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Resistance Of Riparian Trees And Shrubs To Toppling In Large Floods

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SUMMARY:

Large floods cause significant mechanical disturbance to riparian vegetation by toppling (pushing over) trees and shrubs. Floods in East Gippsland, Victoria, in June 1998, inundated large areas of native riparian vegetation. The rotational moment applied about the base of individual plants by the drag force of the flood on the plant exceeded the root system strength of many plants and they toppled over. The flood provided an opportunity to determine the critical moment required to topple trees. This was done by quantifying the toppling moments applied to both upright and toppled trees at two sites. The results indicated similar critical toppling moments for Eucalypt, Wattle and Lilly Pilly trees of the same size. The critical toppling moment generally increased with tree stem diameter, with the exception of young trees with a base diameter of less than 1 cm that were able to flex and escape the full force of the flood. Flood adapted trees and shrubs close to the channel such as River Bottlebrush, Kanookas, and Willows were more resistant to being toppled. It is likely the results are applicable to similar trees at other sites.

THE MAIN POINTS OF THIS PAPER:

- The resistance of a tree to being toppled by a flood can be measured by the moment applied by the drag force on the stem of the tree.
- The resistance of trees to being toppled by flood generally increases with stem diameter, but young trees may flex rather than topple.
- Within a site, the flood toppling resistance of all trees of a similar stem diameter is similar, regardless of species.
- Most shrubs are less resistant than trees of the same stem diameter to being toppled by a flood.

1 INTRODUCTION

The aims of this work were to:

1. Catalogue the relative responses of common riparian plants to a large flood in East Gippsland and identify species of trees and shrubs that were most resistant to being toppled by floods;
2. Quantify the flood forces required to topple trees;
3. Determine the effect of tree stem diameter on toppling resistance;
4. Determine the applicability of this relationship to other sites.

Riparian vegetation is essential to many aspects of stream health. Firstly, a diverse riparian plant community is an important part of the stream ecosystem, providing shade and organic inputs (Cummins 1993). Secondly, riparian vegetation reduces bank erosion by removing the force of flow from the bank. Thirdly, roots reinforce the bank and generally increase bank stability (Thorne 1990; Abernethy and Rutherfurd, this volume).

The response of natural riparian vegetation to floods can be used to improve our understanding of floodplain ecology. In particular, the effect of flood disturbance on the distribution of trees in the riparian zone could be useful for planning and managing revegetation of riverbanks.

Moving floodwaters provide a drag force that acts on plants as a lever arm to produce a rotational moment. This topples the tree if the moment exceeds the strength of the root system. After a flood, trees and shrubs can end up in one of five inclinations shown in Figure 1. Both leaning and uprooted trees and shrubs are defined here as toppled. It is also sensible to group these plants together because those leaning are likely to fall into the uprooted inclination due to damage to the root system.

Conversely, for upright and flexed plants, the strength of the root system has exceeded the overturning force. Flexed plants are likely to straighten over time into the upright inclination. Trees and shrubs can be snapped instead of toppled, however this mechanism is not considered here. It did not occur frequently at the sites included in this study and it involves failure of the stem rather than the root system.

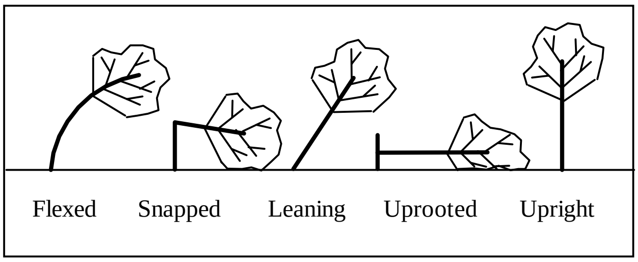

Figure 1: Post Flood Inclination of Trees

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The toppling of trees and shrubs can have a significant impact on the ecology of the riparian zone. Toppled vegetation often dies, reducing its capacity to resist further bank erosion and increasing the light available for weed growth.

The toppling resistance of vegetation should be considered when planning revegetation programs and managing existing riparian vegetation. Plants with more resistance to being toppled by a flood could be planted in frequently inundated areas of a revegetation plot. The variation in resistance to toppling of plants as they grow determines the flood resistance of a revegetation plot over time. As well as toppling, extended immersion and also sediment deposition can kill riparian vegetation or reduce its growth rate (Ewing 1996), however this probably affects young plants most of all, while toppling affects larger plants.

