Hydraulic Characteristics of Vetiver Hedges in Deep Flows

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Abstract: Due to its unique morphological and physiological characteristics, vetiver has been used successfully for riverbank stabilisation and flood erosion control in Queensland, Australia and in several countries in Asia and Africa. However its application has been based on experience rather than hydraulic principles and little knowledge exists concerning the resistance properties of dense plantings of vetiver grass in deep flows.

This project was carried out to determine hydraulic characteristics of vetiver hedges in deep flows. Flume studies were undertaken using hedges at 1 m and 2 m spacings and a diamond pattern, with individual plants at a spacing of 0.5 m on the diagonals. Plots of Manning ***n*** versus depth and ***VR*** were used to assess the behaviour of the various combinations of planting pattern and flow regime. The results showed that vegetation pattern, condition and flow regime have a significant effect on hydraulic resistance. Specifically:

- Dense plantings of vetiver grass in deep, un-submerging flows had a high hydraulic resistance;
- Hedges were found to be in hydraulic retardance class A, with resistance decreasing with increased hedge spacing;
- The hedges significantly reduce the effective flow area of a channel;
- Rows of vetiver are more suited to steep slopes/highly erosive flows where sedimentation is unlikely or acceptable;
- The diamond pattern was found to be in hydraulic retardance class B;
- Diamond patterns are more suited to slower/lower flow rates/shallower slopes where the rate of sedimentation is high or must be kept low; and
- The Manning *n* was found not to quantify retardance adequately.

Recommendations are given for future studies.

Key words: vetiver, hydraulics, resistance, deep flows, Manning, n-VR

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1 INTRODUCTION

Little information exists on the hydraulics of dense plantings of vetiver, especially in deep flows. Studies on vetiver have tended to focus on the ability of vetiver grass hedges to trap sediment in flows (Meyer *et al*., 1995), the hydraulics characteristics of discrete hedges (Dalton, 1997) or determining the physical properties of the plant (Dunn and Dabney, 1996). Vetiver grass is unique in that it is not of uniform flexibility, nor has a similar foliage type or growth pattern to vegetation more commonly selected in hydraulic studies, especially for simulation in laboratory testing (Kouwen and Li, 1980).

A generally applicable hydraulic model that accurately allows for vegetation characteristics and determines the effect on deep flows has yet to be developed for application under a wide range of flow regimes (Fischenich and Abt, 1995). Current methods utilizing derivatives of the Manning equation or

n–VR curves have been shown to be insufficient in accurately determining resistance properties of vegetative linings outside of tested flow conditions (Kouwen and Li, 1980).

This project was carried out to determine hydraulic characteristics of vetiver hedges in deep flows, which are needed for the design of channel bank stabilisation. Flume studies showed that vegetation pattern, its physical properties, the plant response to flow, and the flow regime have a significant effect on hydraulic resistance. The Manning ***n*** was shown to provide a poor description for quantifying retardance properties.

2 HYDRAULIC EXPERIMENT

Hydraulic flume trials were conducted to investigate the behaviour of dense plantings of vetiver grass in deep flows. A review of relevant literature showed that analysis would require channel geometry, flow rates and depths to be recorded for varying flow regimes run though and/or over different planting patterns of vetiver grass.

2.1 Hydraulic Flume Facility

The flume experiment was performed using the outdoor hydraulic flume facility located at the Agricultural Field Station at the University of Southern Queensland, Toowoomba, Queensland. The facility consists of two concrete testing channels, 2 m in width and 20m in length. A 350 mm axial–flow pump supplied water at the maximum rate of 300 L/s through a 400mm diameter delivery pipe. A system of drop board weirs at the downstream end of each channel allowed control of the downstream boundary condition also giving control over the flow depth and velocity and also the form of the water depth profile for any given discharge. Depths of up to 0.6 m and velocities of up to 0.55 m/s were achieved by this means.

