Vegetation and Bank Stability in Relation to Changing Channel Scale

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ABSTRACT: *Many unsubstantiated claims are made about the effectiveness of vegetation in controlling stream bank erosion. As a result of these claims, and other perceived benefits, riparian vegetation is increasingly being used as a first-line technique for river bank stabilisation. This paper argues that the influence of native vegetation on erosion rates and stream hydraulics varies as the size and shape of the river, the erosion processes, and the suite of vegetation species, change through the stream network. The interaction of vegetation and erosion is demonstrated using a scale analysis of the Latrobe River in Gippsland, Victoria. A scale analysis matches the stream erosion processes to the vegetation characteristics.*

Two main erosion processes are identified: bank slumping and corrasion. Slump blocks are larger than average-wattle rootballs in the lower floodplain tract and, in these reaches, slumping dominates the erosion process. Our analysis shows that the surcharge weight of wattles is unlikely to have major implications for bank stability. Moreover, although trees transpire at a greater rate than does pasture, saturated hydraulic conductivities of bank materials are such that bank drainage rates, following draw-down in the channel, are unlikely to be influenced to any substantial degree by riparian cover-type. Increased bank shear strength due to root reinforcement is probably the major effect exerted on bank stability by trees along the Latrobe river with respect to mass stability.

By reducing the velocity of near bank flow, riparian vegetation can have a profound effect on rates of corrasion. In the upper 20% of the catchment area, vegetation occupies a large proportion of the channel and provides a relatively large hydraulic resistance. Finally, the period of inundation of riparian vegetation varies dramatically along the river and this is shown to have management implications. Considering all of these variables we define the river reaches in which vegetation will be most effective for erosion control.

1. INTRODUCTION

Sedimentary deposits older than about 400 million years old (the Silurian) contain only records of braided streams. Coincident with the evolution of plants with roots and rhizomes in the Silurian was the appearance of single thread, meandering channels (Mosselman, 1992). Vegetation both reduced sediment yields and floods from the catchment, and provided bank stability (Pannekoek & van Straaten, 1984). The importance of vegetation in stream stability would come as no surprise to most stream managers, who are increasingly seeing native vegetation as a prerequisite for a healthy, stable stream system.

Native species are now being used to augment or, in some cases, replace traditional structural engineering solutions to stream erosion problems. Indeed, some $10 million per annum is directly spent on riparian re-vegetation schemes in Australia at present (Rutherfurd *et al.*, subm.). But how does a stream manager decide whether a particular vegetation type will work or not? Moreover, in what parts of the river system will replanting programmes produce the best results?

General statements describing the role of vegetation in bank stability abound in the literature; both in terms of perceived benefits and liabilities. Many authors have suggested that tree roots enhance bank shear strength and reduce the occurrence of slumping (e.g. Thorne, 1990; Gray & Leiser, 1982; Stryczen & Morgan, 1995). In addition to this, a root permeated soil is markedly more resistant to direct erosion by corrasion. Experiments by Smith (1976) suggested that bank sediments reinforced by roots were some 20,000 times more resistant to corrasion than non-reinforced sediments. Is this a typical or an extraordinary number? Zimmerman *et al.* (1967) found that the width of small streams in Vermont (USA) were overwhelmingly controlled by riparian vegetation. Forested streams narrowed significantly where they emerged from the trees and flowed in banks lined with rushes and sedges.

This paper presents an approach that we are developing that aims to help stream managers decide where, in a stream network, specific types of vegetation will most effectively assist in bank stabilisation. We call this approach *scale analysis* (after Rutherfurd *et al.*, 1995). The basis of scale analysis is that the influence of vegetation on bank erosion rates varies through the stream network. For instance, it is little use planting a species whose root zone extends to one metre if the main erosion