East Gippsland experienced large floods in several rivers during June 1998. This provided an opportunity to determine what flood moments had toppled trees and shrubs, and what moments had allowed them to remain upright. The boundary between these is the critical toppling moment. This measure of the flood toppling resistance of vegetation is likely to be applicable at other sites in rural South Eastern Australia.

Considerable work has been done on the hydraulic effects of riparian vegetation in increasing flood levels (Li and Shen 1973; Darby and Thorne 1996). However, there has been less research into the impact of floods on the stability of riparian vegetation.

The critical toppling moment (M_c) of many Japanese riparian trees has been measured directly by toppling riparian trees using a cable attached to the stem (TRCRD 1997). This study found that M_c increased with tree stem diameter at breast height (*DBH*) measured approximately 1.3 m from the ground. It also found little variation in M_c across tree species for trees of similar size.

Toppling tests have been carried out on silvicultural trees (Rodgers et al. 1995). However, it is believed that these results have limited applicability to riparian trees. Root system depth of riparian trees is often limited due to stratified soils and high water tables. These factors act to restrict root system depth and thus reduce M_c (Fraser 1962). Research is lacking into the M_c of Australian riparian trees, particularly under flood conditions.

2 STUDY SITES

Sites were investigated on the Bemm and Tambo Rivers in order to obtain results from two different vegetation communities. At both sites, the rivers flowed through dissected terrain. There was limited floodplain development and channel benches were flanked by hillslopes. This produced high flood depths and flow velocities that had a considerable impact on the vegetation.

The sites were close to level gauges that provided data on the flood discharge through manual gauging of previous floods. Near-straight sections of channel were chosen to minimise lateral variation in velocity. The flood had inundated mainly native vegetation, including understorey and large trees.

2.1 The Bemm River Site

This site extended from 50 to 300m upstream of the Princes Highway bridge. The catchment area above the site is 725 km^2 (Rural Water Commission of Victoria 1990). The gauge adjacent to the site measured a peak flood level of 18.39m. The peak discharge was 925 m^3/s (Thiess Environmental Services 1998), giving a mean flow velocity of 0.8 m/s through the section. Using the method in Australian Rainfall and Runoff, the annual return interval of the flood was approximately 100 years. (IE Aust 1987)

This site has a mean annual rainfall of approximately 1000 mm (Bureau of Meteorology 1998) and the soil is silty clay. The riparian zone at this site has never been cleared. There was a closed forest near the banks of the low flow channel and up onto a bench on the right bank at 10 m gauge level. It was dominated by Lilly Pilly (*Acmena smithii*), Blackwoods (*Acacia melanoxyln*), Late Black Wattles (*Acacia mearnsii)*, Soft Treeferns (*Dicksonia antarctica*), Rough Tree Ferns (*Cyathea australis*), Hazel Pomaderris (*Pomaderris aspera*) and, close to the stream, Kanooka (*Tristania laurina*). Many Kanookas and Lilly Pilly trees along the edge of the channel remained upright while the flood toppled most

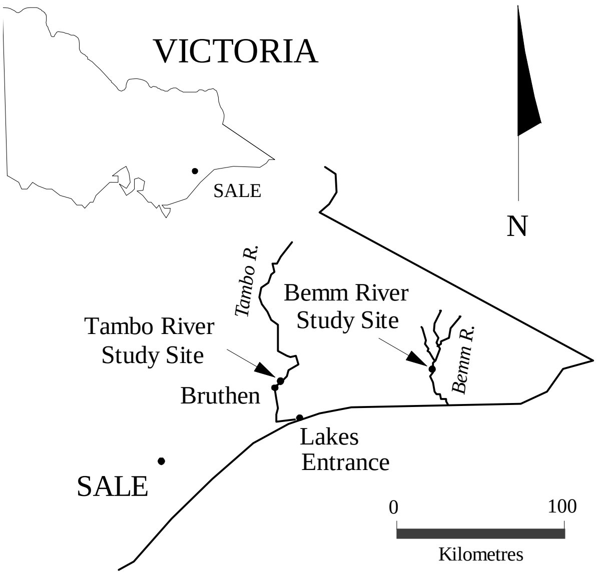

Figure 2: Location of Study Sites in Victoria

vegetation on the bench.