An open–ended manometry system was used to measure water depths at 1 m intervals along the centreline of each channel and depths of flow were measured with a discrimination of 1mm.

2.2 Preparation of Flume Facility

The flume beds were made level in preparation for planting. The flumes were planted with two different patterns. The eastern flume was planted in a diamond pattern with individual vetiver plants at 0.5 m apart on the diagonals (Photo 1) and the western flume as rows spaced 1m apart, perpendicular to the flow direction (Photo 2). The slips of vetiver planted in each row were approximately 125 mm apart. All plants were fertilised on planting and top dressed one month after planting.

Photo 1 *Left*, Diamond pattern planting and *Right*, row planting

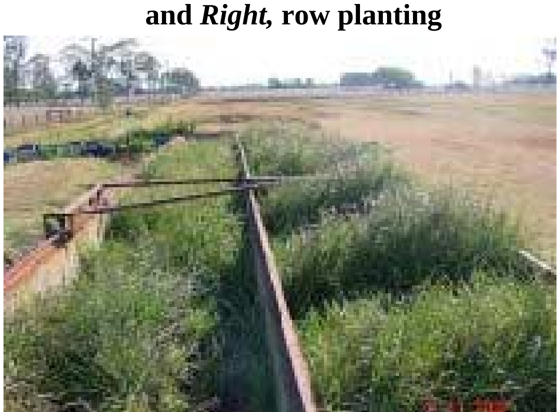


Photo 2 Side view of row planting at 2 m interval

3 EXPERIMENTAL METHOD

The experimental method used in this experiment was similar to that of Dalton (1997). A range of discharges up to 110 L/s was applied to the vetiver plantings. For these discharges a range of flow depths up to 0.61 m were achieved by changing the downstream depth condition using different drop-board weir settings. At the time of testing, vetiver plants were taller than the flume walls so the rows were never completely submerged except where a single plant collapsed (Photo 3 and 4). Plants in the diamond pattern would become completely submerged only where weeds had impeded their growth.

The varied flow rates, drop-board settings and two planting patterns allowed the collection of 44 sets of data of discharge and depths along the flume. Flow behaviours were investigated using derivatives of the Manning equation and trends identified and explained.

Photo 3 Test flow up to full depth of 60 cm showing the stiffness of the young vetiver stems

Photo 4 *Left,* very deep, turbulent flow at inlet flattened the first row. *Below,* note the calm water and very low water level behind last vetiver hedge

4 ANALYSIS

The water surface profiles for each run were recorded as a depth in millimetres against distance downstream in 1 m intervals along the length of the flume. The energy line for each run was calculated using:

$$H = z + y\cos\theta + \frac{\alpha V^2}{2g}$$

Eq. 1

where ***H*** is the energy of water flowing in a channel at a section, with elevation *z*, depth of flow ***y*,** mean velocity ***V*, _** is the bed slope and **_** (Coriolis coefficient) is equal to one (Featherstone and Nalluri, 1988).

4.1 Elimination of Non–representative Data

Certain sections of each flume were eliminated from the analysis where the vegetation was judged unrepresentative due to inconsistencies in the physical characteristics of the vetiver. In the diamond pattern planting vigorous weeds affected the growth of the vetiver in the first 8 m of the flume. As such, only data from the last 12 m of the flume was taken due to the consistent and vigorous growth displayed by these plants. A similar process was also carried out for the data taken from the rows.

The energy slope S_f was calculated by differentiating the value of the energy line ***H*** (m) at each section with respect to change in distance ***x*** (m) along the flume:

$$S_f = -\frac{dH}{dx}$$

Eq. 2

Manning ***n*** was then calculated for each data point in each run using equation 3.