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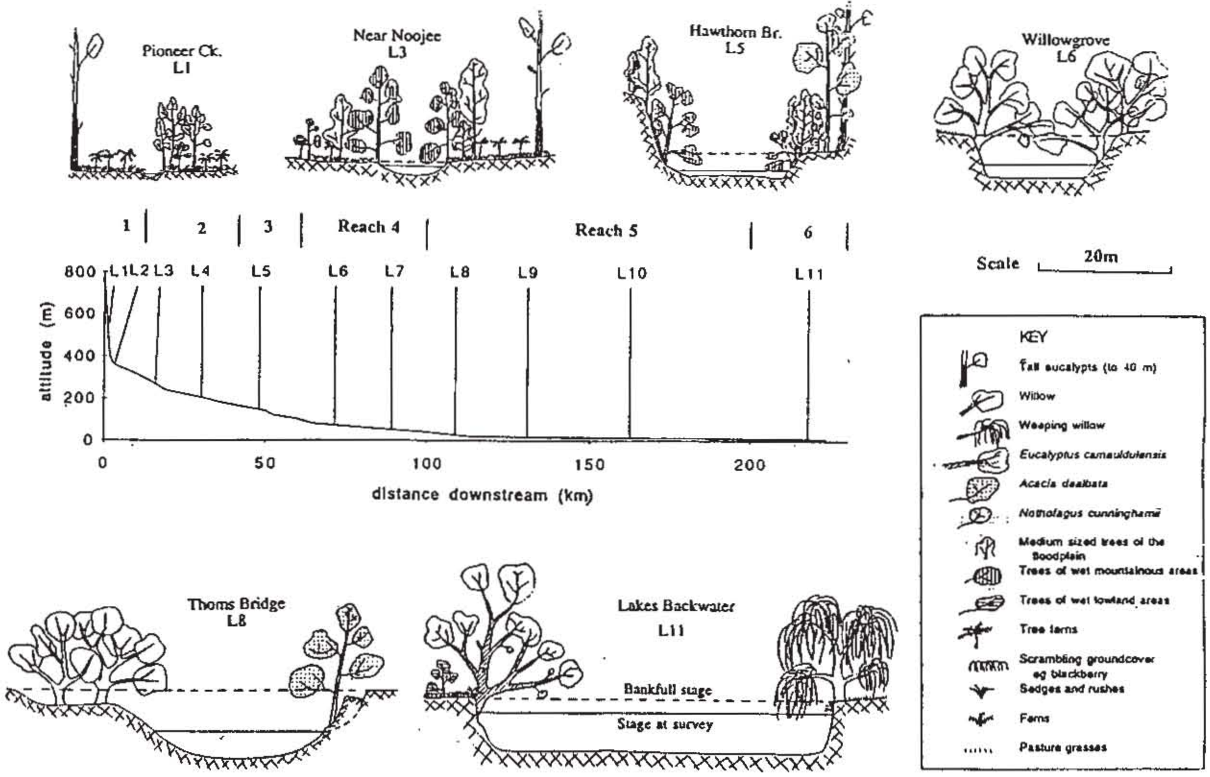

Figure 1: Long profile of Latrobe river with reaches, cross-section locations, and typical vegetation.

process occurs at the toe of a bank two metres high.

The study reported here extends the recent work of Rutherfurd *et al.* (1995) on the Latrobe River. Following a description of the erosion processes and vegetation characteristics of the Latrobe, we present an analysis of the various mechanisms by which vegetation is purported to influence erosion. Our study was undertaken as part of the national riparian zone research project which aims, eventually, to define the role of vegetation in bank stability and other processes.

2. LATROBE RIVER

The Latrobe River, in Gippsland, Victoria, is 242 km long and drains a catchment of 5,200 km^2. The river is almost entirely alluvial, with few bedrock reaches. Lower reaches are characterised by a meandering single thread channel, about 35 m wide and 5-6 m deep; typically with silt-clay banks and a sand bed. Backwater from Lake Wellington influences the final 30 km. The headwaters largely remain forested, whilst the floodplain is cleared for cattle grazing. Rainfall in the catchment ranges from 600 mm to 1600 mm.