Slopes above the bench were dominated by Southern Mahogany gums (*Eucalyptus botriodes*), a few River Peppermint (*Eucalyptus elata*), the above-mentioned Wattles and Tree Ferns. Less of this vegetation was toppled, due to the lower water depths.

2.2 The Tambo River Site

The Tambo River site is approximately 7 km by road upstream of Bruthen. It extended from the junction with Ramrod Creek downstream about 200 m. At the gauge adjacent to this site the river peaked at approximately 12 m, and 1700 m^3/s discharge (Thiess Environmental Services 1998), with a mean velocity of 1.9 m/s through the section. This flood had an annual return interval of 50 years (IE Aust 1987) and the catchment area above the site is 2681 km^2 (Rural Water Commission of Victoria 1990)

The site has a mean annual rainfall of approximately 770 mm (Bureau of Meteorology 1998) and the soil varies from silty to sandy loam. The riparian vegetation at this site was sparser than the Bemm River site, and was most likely regeneration after previous clearing and grazing. The vegetation away from the low flow channel consisted of an open stand of Late Black Wattles and a few River Peppermints. There was an understorey of Hazel Pomaderris, Tree Violet or “Prickly” (*Hymenanthera dentata*), *Leptospermum* sp. and Silver Wattles (*Acacia dealbata*). The flood toppled many of the Late Black Wattles and most of the understorey shrubs.

Nearer the stream, there was White Sallow Wattle (*Acacia floribunda*), River Bottlebrush (*Callistemon paludosus*), Swamp Paperbark (*Melaleuca ericifolia*), Blackwood, a hybrid of Golden Upright Willow (*Salix alba* var *vitellina*) and Crack Willow (*Salix fragilis*). Less of this vegetation was toppled by the flood.

None of the trees or shrubs toppled by the flood were transported, at either site. There was some light, organic debris at the Tambo River site, piled against the stems of larger trees.

3 METHODS

3.1 Toppling Moments Applied To Trees By the Flood

We walked through the sites and recorded data on 120 individual trees and shrubs at the Bemm River site and 140 at the Tambo River site. Common species at each site were included. Not all plants of those species within the sites were included, rather a range of different sized plants that had been exposed to a range of peak flood depths were selected, so as to get a good picture of the behaviour of each species. Both sides of the channel were studied.

$$M = \tfrac{1}{2}\rho C_D (DBH)\bar{v}^2 y^2 / 2$$

where M = toppling moment (Nm)
ρ = density of water (1000 kg/m^3)
C_D = drag coefficient.
DBH = stem diameter at breast height (m).
y = peak flood depth (m).
$\bar{v}$ = mean velocity at the flood peak (m/s).

Equation 1: (TRCRD 1997)

The objective was to calculate the toppling moment applied by the flood to each tree using Equation 1, and correlate this with the inclination of the tree (upright or toppled). The size of shrubs and trees was quantified by *DBH*, except those with height of less than 2.5m high, where stem diameter at the ground surface was used. Stem diameter was seen as having a good correlation with root system strength, and its use also allowed comparison with previous studies. The estimated height of each plant was also recorded. Peak flood depth, *y*, at each plant was estimated by comparing the gauge height at the base with the gauge height of the flood peak, or by using debris marks on stems of upright trees.

The mean velocity during the flood peak, $\bar{v}$, at each site was determined by dividing the peak discharge at the gauge (supplied by the hydrographic service provider) by the surveyed area of the cross section at the site. A 5% dead area was allowed at the Bemm River site due to the density of the vegetation.

The drag coefficient was determined by approximating the tree stem as a cylinder. This allowed use of a pre-determined experimental relationship as given in Gerhart and Gross (1985). The drag coefficient varies with diameter and flow velocity. In this study values between 0.2 and 1.2 were used as appropriate for the *DBH* and mean flood velocity.

Equation 1 shows that *M* is proportional to the stem area exposed to the flow. It is also proportional to the square of $\bar{v}$ and the square of *y*. A flood with a higher $\bar{v}$ therefore requires a smaller *y* to apply the same *M* to a plant.