The Manning equation (Eq. 3) is the most commonly used equation for flows in natural channels:

$$V = \frac{1}{n}\sqrt{S_f}\,R^{2/3}$$

Eq. 3

or, expressed in unit width of flow:

$$q = \frac{1}{n}\sqrt{S_f}\,y^{5/3}$$

Eq. 4

where ***R*** is the hydraulic radius of the flow and equals the cross–sectional area of the flow divided by the wetted perimeter. The Manning roughness coefficient ***n*** is a measure of the resistance to flow produced by the boundary surface including the soil surface and vegetation. Ree (1958) described the ideal cross section of a flume as having a rectangular cross section with walls of some frictionless material. Einstein (cited in Smith *et al*., 1990) found the effect of drag of on the walls of the flume to be negligible. Hence, hydraulic radius ***R*** is taken as equivalent to depth ***y*** for flow per unit width ***q***.

The Manning formula has the twin attributes of simplicity and accuracy, and provides reasonably accurate results for a large range of natural and artificial channels given that the flow is in the rough turbulent zone (Chadwick and Morfett, 1993). For design purposes, it is still the best measure, being the most readily understood and commonly used by engineers throughout the world. Problems arise where ***n*** varies. This variation may be due to change in:

- Stage - depth and speed of flow;
- Time - composition of bed material or channel shape to erosion and deposition;
- Vegetation - in shape, stiffness, location and amount of vegetation.

It can be seen that when the equation is applied to flows over surfaces with large, flexible roughness

4.2 n–VR Curves

Methods of resistance computation that have proven suitable for design use are dependant on the variation of Manning ***n*** with the product of velocity and hydraulic radius **(*VR*)** as developed by the Soil Conservation Service of the United States Department of Agriculture (Temple, 1982) and summarised by Chow (1959) and Smith *et al.* (1990). This procedure divided grass linings into five retardance classes (designated A through E) and provides an independent ***’n–VR*** curve’ for each class. Selection of the retardance class was primarily a matter of engineering judgement (Temple, 1982).

Temple (1982) stated that while ***n–VR*** curves can provide designers with a useful tool, correctly accounting for dominant characteristics of a flow and vegetation, they oversimplify the complex interaction of the flow with vegetal elements. He argued that an understanding of the fundamental behaviour implied by the ***n–VR*** relationship is essential for its proper application. The ***n–VR*** method can have serious deficiencies where designs are made for flow conditions other that those specifically tested (Kouwen and Li, 1980) and limited where slopes are different to those from which data was collected (Fischenich and Abt, 1995).

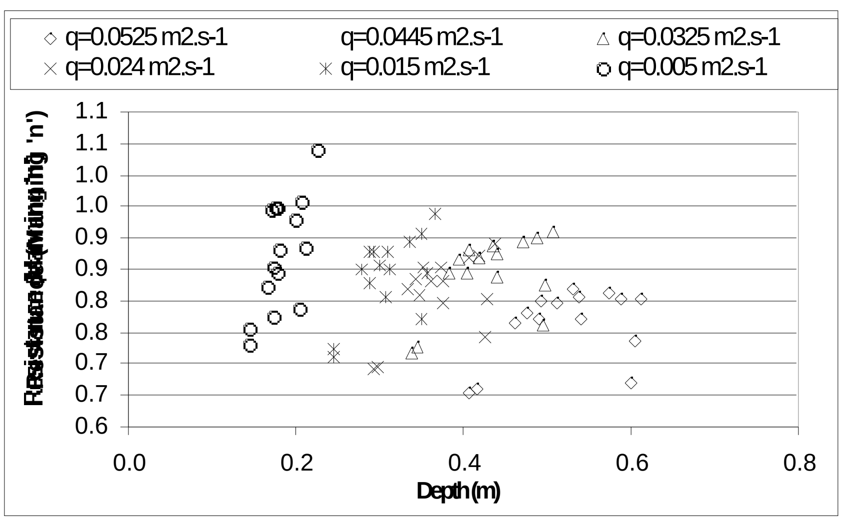
The data sets collected were analysed using the Manning ***n*** versus depth and ***VR*.** Attempts to exactly quantify the resistance of a particular pattern were given only as an estimate of magnitude and to place the regime within a particular retardance class for the conditions tested, rather than a discrete value for any given set of conditions.

