VEGETATION CONTROLS ON CHANNEL STABILITY IN THE BELL RIVER, EASTERN CAPE, SOUTH AFRICA

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INTRODUCTION

The significance of riparian vegetation as a control of channel form and process is increasingly being recognized in fluvial research (Viles, 1988; Rowntree, 1991; Gregory, 1992). Elucidating its influence, however, has been hampered by two factors. Firstly, vegetation is composed of a complex assemblage of life forms and growth stages which elude quantification. Secondly, vegetation operates in a variety of ways: in some circumstances it acts to increase bank stability, in others it may affect the hydraulic action of the flow in such a way as to induce channel instability. This paper examines a situation where encroaching vegetation appears to have acted in both these ways.

A decrease in the width±depth ratio associated with increased bank stability derived from vegetation has been noted by a number of researchers (Charlton et al., 1978; Eschner et al., 1983; Andrews, 1984; Clifton, 1989; Thorne, 1990). Conversely, debris dams can result in channel instability. In steep, low-order channels an increase in width has been observed upstream of dams, which form steps in the channel profile (Keller and Swanson, 1979; Heede, 1981; Marston, 1982; Gurnell and Gregory, 1984; Clifton, 1989). In low-gradient, higher order streams obstruction of flow by in-channel woody debris during high discharge may lead to local avulsion and overbank sedimentation on restricted areas of the floodplain (Gurnell and Gregory, 1984), or to the development of chutes and meander cutoffs (Keller and Swanson, 1979). Mid-channel bars often form immediately downstream of obstructions formed by woody debris, with associated channel widening. Research from the Okavango delta in Botswana has revealed the dynamic role that vegetation plays in channel avulsion in the Okavango River (cf. Ellery et al., 1990, 1993).