Rutherfurd *et al.* (1995) surveyed eleven sites along the length of the river, describing boundary sediments and dominant erosion processes; six of the sites are located at stream gauges. For their purposes, Rutherfurd *et al.* considered vegetation on the edge of the floodplain, on the bank face, and in the channel. Vegetation in the headwaters is wet, closed canopy *Eucalyptus regnans* forest, whilst the downstream floodplain vegetation was originally open forest: wattles (*Acacia dealbata*) and red gum (*E. camaldulensis*). Today, riparian vegetation of the lower channel is dominated by basket willows (*Salix rubens*), and wattles.

The changing role of riparian vegetation in channel erosion processes can be best understood by dividing the river into six reaches, with each having a characteristic relationship between riparian vegetation and erosion process (Figure 1 & Table 1). Vegetation has a profound effect on erosion processes in Reach 1. Fallen trees, or large woody debris (LWD), span and choke the channel and the bank is undercut, by up to 0.5 m, below the 0.3-0.5 m root-zone. The floodplain is narrow and permanently saturated. It is only in this reach that riparian vegetation can buffer hillslope runoff. Downstream, the floodplain widens and the channel is progressively isolated from the hillslopes.

The channel banks of Reach 2 are vertical and too low to sustain trees on the bank face. Undercutting below the root-zone remains the dominant erosion process.

Table 1: Latrobe reach characteristics.

Reach No.	1	2	3	4	5	6
Distance From Divide (km)	<10	10-40	40-60	60-100	100-200	200-230
Channel Width (m)	4-6	6-16	17-18	20-40	40-50	50
Bank Height (m)	<1	1.5-2	3-4	3.5-4	4-8	2-3
Riparian Vegetation	Ferns & Sedges	Paper Barks	Paper Barks	Wattles & Red Gums	Wattles & Red Gums	Wattles & Red Gums
Vegetation Height (m)	~1	~10	~8	10-20	10-20	10-20
Dominant Erosion Process	Corrasion	Corrasion	Corrasion	Slumping	Slumping & Corrasion	Corrasion
Effect of Vegetation	Flow Resistance	Flow Resistance	Flow Resistance	Bank Strength	Bank Strength	Bank Strength

Major changes occur in Reach 3 as the river flows out of the confined floodplain reaches into the broad alluvial floodplain. Trees grow on the bank face and their roots often extend below the water line. The channel is broader than trees are tall. LWD tends to be swept against the bank at an angle of about 30° and does not divert flow onto the banks. Meandering commences in this reach so that undercutting is concentrated on the outer bank of bends.

Levees develop in Reach 4, and the floodplain slopes away from the channel; riparian vegetation has little or no role in buffering runoff. The dominant erosion process is bank slumping. Slump blocks are smaller than the average size of wattle rootballs and tree roots extend through potential shear planes, increasing bank shear strength.

The river attains its largest dimensions in Reach 5, being up to 50 m wide and 7 m deep. Erosion is most pronounced on vertical concave banks where slumping occurs. On these bank sections, roots of bank-top trees do not extend to the mean water level; outer banks with trees are often undercut by up to two metres. Slump blocks in this reach are over twice as large as those in reach four and are often larger than the typical wattle rootball.

Reach 6 is located in the backwater of Lake Wellington. Here, the channel widens, banks are vertical and the stage varies by only 0.5 m. Water logged sediments limit root depth to about 1 m deep and, as in reaches one to three erosion is by undercutting below the root-zone. There is little slumping.

The Latrobe reach descriptions indicate that we may simplify bank erosion as the product of two major processes. Banks erode by either the removal of individual grains, termed corrasion, or mass failure under gravity, where the shear forces acting on a bank section overcome its shear resistance. Both processes act throughout the length of the river but one process dominates over the other, depending on the scale of the river in a given reach. The same suite of vegetation - groundcover, understorey, trees - may exert a more or less significant role in the erosion process at different river scales.