Data was not collected from plants in the wake of others upstream, or those near the edge of the cross section. These plants would have experienced much less than the mean velocity during the flood. A few toppled trees associated with mass failure of a road embankment at the Tambo River site were also neglected, since their inclination was not related to the flood flow. Multi-stemmed trees were neglected, since they had a larger stem area exposed to the flow.

The toppling moment could not be determined accurately for plants that had their canopy even partly submerged at the peak of the flood, since Equation 1 only includes the form drag on the stem itself. Drag on the canopy increases the toppling moment and is more complicated to calculate. Thus, toppling moments were not calculated for shrubs. For trees, the height to the first branch was estimated and canopy submergence was determined by subtracting this height from *y*. Where a rootball had been excavated, its width and depth were recorded, to describe the uprooting process.

The plants were grouped according to whether they were upright or toppled. Toppled plants had been exposed to greater than M_c. Upright plants had been exposed to less than M_c.

The survival of each plant through the flood was also recorded. Fieldwork was carried out approximately 3 months after the flood, by which time the survival or otherwise of each plant through the flood was clear. Plants with full leaf cover, or reduced leaf cover but healthy shoots, were classed as alive. Some of the trees classed as not surviving the flood still had some green foliage left, but were drooping and had no fresh shoots.

4 RESULTS

4.1 Critical Toppling Moments of Trees

Toppling moments were determined for Wattles, Lilly Pilly and Eucalypts. The moment applied to each tree was plotted against *DBH* (Figure 3). A line was fitted by eye below the data points for toppled trees. This produced a conservative threshold of M_c below which no trees toppled, but above which some trees remained upright. Eucalypt, Wattle and Lilly Pilly trees of similar *DBH* had similar M_c above which they were toppled, so the results were plotted together. As shown by the positive slope of the line, M_c increased with *DBH*. The line fits the relationship:

$$M_c = 12{,}000(DBH)^{1.3} \qquad \text{Equation 2}$$

Despite the fact that moments applied to the canopy could not be determined, some of the trees whose canopy was partly submerged were included in the plots. The actual moments applied to these trees would have been higher than trees where only the stem was submerged, making the M_c line conservative. In the absence of better information, this data extended the limit of toppling resistance for that species.

4.2 Flood Toppling Resistance Of Trees

Equation 2 also implies that larger trees required a larger flood depth to be toppled. However, there were two exceptions to the general rule that larger trees were more resistant to toppling:

Firstly, Late Black Wattles and River Bottlebrush above a *DBH* of approximately 0.2 m had less resistance to toppling, probably because they were fully mature at this size, and had rot in the root system. Secondly, very small Lilly Pilly or Silver Wattle trees (*DBH* < 0.04 m) flexed rather than being toppled. They were gradually springing back to an upright position 3 months after the flood. Late Black Wattles also showed this behaviour but only up to 0.01 m diameter. Although there were no Eucalypts at the two sites small enough to flex, this behaviour was observed in Eucalypts at other sites.