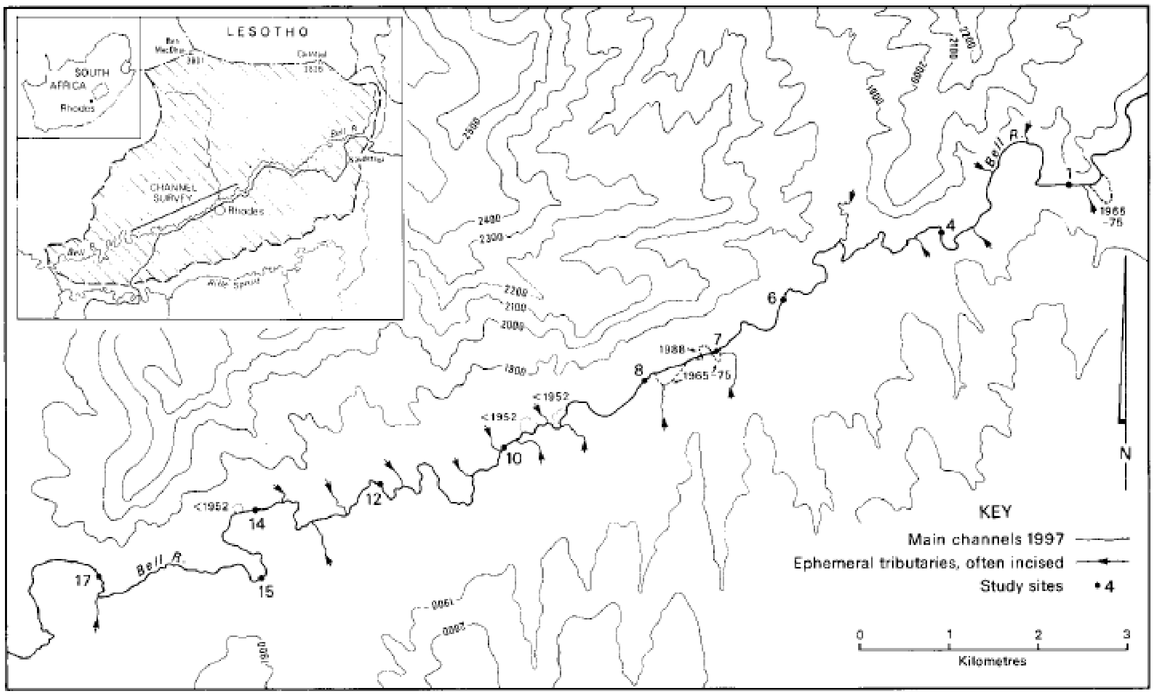

Figure 1: Study area and location of cut-off meanders and sampling sites

The Bell River, which drains a mountainous catchment with an area of approximately 430 km2 in the Eastern Cape of South Africa (Figure 1), shows evidence of recent instability in the form of meander cutoffs and channel widening, resulting in a shift from a meandering to a straighter, divided channel (Dollar, 1992; Rowntree and Dollar, 1996). At least seven cutoffs are evident from aerial photographs: three occurred prior to 1952, three between 1969 and 1975, and one in 1988 as indicated on Figure 1. Brierly (1996) distinguishes two types of avulsion: neck cutoffs and chute cutoffs. Neck cutoffs are the result of mobile meanders with the cutoff occurring across a narrow neck between meander loops. Chute cutoffs occur in more stable channels where the new channel forms across the floodplain, short-circuiting the old channel. It is this latter type of cutoff which is characteristic of the Bell River.

Channel straightening and steepening have been associated with an increase in either the channel-forming discharge or the volume and/or caliber of the bedload (Ferguson, 1987). Channel widening and a tendency to braid have been associated with an increased bedload (Knighton, 1989; Harvey, 1991). There is evidence to support the hypothesis that the instability observed in the Bell River is the response to an increased sediment input from the catchment due to sheet and gully erosion resulting from poor veld management since European occupation in the 1870s (Dollar and Rowntree, 1995). Erosion mapping showed that the sediment input into the channels increased significantly during the last century, possibly due to overgrazing in the 1920s. An analysis of rainfall gives no evidence for a progressive change in climate, but periods of high rainfall may have been responsible for triggering instability in a system already close to its geomorphic threshold. Dollar and Rowntree (1995) conclude that channel change in the Bell River is the result of upstream disturbances which resulted in an increase in bedload. Rowntree and Dollar (1996) examined the spatial variability of channel form and found that both bank and bed material and bank vegetation acted as important controls on channel form. Wide, shallower, more unstable channel reaches were associated with higher caliber bed material and relatively low riparian vegetation. Narrow, stable channels were associated with finer bed material and stable tree-lined banks.

Table I. Vegetation characteristics for selected reaches, Bell River

Site number	1	4	6	7	8	10	12	14	15	17
Channel type	Single, meandering	Single, meandering	Single, straight	Single, divided	Single, straight	Single, meandering	Single, meandering	Single, straight	Single, meandering	Single, meandering
Vegetation type	Trees	Grass and trees	Grass and trees	Grasses and shrubs	Grasses, shrubs and trees	Grasses and trees	Trees	Grasses and trees	Trees	Grasses and trees
Dominant woody species	*S. caprea*	*S. caprea*	*S. caprea*	*S. caprea*	*S. babylonica*	*S. caprea*	*S. caprea*	*S. caprea with S. babylonica*	*S. caprea*	*S. caprea S. babylonica*
Density	Sparse	Dense	Open	Sparse	Open	Open	Open	Open	Dense	Sparse
Age	Immature	Immature/ mature	Mature	Mature	Mature	Immature/ mature	Immature/ mature	Immature/ mature	Immature/ mature	Mature
Height	Medium	Tall/short	Tall	Medium	Tall	Tall /medium	Tall	Tall	Tall	Tall
Position	Bank toe	Bank toe	Bank toe	Bank toe and mid-bank	Bank top	Bank toe, mid-bank and top bank	Bank toe and mid-bank	Bank toe, mid-bank and top bank	Bank toe and mid-bank	Top bank
Spacing	Wide	Close	Close	Wide	Wide	Wide	Continuous	Close	Close	Wide
Extent	Medium	Narrow	Medium	Wide	Medium	Medium	Medium	Medium	Medium	Wide
Density	Low	High	Medium	Low	Medium	Medium	High	Medium	High	Low
Rank	9	2	5	10	7	6	3	4	1	8

Riparian owners along the Bell River responded to early channel instability by planting Salix caprea along the river banks. Planting started in the 1950s in response to advice from the Agricultural Extension Service who stated that this would lead to channel stabilization (Dollar, 1992). Since then the tree has spread rapidly. It is an effective colonizer of unstable areas and exposed gravel bars. A second common riparian species is S. babylonica which was introduced in 1917, probably for aesthetic purposes or for providing firewood rather than as a bank stabilizer per se. The geomorphological effects of these two tree species are examined further in this paper.