3. VEGETATION AND BANK STABILITY

In considering changing channel scale down the length of the river it becomes clear that the degree and type of vegetative effects vary in different reaches. Bank instability leading to erosion by slumping is only a major process on Reaches 4 and 5. The process is most prominent in Reach 5 around the Thoms Bridge gauge where the banks attain their maximum height. What would be the effect of revegetating this reach with wattles and river red gums? Many locals argue that wattles contribute to slumping by surcharging the banks, while the literature suggests that soil moisture modification, slope buttressing and soil arching, and root reinforcement are important considerations in the bank stability problem.

3.1 Surcharging

Depending on the slope angle and the position of a tree on the bank, surcharge due to the weight of a tree may be beneficial or detrimental to bank stability (Gray & Leiser, 1982). On gently sloping banks, the slope normal contribution of surcharge is much greater than the downslope component. Consequently, the net effect of surcharging is to increase stability through increasing frictional resistance to shearing (Thorne, 1990). On steep banks surcharging decreases stability because additional weight tends to produce a shear force and turning moment that may aid in toppling failure mechanisms. The effect is exaggerated when trees lean over the channel due to wind loading or asymmetrical growth patterns. In this regard a wide stand of trees is preferable to a single line of trees on the bank top (Thorne, 1990).

Wattles growing on the banks of the Latrobe River probably have little surcharging effect. This is shown by considering typical slump blocks in Reaches 4 and 5. The dimensions of slump blocks are shown in Table 2. Wattles tend to grow at about 2m spacings, so that only one tree can be accommodated on a slump block in Reach 4 and five trees on a slump in Reach 5. The weight of an average wattle was estimated in the field to be about 235 kg.

Table 2: Slump block dimensions.

	Reach 4	Reach 5
Size of slump blocks (m^3)	4	48
Bulk density (kg/m^3)[†]	1,320	1,320
O.D. slump block weight (kg)	5,160	63,380
Sat. slump block weight (kg)[‡]	7,115	87,470
Weight of trees (kg)	326	1,175

[†] Mean oven dried bulk density of bank materials.

[‡] The total porosity of a soil estimated from:

$$\text{Porosity \%} = \left(1 - \frac{BD}{SG}\right) \times 100$$
$$= 50.2\%$$

where *BD* is the bulk density of oven dried slump material and *SG* is the specific gravity of the soil particles (assumed here to be 2.65 after Craze & Hamilton, 1991).

In Reach 5, the surcharge weight of five wattles represents only about 1.8% of the weight of a dry, and 1.3% of a saturated slump block. This weight is probably trivial in terms of initiating a slump failure, particularly when it is compared with bank saturation. Surcharging due to bank saturation increases the slump block weight by some 40%.

In Reach 4 the effect of surcharge is somewhat more pronounced as slump blocks tend to be smaller. Here the weight of a tree represents about 4.4% of dry slump block weight, falling to about 3.2% as the block saturates. Again much of this weight aids in bank stability and we consider that surcharging is unlikely to contribute to failure initiation. In this reach however, the additional surcharge effect may aid in moving slumps down the banks after initial failure. Additional forces produced by wind loading lead to only marginal increases in bank loading and for the scale of the processes we are discussing here remain largely insignificant.

3.2 Soil Moisture Modification

Vegetated slopes are more stable, with respect to mass failure, because they are drier and better drained than their unvegetated counterparts (Gray & Leiser, 1982). Vegetation reduces the bulk unit weight of soil due to the proliferation of macropores and other soil structure modifications, and increases the effective and apparent cohesion (Thorne, 1990).

Stream banks are most likely to fail following rapid drawdown of the stream (Twidale, 1964). Can trees remove water from the banks of the Latrobe River at a fast enough rate to affect bank slumping? That is, if slumping occurs following drawdown, can vegetation, by evapotranspiration, reduce the time that the banks are saturated?