5 ANALYSIS OF RESULTS

5.1 Resistance against Depth

5.1.1 Row planting

Fig. 1 Resistance (Manning *n*) against Depth: Mature rows, 1 m spacing, low downstream boundary condition, flow in m^2/s



An example of the results for 1 m spaced mature hedges is shown in Figure 1 as a plot of ***n*** versus depth. The trends were similar to that for the diamond pattern except for the higher flows where resistance reached a maximum before the flow went through the higher, more sparse and flexible portions of the hedges. The greater resistance posed by the closed barrier of a hedge as compared to clumps and the ‘toppling’ failure mechanism caused this behaviour. Similar trends were observed for all mature

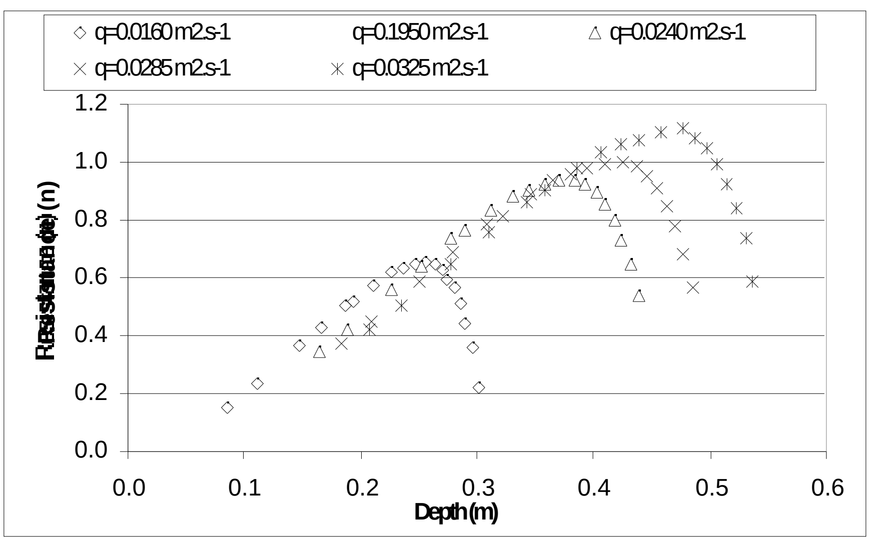
As depth continues to increase it is expected that the resistance would reach a point of inflection and a lower rate of decrease of resistance as flows submerge the vegetation and tend toward a streamlined condition, as demonstrated by Ree (1949). Flows during the trials were never sufficiently deep to reach this stage for mature hedges. At no point were the mature hedges fully submerged, although this behaviour was observed for the shorter, more flexible immature hedges.

It can be seen that resistance is dependant on flow. Resistance generally trends downward as depth increases, though resistance increases with increased velocity while the water continues to flow within the middle portion of the hedges (Fig. 2). The upper depth of the flow is passing through the upper portion of the hedge that flexes readily and bends parallel to the flow. The greatest values of resistance occur where the bulk of the flow is within the middle portion of the hedges. It can be observed that for a similar depth of flow, resistance is less for greater velocities. This is due to the decreased effective area presented to the flow because of stem deflection as described by Kouwen *et al*. (1981). When hedge spacings were increased to 2 m slightly different behaviours were observed. While the same trend remained where overall resistance decreased with depth, the turning point where resistance began to decrease with increasing depth was not observed. It is likely that the behaviour would be similar to that described by Ree (1949) but the point of inflection is outside the range of collected data.

This was not an expected result, though the trends in the data were similar to those observed for runs in the diamond pattern with a similar flow regime (Fig. 3). For a constant depth of flow, resistance was seen to decrease with increasing velocity. The range in values of resistance ***n*** and average resistance becomes smaller as depth of flow increases. It was expected that the overall resistance would trend toward a constant decreasing value with increasing depth and velocity.