METHODS

A stretch of river 17km long was selected for the study. This included both stable and unstable sections. At 10 sites surveys of channel cross-section, gradient and bank vegetation characteristics were carried out. Sites with a large bedrock component in the bank or bed were excluded. The channel cross-section and local channel gradient were surveyed using a surveyor's level. All cross-sections had a clear break between channel bank and floodplain so that width, cross-sectional area and average depth were readily estimated. Bed and bank sediments were collected over a 100m length of channel at each site. The particle size distribution of bed sediments was derived from a combination of surface clast measurements (for coarse sediments) and bulk surface sampling and sieving (for gravel-grade sediments and finer). Bank sediments were analysed using the hydrometer method (British Standards Institution, 1975) to determine the percentage sand, silt and clay. The percentage silt plus clay (B) was used to express bank material size (Richards, 1982). Manning's equation was used to estimate bankfull discharge. Roughness was estimated in the field using visual estimates after Barnes (1967) Bank vegetation was described according to a classification system based on Thorne (1990) detailed in Table I. Each site was ranked from 1 to 10 according to its vegetation density (1 = high; 10 =low) and was categorized as having high, medium and low vegetation densities.

RESULTS

The vegetation assessments for the 10 sites are summarized in Table I and the form variables are given in Table II. A quantitative analysis of the channel form±vegetation relationship revealed that dense woody vegetation acted to stabilize the banks and to reduce the form ratio. The relationship between form variables (width, form ratio and cross-sectional area) and vegetation characteristics was tested using the non-parametric Spearman's Rank correlation coefficient (rs). Results indicated that vegetation is negatively correlated to width (rs=±0.83) and form ratio (rs=±0.89), both significant at the 95 per cent level. There is also a negative correlation between vegetation and cross-sectional area (rs=±0.60), but it is not significant at the 95 per cent level. These results demonstrate that the higher the density of riparian vegetation, the narrower the width and the smaller the form ratio and channel capacity, supporting findings elsewhere (Charlton et al, 1978; Eschner et al, 1983; Andrews, 1984; Clifton, 1989). Vegetation density clearly has a significant impact on channel form. Estimates of bankfull discharge presented in Table II vary widely from 407 m3s-1 to 22 m3s-1 with a median of around 90m3 s-1. There is no consistent downstream trend. Given the short length of river with only one significant tributary occurring between sites 4 and 6, the downstream increase in discharge should be in the order of 18 per cent due to the increase in drainage area (Rowntree and Dollar 1996).

Given the difficulties of applying Manning's n, especially where there is a significant vegetation component, these results should be treated with circumspection. They do, however, point to a channel-forming discharge of around 90m3 s-1. Moreover, if the effect of vegetation is to decrease the form ratio and the channel cross-sectional area, the knock on effect is clearly to increase the potential for overbank flooding.

The relative role of bank material and vegetation in controlling channel form were explored further. Firstly the observed relationship between percentage silt plus clay and form ratio was compared to that described by Richards (1982). Secondly, the relative effectiveness of vegetation as a silt±clay equivalent was examined.

Table II. Channel form variables for sites on the Bell River

Site Number	Vegetation density	Rank	Width (m)	Depth (m)	Cross-sectional area (m^2)	Form ratio (w/d)	Q_b ($m^3 s^{-1}$)
1	Low	9	38·8	1·3	48·83	31·4	128·41
4	High	2	19·5	2·0	38·65	9·9	152·67
6	Medium	5	30·00	1·8	52·80	17·0	62·30
7	Low	10	60·00	2·0	122·25	30·5	407·09
8	Medium	7	31·00	2·2	67·80	14·0	95·60
10	Medium	6	25·2	2·0	49·72	12·8	82·54
12	High	3	19·5	1·9	37·28	10·2	95·82
14	Medium	4	19·5	1·2	23·42	16·3	22·02
15	High	1	21·4	2·3	48·22	9·5	32·31
17	Low	8	27·1	1·6	42·07	17·5	90·86

Table III. Prediction of form ratio (F) from silt±clay content (B)

Site	Silt–clay (%)	Measured F (Fm)	Predicted F (Fp)	Fm/Fp
1	34	31	23	1·36
4	20	10	43	0·23
6	30	17	27	0·63
7	14	30	70	0·43
8	30	14	27	0·52
10	21	13	41	0·31
12	17	10	53	0·19
14	17	16	53	0·31
15	25	10	34	0·28
17	24	18	35	0·50

Table III compares the measured form ratio (Fm) with the form ratio predicted from the silt-clay percentage (Fp) using the Equation presented by Richards (1982):

$$Fp = 800{Q_b}^{0 \cdot 15} B^{-1 \cdot 20}$$

where Qb is bankfull discharge and B is percentage of silt±clay in the channel banks. Qb was taken to be 90m3 s±1. Apart from site 1, which has a higher-than-predicted F value, all sites have a significantly lower-than-predicted F value, the ratio of Fm to Fp ranging from 0´19 to 0´63. The variability exhibited by this ratio suggests that variables other than bank composition are more significant in determining channel form.