Trees use more water than does pasture. Eastham *et al.* (1990) showed that a greater proportion of soil water was extracted from deeper down the soil profile under trees than under pasture, owing to lower soil water contents in upper horizons and the deeper and denser rooting patterns of trees compared to pasture. Greenwood *et al.* (1985) found that evaporation from *Eucalyptus* plantations (4.3-7.4 mm/day) can be up to seven times that from surrounding grazed pasture (1.1 mm/day). Evapotranspiration rates of red gums growing on river banks are in the order of 3 mm/day (Jim Morris, DCNR; pers. comm.).

Draw down rates in the Latrobe River vary from reach to reach (Fig. 2). At the Noojee gauge, for example (Reach 2), the draw down rate is on average 45 cm/day during the first 24 hours after bankfull flow, whilst at Thoms Bridge (Reach 5) drawdown is 105 cm/day and at Rosedale it is only 20 cm/day.

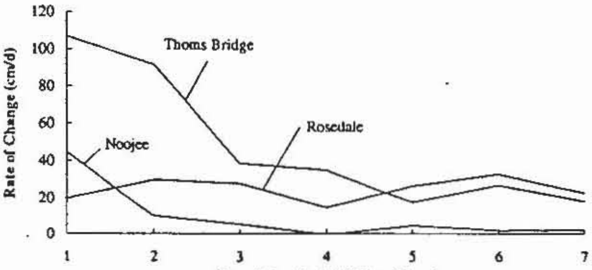

Figure 2: Mean rate of change of stage at Latrobe R. Gauges.

Field tests of hydraulic conductivity show that replacing pasture with trees is unlikely to reduce the effect of drawdown in Reach 5. Field tests of bank materials under pasture and wattles at Glengarry Bridge yield saturated hydraulic conductivities (k_{sat}) ranging from 16 to 117 cm/day depending on the bank materials. In reach five the average time for the stage to fall from bankfull (5.5 m) to normal flow

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levels (2.0 m) is about 7 days, and this rate is consistent between hydrographs. At this rate of drawdown it is likely that water will be able to drain from the bank back into the channel at a rate that can pace the falling stage in the channel, and is many times faster than the evapotranspiration rate of the trees.

3.3 Root Reinforcement

The most obvious way that vegetation stabilises river banks is by root reinforcement. The intermingled, lateral roots of plants tend to bind the soil together in a monolithic mass. According to Gray & Leiser (1982), a root-reinforced soil behaves as a composite material in which elastic roots of relatively high tensile strength are embedded in a matrix of relatively plastic soil. Additional strength is mobilised within the composite material by the development of tractive forces between the roots and the surrounding soil. Shear stresses in the soil mobilise tensile resistance in the roots, which in turn imparts greater strength to the soil (Thorne, 1990).

In Reaches 1, 2 and 6, slumping is rare because the banks are low (less than 1.5 metres high), and the roots of trees pass through potential slump-failure planes. Similarly in Reach 4, where slump-blocks tend to be smaller than the root balls of wattles, the roots pass through both the back and base of the failure plane and restrict the incidence of large scale slumping. As the banks get higher and the size of potential slump blocks increase in Reach 5, fewer roots pass through the base of the block. Nevertheless, observations in Reaches 4 and 5 show that bank sections under only pasture and isolated trees are more prone to slumping than those sections of bank with trees in greater density. Our future research will examine the influence of vegetation roots in more detail, as it is probably the critical role of trees in slumping.

3.4 Slope Buttressing and Soil Arching

Well rooted and closely spaced trees along the toe of a river bank can provide an effective buttressing effect which retains the slope and loads the toe against shear failure (Thorne, 1990; Gray & Leiser, 1982). Examples of buttressing can be found in Reach 5 where slumps have occurred, only to be held at the toe of the bank by a row of wattles. Where there is no buttressing, slump blocks reach the toe of the bank, where it is subsequently removed by corrasion.

4. VEGETATION AND CORRASION

Bank vegetation increases flow resistance, thus reducing the forces of drag and lift acting on the bank surface. As the boundary shear stress is proportional to the square of near bank velocity, a reduction in this velocity produces a great reduction in the forces responsible for corrasion (Ikeda *et al.*, 1981).