At higher flow depths and velocities the resistance of both patterns is within a relatively narrower range of values compared to smaller flows and appears to of a similar magnitude.

Fig. 2 Resistance (Manning *n*) against Depth: Young row, low downstream boundary condition, run B, flow in m^2/s at a lesser rate than the velocity increases

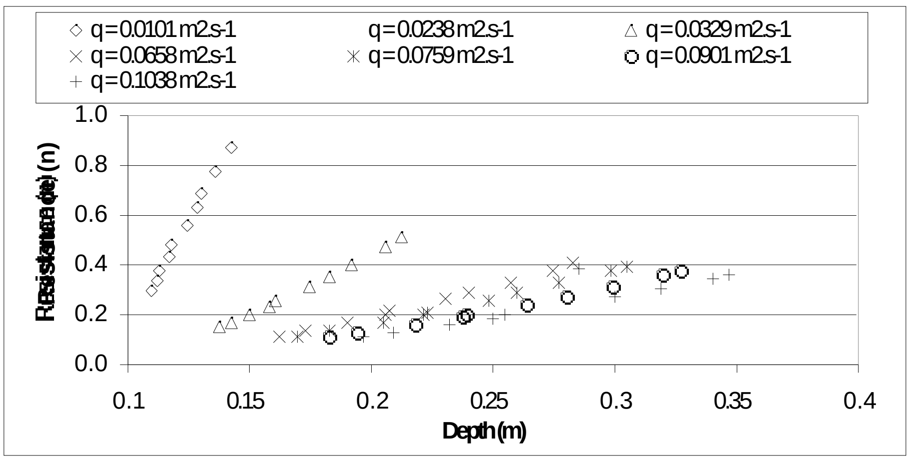


An example of the results for 1 m spaced immature hedges is shown in Fig. 2 as a plot of *n* versus depth. It can be seen that resistance initially increases with flow depth, reaching a maximum when depth is about half the hedge height where resistance starts to decrease. This turning point appears to vary with discharge and flow velocity. It was noted that the turning point is at a greater depth for greater discharges. It is possible that more rapid flows generate greater turbulence in the flow extending higher above the bed level.

5.1.2 Diamond pattern planting

Fig. 3 displays the resistance–depth relationships for the mature diamond pattern that appear to be similar to those for rows at 2 m spacing. The resistance is lower overall due to having less foliage exposed the flow and the flow being able to flow freely between the vetiver clumps down to the channel bed. Overall, resistance decreases and trends toward a constant value with increasing depths and flow rates. At a constant depth for any flow, resistance decreases with increasing velocity and flow depth as the plants are deflected by the flow. Resistance is increasing with depth, but with higher discharges the rate of increase in resistance is less. This is likely due to the streamlining of the clumps for greater discharges. The clumps were never submerged so a maximum *n* was never reached.

Fig. 3 Resistance (Manning '*n*') against Depth (m): Mature diamond pattern, Low downstream boundary condition, flow in m^2/s



The important difference to note is the overall lower value of resistance compared to both 2 m and 1 m spaced hedges, for similar flow rates and conditions. Some of this difference would be offset if the grass clumps in the diamond pattern had grown as vigorously those in the hedges. However even if this were the case, the hedges would still present a greater area for shear given the greater number of plants per unit area.

The lesser resistance at shallower depths would be explained by the water being able to flow freely around individual clumps of vetiver. As flow depths increase, the proportion of vegetation causing shear will increase in relation to the cross sectional area of the flow. Setting a higher downstream condition for the diamond pattern resulted in similar values of resistance for similar flow rates though translated to greater depths. The flow was still within the height of the vegetation – a non–submerging flow. The data may be interpreted as an extrapolation of the results from the same pattern and flow regime barring the increased downstream depth.

