WILL REPLANTING VEGETATION ALONG RIVER BANKS MAKE FLOODS WORSE?

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Background

We live in a technologically advanced age, however as a society we remain vulnerable to the forces of nature; to earthquakes and hurricanes, floods, bush fires, and Tsunami. In terms of frequency, floods represent over one third of these events. Of the top ten most destructive natural disasters in history, four are floods. In Australia, the disruption and destruction caused by floods is estimated to cost the economy an average of $400 million per annum, or almost half of the total annual cost of all natural disasters. However, of even greater concern is the human toll. A tragic reminder of the deadly nature of floods occurred on June 30 this year when two people lost their lives to a fast rising Coomera River on the Gold Coast. While our attention may currently be focussed on the ravages of back to back droughts, these deaths show that the threat of flooding remains undiminished.

Floods rise following heavy rainfall, when the volume of runoff delivered to our river networks exceeds the capacity of the system. One approach to reducing the risk of flooding is by increasing the network capacity. Capacity is principally limited by the amount of resistance in the channels that make up the network. Resistance can be thought of the friction that slows down flow; greater resistance reduces the volume of water that a channel can hold before overflowing. Resistance is high at rapids were the stream bed is rough, and where the channel winds around tight bends. High resistance is also caused by vegetation, which occupies space in the channel and presents obstacles that slow down flow. It also happens that vegetation is relatively easy to remove. Therefore, the removal of vegetation from the area in and near stream channels (the riparian zone) has been practiced in the name of flood mitigation by generations of Australian landholders, sponsored by governments through major drainage and channelisation campaigns. Figure 1 depicts the most extreme case, where the riparian vegetation has been completely removed.

Figure 1 Pictures of a healthy riparian zone (left) and a degraded riparian zone (right).

The cost of this approach has been the impoverishment of riparian plant communities. A wealth of evidence now links the degradation of riparian zones with the declining health of aquatic and terrestrial ecosystems. In response, governments in Australia and around the world are investing heavily in riparian rehabilitation programs. In the United States the investment in stream restoration has exceeded $US 1 billion per annum since 1990 (Bernhardt et al., 2005). In Australia, stream managers are now contemplating the revegetation of the entire stream network of large catchments.

A start has already been made on this work. For example, in 2004/5 the Victorian Department of Sustainability and Environment replanting 325,000 native trees along 775km of stream frontage, as well as fencing some 1442km of streams (Paul Wilson, pers. comm., 2005).

Whilst the explosion of riparian revegetation is an exciting development for stream health, it represents a sudden change to public and private practice. There can be a tendency to rush in without first considering all of the implications of suddenly reversing 150 years of activity. In fact, it is common for landholders to resist riparian revegetation, saying to managers, "putting that vegetation back on the banks will make floods worse. We have spent decades making our farms safe from flooding, and now you want to undo all of that?". This seems a fair question. It is easy to criticise earlier generations for acting without considering some of the longer-term consequences, but we could be accused of doing the same thing with the sudden rush to revegetate riparian zones. Thus, this research addresses the question: will replanting vegetation along river banks make floods worse?

This study sets about determining whether the revegetation of an entire catchment has any influence on flood size. Floods in this work are measured by two characteristics: the **peak stage** (maximum depth of water) and the **inundation duration** (time that flow is not confined within the banks of the river). Intuitively, the result of adding vegetation should be to reverse the channel capacity improvements won by vegetation removal. The question is by how much. It is important to recognise that replanting riparian zones is very different from complete restoration (i.e. a return to pre-European condition). There are extra dimensions to the problem, with practical questions to consider such as: what proportion of the network is subject to rehabilitation; where replanting occurs in the stream network; and what combination of plant species is planted.

To measure or to compute?

The most scientifically rigorous way to determine how floods change when a catchment is revegetated is to measure the change directly. To take measurements we would need two catchments with riparian corridors that are essentially clear of vegetation, compare the stage and duration of floods from the previous two decades, and then replant the riparian zone of one of the catchments. After allowing some time for the plants to mature (say another decade), the size of floods in both catchments would be remeasured, again for at least two decades. Many such paired-catchment studies have been completed, to investigate for example impacts associated with deforestation (Best et al., 2003), but exploring changes associated with growing new vegetation is fundamentally a bigger problem. While we could accelerate the experiment by removing riparian vegetation from a well-vegetated catchment, this would still take decades to produce a result.

