a V_{max} of 0.5 m/s and Manning *n* of 0.03

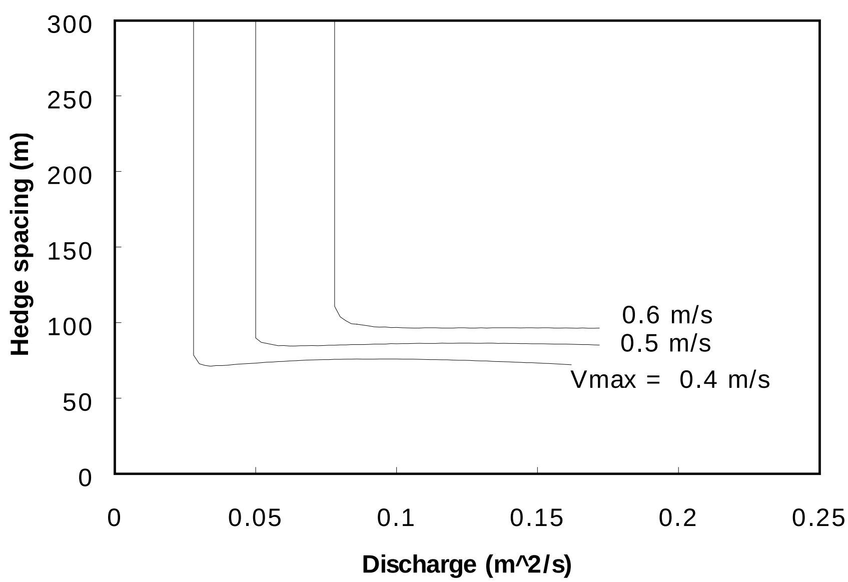

Figure 7: Effect of maximum permissible velocity on hedge spacing for a slope of 0.5% and Manning *n* of 0.03

The selection of a hedge spacing is made easy by the fact that there is a minimum discharge below which hedges are not required for erosion control and above which the hedge spacings are essentially independent of the discharge. For example, Figure 6 shows that for a slope of 0.5% the hedge spacing is infinite below a discharge 0f 0.05 m^2s^{-1} and is approximately 85 m at discharges above 0.05 m^2s^{-1}. Figure 7 shows the sensitivity of the soil erodibility parameter V_{max}. An appropriate value of V_{max} would be selected for the soil type.

The calculation of hedge spacing is based on the retardance of vetiver hedges only to erosive flows. The presence of crops or stubble between the hedges will serve as greater protection to the soil.

The hedge spacings calculated suggest that vetiver hedges are a feasible option for erosion control on cropped flood plains. From Figure 6 the narrow spacings of vetiver on lands steeper than 2% in slope does not appear practical. However on these steeper upland slopes the flow model used in the above design would not apply. The flow would be unsteady, fed by local rainfall. Overland flow from rainfall further upstream in the catchment would be less significant. The application of an unsteady flow model to vetiver spacing design on the steeper upland slopes may provide hedge spacings that are practical in that situation.

In accordance with the above model of flow through vetiver hedges on a flood plain design spacings were selected for a field trial site near Mt. Maria, on the Darling Downs of Queensland, Australia. The various catchment and farm characteristics critical to the selection of the vetiver hedge spacing were considered before a hedge spacing of 91.5 m was selected for the site to be compatible with the existing cropping practices. In December 1993 six rows of vetiver totalling over 3000 m were planted on the contour at this spacing and these rows have developed into substantial hedges averaging 1.7 m in height (Figure 8).

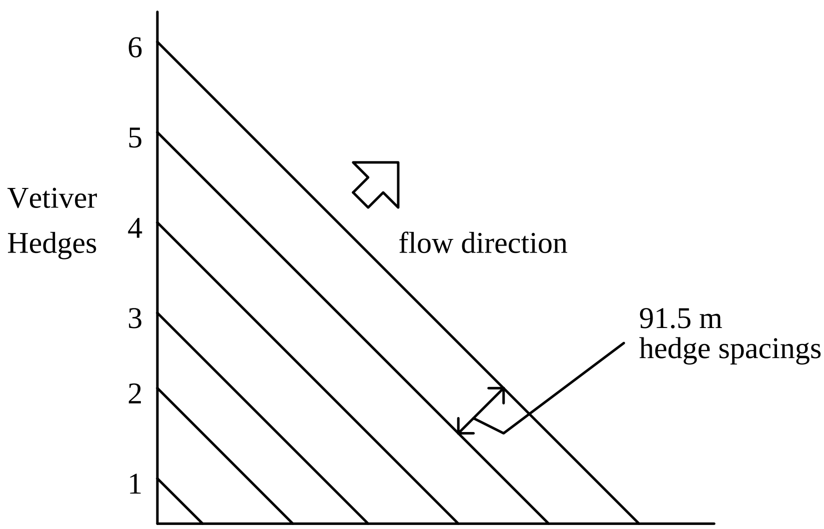

Figure 8: The layout of the Mt. Maria flood plain field site.

Flood discharges and depths and sediment movement are being monitored at this site to validate the hedge spacing model and monitor the effectiveness of the hedges. Monitoring of flood flow and sediment movement on this site has been limited by the current dry period that the region is experiencing. However the results presented in Table 2 of a small flow over the site in February 1995 show that the hedges reduce significantly the depth and therefore energy of flow through the hedges. Depths and velocities of flow were measured upstream and downstream of the hedges and between the hedges. The velocities measured across the site did not exceed the design maximum permissible velocity, V_{max} of 0.6 ms^{-1}. In maintaining the velocity below this value it was observed that minimal scouring occurred over the field. At the region of minimum flow velocity (occurring immediately upstream of the hedges) the largest amount of trapped sediment was measured at 7.25 tonnes at a low depression upstream of hedge 3. The depth of sediment trapped was approximately 80 mm at the hedge which contributed significantly to reclaiming the small depression across the field. More quantitative data is anticipated from this site at the occurrence of a major flood event.

Table 2: Depth and velocity results of the February 1995 flood at the Mt. Maria field site.

Vetiver Hedge	Upstream Depth (m)	Downstream Depth (m)	Upstream Velocity (ms^{-1})	Downstream Velocity (ms^{-1})
3	0.285	0.197	0.376	0.243
4	0.341	0.241	0.217	0.325
5	0.344	0.319	0.343	0.343

Conclusions

The flow of water through a hedge can be described by a simple equation relating discharge to the depths upstream and downstream of the hedge, with upwards of 90% of the variation in discharge described by the equation. Secondly it appears hydraulically feasible to use vetiver hedges to control flood flow and erosion on a cropped flood plain.

It also appears that vetiver grass hedge spacings are practical up to land slopes of 2%. At this land slope and beyond the design for vetiver hedge spacing would require a different model of flow. Although the discharge depth equation has only been applied to design spacings on a flood plain it might be assumed that the hydraulic equation could be applied to vetiver hedge spacing design for soil conservation on various topographical situations provided the hedge remains unsubmerged in the flow. The design would also involve using an appropriate model of the flow between the hedges. The work to evaluate the performance of hedges in field trials on the flood plain will continue for several years to validate this theory and design.

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