Richards (1982) shows that detachment and entrainment of boundary materials usually occur under turbulent eddies, where velocities may, for short durations, attain values in excess of the time-averaged mean. Vegetation reduces the magnitude of instantaneous velocity and shear stress peaks by suppressing meso- and macro-scale eddies thus reducing the erosive attack on the banks (Thorne, 1990).

The rate of bank migration in a meandering stream is proportional to the strength of the secondary circulation cells in a bend, which are proportional to the velocity gradient between the near bank velocity and the mean cross-section velocity (Ikeda *et al.*, 1981). The role of vegetation in reducing this velocity gradient is a product of scale, for two reasons. As we shall show, vegetation has a relatively greater role in small streams, but there is also the issue of flow duration.

4.1 Flow duration

In terms of flow resistance and direct protection of the banks from scour, vegetation can only have an influence if it is in contact with the flow. The period of time that bank vegetation will be in contact with the flow varies dramatically along the Latrobe because of the changing shape of the cross-section.

When stage duration is plotted relative to bankfull depth (Fig. 3) it is clear that the shape and hydrology of different reaches means that different portions of the bank are underwater for different amounts of time. For example, planting vegetation on the upper-half of the bank at Hawthorn Bridge (Reach 3), where flow occupies the top three fifths of the bank for less than 2% of the time, would be less effective than at Noojee, where flows occupy the top three fifths for 97% of the time. Similarly, revegetating the top metre of the bank at Rosedale would provide direct protection for more than 10% of the time, but less than 1% of the time at Willowgrove or Thoms Bridge.

4.2 Effects on channel hydraulics

Flow velocity is affected by live vegetation projecting into the channel area, and also by dead vegetation (LWD) in the channel bed. The hydraulic effects of vegetation in flow are complex (Kouwen, 1988), so we assume here that the hydraulic effect is proportional to the area that the vegetation projects into the bankfull flow (the blockage ratio). This area

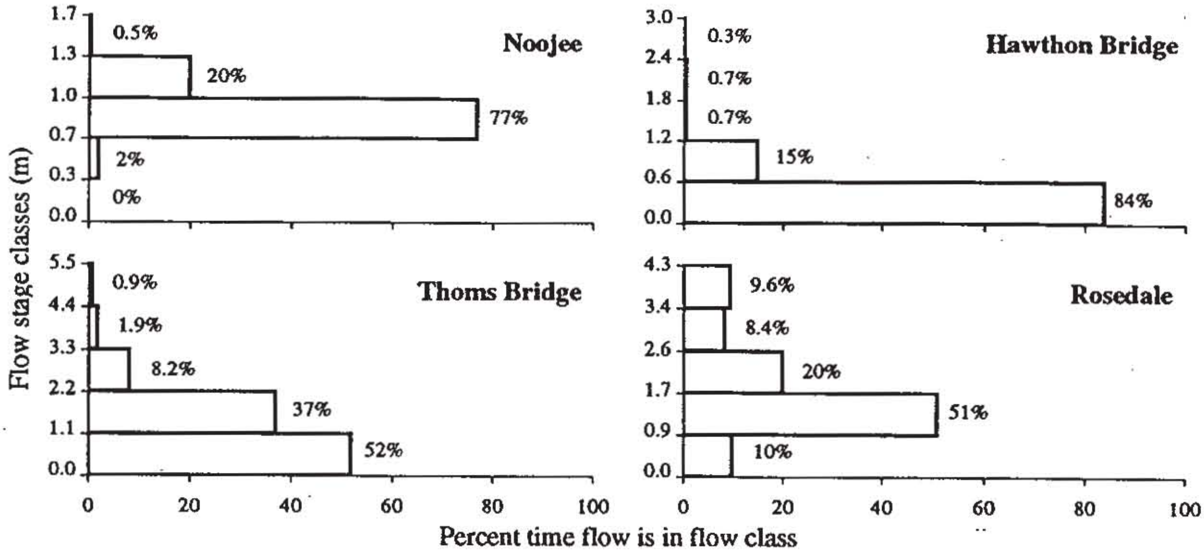

Figure 3: Bankfull depth at four gauges on the Latrobe R. Is divided into 5 stage classes. The graphs show the percentage of time that the flow stage lies within each class.

is estimated for the natural suite of vegetation that would have lined the banks prior to clearing.