For this problem computer simulation offers a practical alternative to field experimentation. A wide range of numerical models are available that simulate flood dynamics (known as flood routing). Flood routing models are considered sufficiently accurate to be relied upon to designate flood prone regions in towns, provide assessments of flood risk, and to design appropriate flood mitigation measures (e.g. structural defences such as levee banks and retarding basins). However the software that was available has key weaknesses that had to be addressed. The two main impediments were:

- First, the representation of vegetation in existing flood routing software is highly simplified and therefore this software is not at all suitable for exploring the impact of vegetation on floods. Given that an accurate representation was vital, a large part of this research was dedicated to filling this gap. The result is my new model of vegetation roughness called ROVER (Roughness of VEgetation in Rivers).

- Second, while it is technically possible to route floods down large catchments, such as the Goulburn in Victoria (10,000 km^2), such simulations demand a mass of input data and the time to generate a single flood runs to many hours if not days. Instead of attempting to construct an all encompassing model, the impact of vegetation on flow was explored by applying a series of models dealing with successively larger scales.

These hurdles were overcome in three stages. First, the foundation was laid by developing and verifying the accuracy of the new vegetation resistance model, ROVER. Next, ROVER results were added to a high resolution flow model, making it possible to simulate flood waves travelling down a 10 km river reach with vegetation. Finally, a much simpler numerical scheme was used to explore the impact of vegetation on floods moving down large-scale channel networks.

Problem 1: How much flow resistance does vegetation cause?

The value of resistance is a critical parameter in flood routing. Its value essentially determines how fast a flood moves and how deep the flow is. Flow resistance is defined in numerical flood simulations via a parameter called a flow resistance coefficient. In Australia the coefficient most commonly used is called Manning's n, with high values of Manning's n indicating high flow resistance. The data plotted in Figure 2 confirms that vegetation can have a large impact on channel resistance; however the spread of Manning's n values suggests that the increase due to vegetation is highly variable, probably multi-factorial.

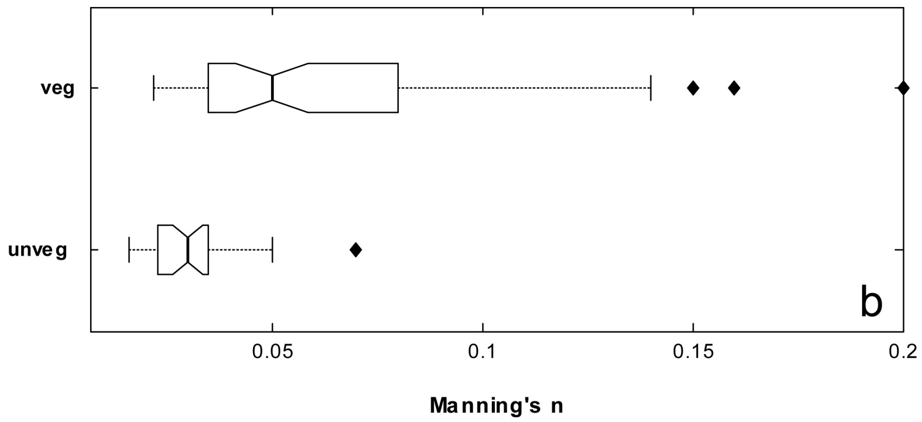

Figure 2 Boxplot showing the range of flow resistance values recommended for stream channels with vegetation (veg) and without vegetation (unveg); taken from a table compiled by Chow (1959).

Generally it is necessary to estimate (rather than measure) the value of the resistance coefficient for a particular situation, and a wide range of methods are available for this purpose. However, after over a century of experiments in the field and with flumes[1], the selection of resistance coefficients remains more an art than a science. This is especially true in the case of vegetation. Plants are challenging to describe numerically because they come in a myriad of shapes and sizes, and grow in complex mosaics along rivers. We undertook a critical review of existing procedures for estimating vegetation resistance only to find that, in general, very coarse simplifying assumption are used and consequently important features of vegetation resistance are neglected. Furthermore, these

[1] A flume is an artificial channel for experiments involving flowing water, similar to a wind tunnel.

procedures usually focus on only a single plant type, with scant attention paid to the characteristics of multi-layered communities that dominate the highly fertile riparian zone.

Development and testing a new model: ROVER

I addressed the deficiencies of the existing models in ROVER. In examining over 200 existing vegetation resistance studies it became clear that, despite the myriad of forms, plants behave in very similar ways. Four key properties determine vegetation resistance: 1) stem density, which increases resistance; and three factors that moderate the impact of vegetation: 2) free space; 3) flexibility and 4) flow depth. Table 1 provides some more detail on each mechanism, and gives an indication of the size of the impact. ROVER consists of numerical algorithms for each plant property.

Table 1 Key plant properties used in ROVER; the resistance mechanism and indicative impact.