The effectiveness of vegetation as an equivalent silt±clay content was estimated as follows. The measured F value (Fm in Table III) was inserted in Equation 1 so that the equivalent B value could be calculated for each site (the fourth column in Table IV). The third column in Table IV gives the ratio of Fm to Fp for sites grouped by the density of bank vegetation. It can be seen from this table that where the vegetation density is high the form ratio is between 0´19 and 0´28 of that predicted for bank material alone, a medium density of bank vegetation gives a ratio of between 0´31 and 0´63, whereas a low density of bank vegetation is associated with a more variable ratio of between 0´43 and 1´36. From the fourth column in Table IV it can be seen that the resistance offered by a high vegetation density is equivalent to that for a silt±clay content close to 70 per cent. The corresponding value for a medium vegetation density is between 45 to 55 per cent. The lower and more variable values for the low vegetation category (25 to 40 per cent) reflect the decreased influence of the vegetation relative to the bank material itself.

Table IV. Effect of bank vegetation on channel form

Site number	Density of bank vegetation	*Fm/Fp*	Equivalent silt–clay content, *B* (%)
1, 7, 17	Low	1·36, 0·43, 0·50	26, 27, 41
6, 8, 10, 14	Medium	0·63, 0·52, 0·31, 0·31	43, 51, 46, 54
4, 12, 15	High	0·28, 0·23, 0·19	68, 68, 68

These results confirm that bank vegetation has an important impact on bank stability and therefore channel form. In the Bell River, the effectiveness of vegetation in stabilizing channel banks far outweighs that of the silt±clay content of the bank material. Although the quantitative analysis of channel form±vegetation relationships is useful in confirming the stabilizing effect of vegetation, a better understanding of vegetative processes requires additional qualitative observations. The effect of vegetation depended on the species, the growth form and the position with respect to the bank. S. caprea had the most obvious stabilizing effect. The trees were commonly planted at the toe of the bank where they have formed dense lateral stands. The tree roots extend into the water as a thick mat which collects fine sediments and forms a low shelf. Good examples are illustrated in Figure 2. During floods, sediment and organic debris collect behind the tree trunks, thus resulting in a general narrowing of the channel. This effect is illustrated by site 14 on Figure 2a. In a few cases, the tree growth was observed to be so dense that it was beginning to block the channel. Site 15 was a good case in point. At this site scouring of the floodplain behind the riparian vegetation, but parallel to the channel, was observed. S. caprea spreads rapidly from shoots which break off and are carried downstream. It is a rapid colonizer of exposed gravel bars and cutoff channels.

It was noted that many of the former banks of cutoff meanders had been lined with mature S. caprea so that, although promoting bank stability, the presence of trees clearly had not prevented channel straightening. S. babylonica tends to grow as isolated trees on the bank tops and has a more massive growth form. Although its roots do offer some protection to the bank they do not form the dense mats characteristic of S. caprea.Where bank undercutting occurs the trees will topple into the channel, causing obstructions and possible further instability. Another effect of S. babylonica noted in the field was bank slumping due to the increased weight of the tree (Figure 2c).