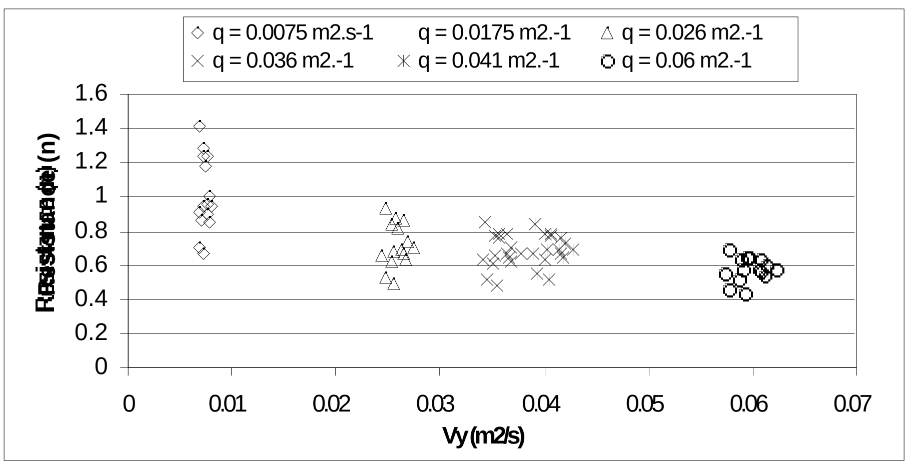
There is an overall decrease in resistance with increasing depth with a trend toward a constant value likely similar to the value of resistance for the low downstream boundary condition for the same pattern.

5.1.3 Resistance against product Vy

Essentially vetiver falls into the two highest retardance classes as set out by Kouwen *et al.* (1981): rows fall into the highest (A) and diamond pattern into class B. Plots of Manning ***n*** against the product plots did give some indication of constant values of resistance toward which the different flow regimes and patterns were appeared to be trending. Resistance decreases with increasing product ***Vy*** and appears to be nearing a constant Manning ***n*** value of 0.6 – 0.7. This would place vetiver, for 1 m spaced hedges and within the tested flow regimes, in or above the highest retardance class (A) from the "Handbook of Channel Design for Soil and Water Conservation" described in Table 2 of Kouwen *et al*. (1981). The validity of this conclusion is difficult to substantiate as the data falls on the outer limits of the retardance class curves. It appears likely that the plotted curves would trend into a single curve as the product ***Vy*** increased due to increased depths of flow tested.

A similar situation is seen when the hedges spaced at 2 m is treated (Fig. 4). As the values of product ***Vy*** increase the range of ***n*** values narrows, trends downward and appears to near a constant value of approximately 0.5. This places the pattern in the highest retardance class A as given in Table 2 of Kouwen *et al.* (1981). It appears likely that the plotted curves would trend into a discrete curve as the product ***Vy*** increased. The lesser resistance posed by the diamond pattern allowed greater flow rates to be run. Converting data for the mature diamond pattern revealed an effectively constant *n* value of approximately 0.25 for ***Vy*** greater than 0.05, equivalent to flow rates per unit width greater than 0.06 m^2/s. This would place the mature diamond pattern for the given flow conditions in resistance class B (Kouwen *et al*., 1981).

Fig. 4 Resistance (Manning '*n*') against *Vy*: Mature rows, 2 m increment, Low downstream boundary condition, flow in *m^2/s*



The resistance is becoming more uniform as discharge and velocity increase

5.2 Sources of Error

Data sets were smoothed using regression analysis to reduce errors due to changes in bed height from scour and deposition, air in and slight misorientation of manometer tubes and those due to operator error. Soil was eroded from between plants and either flushed from the channel or deposited in the lee side of the vetiver clumps. This occurrence was not even across the channel cross section, mostly due to the flow across the channel cross-section not being uniform. This would substantially reduce overall resistance to the flow as streamlines develop in some portions of the flume.