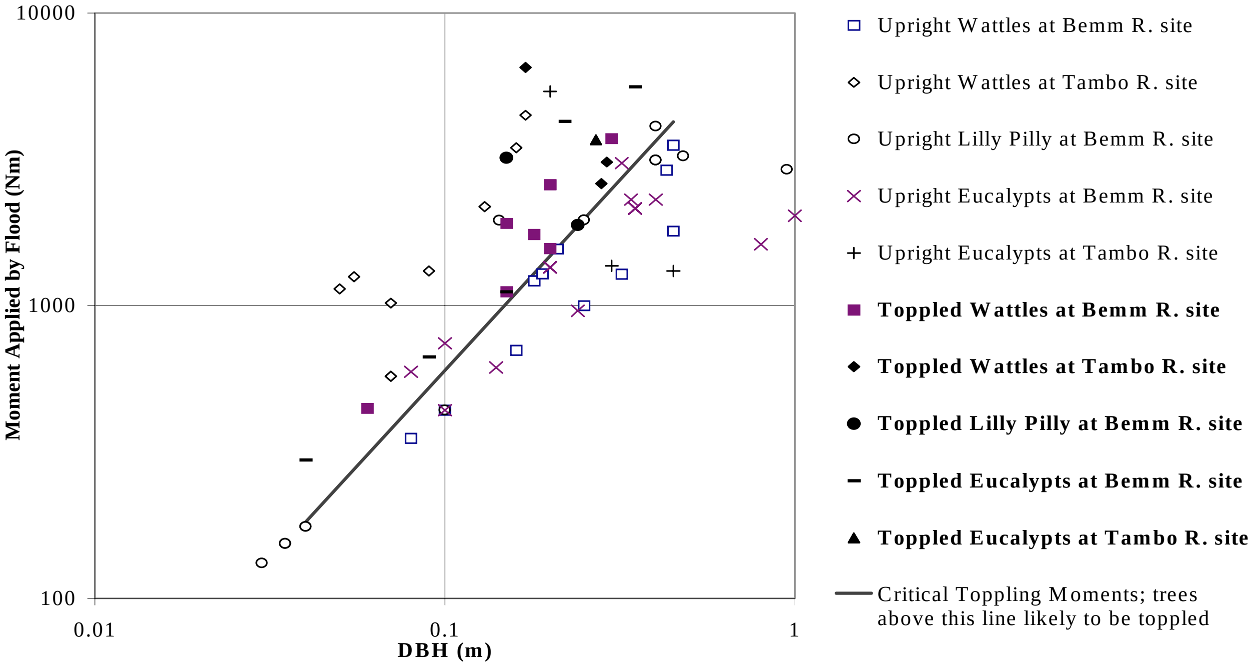

Figure 3: Critical Moments for Toppling Eucalypt, Lilly Pilly and Wattle Trees

Root ball diameters for uprooted trees and shrubs generally ranged from 4 to 8 times *DBH*. The root systems were generally shallow, with root ball depths ranging from 0.25 to 0.5 times the root ball diameter.

4.3 Flood Survival of Trees

Not all trees toppled by the flood were killed as a result. Sometimes roots on the lower side of the root-ball flexed rather than breaking off. Consequently, flood survival was less well predicted by *DBH* and peak depth than was post flood inclination.

The survival rate of toppled trees was very species dependent. Willows were particularly resilient, with all uprooted plants surviving. Lilly Pilly, Eucalypts and Blackwoods generally did not survive being toppled, while the survival of toppled Late Black Wattle was mixed.

4.4 Resistance Of ShrubsTo Toppling

Most understorey shrubs from which data was recorded had experienced a peak flood depth of over 5 m. Nearly all these shrubs were toppled, at both sites. However, a higher proportion of toppled shrubs survived than did toppled trees. Hazel Pomaderris, *Leptospermum* sp, White Sallow Wattle and Treeferns were particularly resilient, with all uprooted plants surviving. Most other toppled shrubs survived. Spiny-headed Mat-rush (*Lomandra longifolia*) all survived at both sites.

4.5 Resistance Of Plants Near The Low Flow Channel To Toppling

In this flood, vegetation along the banks of the low flow channel was immersed for over 48 hours. However, the trees and shrubs here were impacted less than those further away from the channel, indicating that length of immersion was not the determining factor in flood survival. They had been exposed to more frequent flooding, and were therefore better adapted.

River Bottlebrush, Kanookas and Willows were perhaps the most flood resistant plants, often growing in a streamlined form. Only a small proportion was toppled into a leaning position and all survived. White Sallow Wattle at the Tambo River site was more sensitive to flooding, with most plants being toppled, although all survived.

5 DISCUSSION

5.1 Implications of Critical Toppling Moment Results

The M_c as shown in Figure 3 would apply to similar sized trees in similar soil at other nearby sites. However, variation in M_c between dissimilar sites should be expected. Toppling tests on riparian trees in Japan indicated M_c 4 times higher than in our study for trees of *DBH* = 0.1 m, and 9 times higher for trees of *DBH* = 0.3 m. (TRCRD1997). They found that M_c depended on *DBH* as:

$$M_c = 245{,}250(DBH)^2 \qquad \text{Equation 3}$$

(TRCRD 1997)

The differences in methodology between the present study and the Japanese study may contribute to the discrepancy between the two results. The toppling tests in the Japanese study were performed with dry soil, whereas the soil around the trees in our study had been submerged for at least 7-10 hours before the peak of the flood. It is likely that this reduced the strength of the root-soil matrix. Also, the species in the Japanese study were deciduous, and may have had different root systems to the Australian species. Especially at the Bemm River site, trees uprooted a shallow plate rather than a rootball.