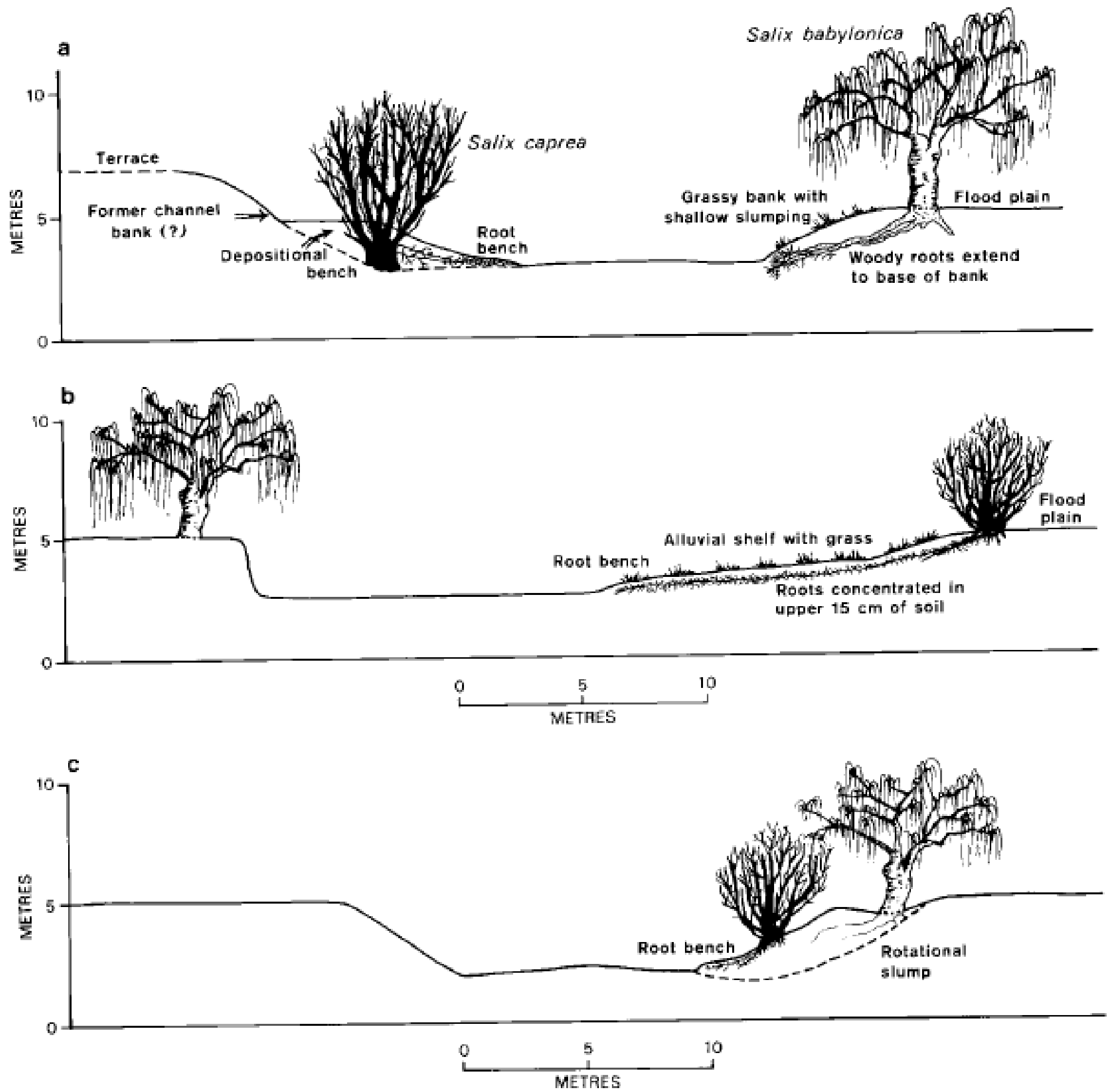

Figure 2: The effects of Salix species on channel cross-section form.

DISCUSSION

Channel vegetation surveys have shown that where S. caprea has colonized the bank, dense root matting has led to bank stabilization. Bank vegetation has stabilized the channel banks and induced bank accretion, resulting in the formation of channel benches. The end result is a reduction in the form ratio and channel cross-sectional area, reducing the channel capacity and increasing the frequency of overbank flooding. This effect is aggravated wherever woody debris falls into the channel, causing further obstructions. Chute formation can be explained as the logical progression as the water scours a more efficient channel across the grassed floodplain. The new channel would lack woody vegetation, have a steeper gradient than the meander, and often be formed on the coarse sublayer of the alluvium constituting the floodplain. The release of fine sediment from the upper strata of the floodplain alluvium into the sections downstream of the cutoff would have further implications for sediment loading and channel stability.

The formation of meander cutoffs may be part of the intrinsic adjustment of a river system as it develops through time and is not necessarily the result of disequilibrium (Schumm, 1980). Such intrinsic adjustment would be accompanied by the development of meanders elsewhere along the channel so as to maintain the overall sinuosity. This does not appear to be the case in the Bell River. Channel straightening with attendant steepening has changed the channel pattern of certain stretches in the Bell River from a meandering to a divided or braided pattern with concomitant reductions in measured sinuosity. Dollar and Rowntree (1995) ascribed the overall process of channel straightening to increased sediment yields, but riparian vegetation has clearly played a part in modifying the process. Vegetation can be seen as a dynamic component of this system with complex effects that may not be easy to predict.

If woody vegetation is to be used to stabilize river banks it is necessary to have a good understanding of the dynamics of the particular fluvial system and the way that woody vegetation will impact on them. In the Bell River it would appear that vegetation is able to play only a short-term role in combating the combined effects of a high-energy environment and increased sediment loading due to catchment erosion. Riparian zone management in mountain areas must be flexible enough to incorporate the consequences of natural instability, while looking to catchment management to control some of its less natural causes.

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