Below Willowgrove, LWD has been artificially removed up to four times, so natural LWD projected area is estimated from measurements made by Gippel *et al.* (1992) in the nearby lower Thomson River that has not been snagged. The median LWD projected area on the lower Thomson (similar size to the Latrobe at about Thoms Bridge) is about 1 m^2/m. Figure 4 shows that more of the channel is blocked by LWD than by live vegetation, and that both live vegetation and LWD occupy a progressively smaller proportion of the channel downstream.

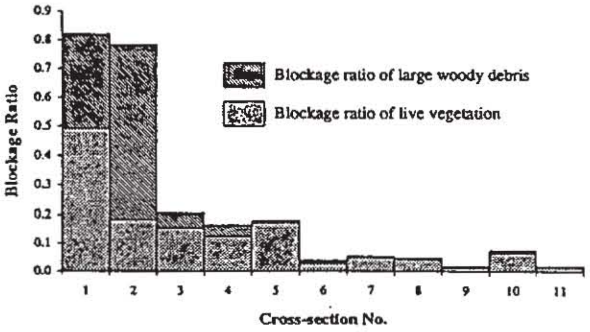

Figure 4: Proportion of cross-section (blockage ratio) occupied by vegetation.

Gippel *et al.* (1992) suggest that LWD will have little influence on velocity below a blockage ratio of 10%. In the upper reaches, the vegetation and LWD occupy up to 80% of the cross-section, having a large impact on flow resistance. The combined blockage ratio falls rapidly to 20% Reach 2, and to only 2% at the mouth of the river. Thus, for over 80% of the river's length, vegetation probably has little influence on mean flow velocity, although it may still influence the near-bank velocity.

5. CONCLUSIONS

The influence of vegetation on bank erosion rates varies through a stream network. This is because, along the stream network, the size and shape of the river, the erosion processes, hydrology, and the suite of vegetation, all change. A scale analysis matches the stream erosion processes to the vegetation characteristics so that managers can plant vegetation in the reaches of the river where it will be most effective. In this case study of the Latrobe River, we have attempted to give a brief overview of the changing hydromechanical effect of riparian vegetation on river bank stability in relation to channel scale. We draw the following conclusions for the role of vegetation in bank stability on the Latrobe River.

- Slumping is an important erosion process in the floodplain reaches of the Latrobe. Replacing pasture with trees (i.e. wattles) will not lead to increased slumping because of surcharge. The weight of the trees is trivial in comparison to the weight of the slump blocks.

- The role of vegetation in drying out stream banks following drawdown of the river is also negligible on the Latrobe because the water-table probably drains at the same rate as even the fastest drawdown in Reach 5. This means that the influence of roots on bank strength is probably the most important role of vegetation in the Latrobe, and this is most important in Reach 4 where the roots cross both the back and base of the failure blocks.

- Vegetation also influences corrasion rates by reducing flow velocities. The effect of live and dead vegetation on mean velocity is dramatic in the top 20% of the stream length, but this becomes negligible through most of the channel length. Furthermore, because of changes in the shape of the cross-section, vegetation planted on the banks will be in contact with flow for very different lengths of time.

- Overall, replacing pasture with trees will have the most pronounced effect on bank erosion rates in the upper end of the lower floodplain reach (Reach 4) where slump blocks are small in relation to the size of rootballs. Revegetation with wattles is unlikely to increase the frequency of bank slump failures because of surcharge, this is particularly true where trees grow on a sloping bank.

This paper has presented a rational method for deciding where vegetation may, or may not, be preferable to more expensive bank stabilising options. Moreover, in pursuing this technique we expect that the theory required for locating these zones will strengthen our understanding of the mechanisms of river bank failure.

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