That M_c was independent of tree species, in both this and the Japanese studies, suggests that the anchoring strength of the root-soil system of similar sized trees is also independent of species. Abernethy and Rutherfurd (this volume), indicate similar tensile strengths for River Red Gum (*Eucalyptus camaldulensis*) and Swamp Paperbark roots of a similar diameter.

As mentioned, the toppling resistance of all tree species was similar. However, tree species are not generally distributed evenly across the riparian zone and this was the case at the two sites studied. Eucalypts were common on the outer fringes of the flooded area, with other species such as Lilly Pilly and Wattles being dominant in the more frequently flooded area closer to the banks of the low flow channel. This implies that the distribution is determined by factors other than toppling resistance, e.g. regeneration capacity and habitat preference.

5.2 Flood Duration

The amount of vegetation disturbance from a flood depends on the flood duration as well as its peak height (Huckleberry 1994). The East Gippsland floods applied toppling forces to vegetation for much longer than in the pull-over tests conducted in the Japanese study, and thus the results presented here may be more representative of the M_c required in flood situations.

The toppling moments in Figure 3 were calculated at the flood peaks, which lasted for at least 15 minutes. At present it is not known if the critical conditions for toppling occur at the peak of a flood or sometime after. However, it is likely that most trees toppled while the flood was close to its peak level, since at both sites, the river level was within 2 m of the peak for 13 hours.

5.3 Effect of Flood Velocity Approximation

The flood velocity was approximated as being uniform across the cross section, however it would have been less than this near the edges of the cross section. Trees near the edges of the cross section would thus have experienced lower moments than shown in Figure 3. This explains why many Wattles at the Tambo River site remained upright despite plotting above the M_c line.

Conversely, trees near the centre of the channel would have been exposed to higher moments than those presented in Figure 3, due to the higher velocities there, especially near the surface. Therefore, the effect of approximating the velocity as uniform across the cross section is to make the M_c line in Figure 3 conservative, i.e. trees are shown as toppling at lower moments than what actually occurred.

5.4 Distribution of disturbance to vegetation

The morphology of the valley can affect the distribution of disturbance to riparian vegetation. For example, a narrow channel with deep, well-vegetated banks can slow the flood velocity there to below that on the floodplain, due to the inefficient cross sectional shape. This would explain why nearly all vegetation adjacent to the low flow channel at the Bemm River site remained upright, despite the same species up on the flood bench above being toppled.

Point bars are areas of high flood disturbance to vegetation. The flood slope is steeper due to the shorter course across the point bar, creating higher velocities and toppling moments for the same flood depth.

6 CONCLUSIONS

Record floods in East Gippsland in June 1998 inundated large amounts of native vegetation. The drag force of the floodwaters produced a moment acting to topple many trees and shrubs into a leaning or uprooted position.

The moment required to topple a tree was found to be dependent on the *DBH* of the tree stem. Generally, the larger the *DBH*, the greater the critical toppling moment (M_c) and flood depth required to topple a tree. Eucalypt, Wattle and Lilly Pilly trees of the same *DBH* had similar M_c. The M_c relationship determined was conservative, and should be applicable to trees in other floods, with appropriate allowances for uncertainties.

Small trees were able to avoid being toppled by flexing their stem and so reducing the toppling moment applied to the root system. Mature trees with rot in the root system had reduced toppling resistance. Willows were slightly more resistant to toppling than native trees of a similar *DBH*. Most shrubs, except flood adapted species such as River Bottlebrush, were less resistant to toppling than trees of the same *DBH*, however, the survival rate of toppled shrubs was better than that of trees.

As well as *DBH*, critical toppling moments of trees are dependent on soil type, water table depth, rooting depth and soil strength. These other parameters must be considered when applying relationships between critical toppling moments and *DBH* to new sites.

7 ACKNOWLEDGEMENTS

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