6 DISCUSSION AND OBSERVATIONS

6.1 Establishment of Vegetation

The establishment of the rows was much easier as mature hedges tended to form a closed canopy plenty of sunlight to reach the channel bed. Weeds were observed to out-compete the vetiver in the diamond pattern where the fertile seed or plants still existed. Better preparation of the flume beds first with a herbicide then a pre–emergent herbicide to prevent the germination of seed would have reduced this effect. This must be observed for future research or real applications. Mowing would be able to control weeds occurring between hedges. This would be much more difficult in the diamond pattern.

6.2 Effects of Vegetation on Flow

Differences in pattern and condition of vegetation had a significant effect on flow resistance. The hedges increasingly closed and interlocked with maturity. This characteristic was observed by Dalton (1997) and has been described in much literature concerning vetiver (Greenfield, 2002) and appears to significantly increase the resistance to deformation of the hedge as a whole. The interlocking of stems is expected to have a similar effect to the trapping of debris from a flow in increasing the resistance of the hedge due to shear. These effects are described by Dudley *et al.* (1998).

6.3 Reduction of Effective Flow Area

Dense hedges were observed to create still water between hedges in the lower to middle sections of the hedge. This causes a decrease in effective flow area. It is expected that the hedges will have effect of a wavy surface in very deep flows with the flow being quasi–smooth. Chow (1959) describes this in detail. The lower portion of a vetiver hedge forms a very stiff, porous barrier that effectively dams a flow. It is likely that this slowing of the flow would cause sediment to fall out of a flow and be trapped in or between hedges. Over time this would lead to a reduction in channel capacity as the hedge continues to grow above the sediment. This should be allowed for in the application of densely planted hedges.

The diamond pattern allowed water to circulate through to the channel bed, hence allowing the flushing of sediment. Fairbanks and Diplas described flow velocities and turbulence throughout staggered resistance elements. It is expected that the effects on very deep flows will be similar to that for hedges with the exception that the turbulent zone extends to the bed level and no still-water effects will occur. The removing of vegetation would be expected to reduce water levels and increase the flow capacity (Klaassen and van der Zwaard, 1974). Hedges at close spacings could be effective in very rapid flows where a failed hedge would still offer protection by covering the bed surface immediately downstream of the hedge failure. The height of mature, closely spaced hedges would mean that a failed section of hedge would fall onto or directly in front of the next hedge.

6.4 Diamond Pattern

Although the diamond pattern had a lesser resistance to flow than the hedges it readily allowed flows to pass as discussed in the previous section. The greater velocities of flow at shallower depths contributed to scour and deformation of the channel bed. Over the duration of the project this was observed to stabilise for the tested flows as lighter, looser sediments were eroded and washed out of or deposited elsewhere in the lee-side of vetiver clumps. It is expected that channel bed would remain at approximately the same level over time as long as sedimentation is not encouraged by a cover of vegetation between vetiver clumps. If such a cover were to establish it should not affect vetiver growth after establishment, have low sediment trapping ability and minimise establishment of weed plants. A type of creeping grass may fulfil these criteria.

7 CONCLUSIONS

Conclusions could only be drawn for the flow conditions and planting patterns tested. Submerging flows were not achieved. Investigating the effects of dense plantings of vetiver for greater flow depths and behaviour of dissimilar vegetation in deep flows. Further studies would need to take this into account.

The closer the spacing of hedges the greater the resistance to flow. The use of the Manning equation and n–VR curve method provided some indication of the resistance properties of a dense planting of vetiver and related it to vegetation types and patterns with a similar roughness.

A diamond pattern would more suited as a channel lining for moderate to slow flows as it mitigates sedimentation while reinforcing the channel bed. In more erosive flows, hedges at close spacings (less than 2 m) would offer better protection to the channel bed. If closely spaced hedges were applied to moderate to slow flows there is a risk that sedimentation would cause an unacceptable decrease in the conveyance capacity of a channel.

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A Brief Introduction to the First Author

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