Plant Property	Mechanism	Resistance impact
Stem Density	Stems and leaves create drag by causing turbulence. Resistance usually increases in proportion to density; so twice the density causes twice the resistance.	High stem density may increase resistance by a factor of 2 - 4.
Free Space	Rivers are rarely choked by vegetation and the free space between plants reduces the overall resistance as water preferentially flows along unobstructed pathways.	Negligible until plants occupy more than 10% of the flow area.
Flexibility	The force of flowing water can cause flexible stems to bend, become more streamlined, and hence produce lower drag.	Resistance may decline by 50% or more.
Flow Depth	As plants become submerged, a layer of water is able to pass freely over the plant, decreasing total resistance rapidly.	Resistance declines exponentially with the depth of the free layer.

A feature of the resistance of plants is the wide fluctuation with flow depth. Therefore, in ROVER, plant resistance is described by a curve showing the variation of Manning's n with flow depth. The specific shape of the curve depends on the four plant properties (via a set of numerical relationships). The model curves were calibrated using characteristics measured for a wide range of different plant types. These calibrations showed that the model was able to accurately reproduce the resistance of the following plant types: mature trees; grasses; aquatic plants; flexible saplings (cedar, spruce and willow); and fallen timber (commonly called large woody debris).

ROVER differs from previous models in three important ways. First the model is capable of representing a wide range of plant types; from river red gum to spiny rush, from aquatic sedges to thick swards of kikuyu grass. Second, every plant type is defined using the same four properties, with different resistance characteristics set simply by changing parameter values. Third, the resistance characteristics of multi-layered communities, and those with patchy distributions around the stream cross-section, can be estimated. The later step is made possible because all the plants are defined in the same way; effectively ROVER combines apples with apples.

ROVER can now be applied to calculate the decrease in network capacity. The decrease is however not consistent across a catchment. The influence of vegetation is small in large channels; plants do not occupy much of the flow area when channels are a hundred metres wide! In small channels, vegetation can obstruct a significant flow area, but resistance tends to be high in these streams even without vegetation and so the proportional increase in resistance is low. Therefore, vegetation tends to change resistance the most in streams of moderate size. So, we are now in a position to estimate the increase in flow depth, and the accompanying decrease in flow velocity, caused by the presence of vegetation at different locations throughout the channel network. The question is do these incremental changes across the network add up to a significant change in a flood?

Where do flood waves come from?

A flood travels like a slow moving wave. The wave is built from many smaller waves that build up in the various arms of the upstream channel network. If these smaller waves travel quickly, they tend to build a wave with a higher peak discharge but a shorter duration than slower waves. Another important influence on the size of the wave is that of floodplains. Floodplains reduce the size of the wave by siphoning off some of the water from the main flow and storing it for a time, effectively slowing down a part of the flow. The size of the wave (peak discharge) at a given location therefore depends on how fast waves from the various tributaries come together, and how much water has been detained along the way. The question is: does vegetation influence the size of the flood wave?

Problem 2: Does vegetation influence moving flood waves?

The presence of vegetation in the upstream channels, by increasing flow resistance, will slow down a flood wave. Also, because vegetation reduces channel capacity, more of the flood water will be pushed out onto floodplains. Therefore, the effect of vegetation is to inhibit the development of large waves. Thus, a trade-off exists between the increase in flow depth caused by reduced channel capacity and the potential decrease in peak discharge of the flood wave that a densely vegetated channel network produces. **This trade-off has not been explicitly recognised in any past work.**

The first part of the trade-off - the increase in flow depth - is readily calculated at a particular site by applying ROVER. The problem therefore became how to quantify the sensitivity of flood wave size to the amount of vegetation in the channel network upstream of the site. While similar sensitivity tests have been run in the past by other investigators, resistance was specified in these tests as a single constant value, and the effect of vegetation was added as a second constant increment. This work therefore breaks new ground by considering vegetation resistance as a property that varies with flow depth, and changing the resistance increment according to channel size and slope. To explore this variability required not only high resolution flood routing (to handle the variation of resistance with flow depth) but also a large number of trials.

Numerical simulations were run for flood waves traversing a 50km river reach with ROVER used to generate appropriate resistance functions for densely vegetated channels and floodplains. A series of channels of different shapes, sizes and slopes were tested, and in total the passage of several thousand floods was simulated. Figure 3 shows the results for four typical simulations. Floods of two different sizes were injected at the top of the reach; a large flood (light grey shading) and a moderate flood (dark grey shading). The two events were routed down an identical 50km reach, once with dense vegetation flanking the channel (dashed lines) and then with no vegetation present (solid lines).

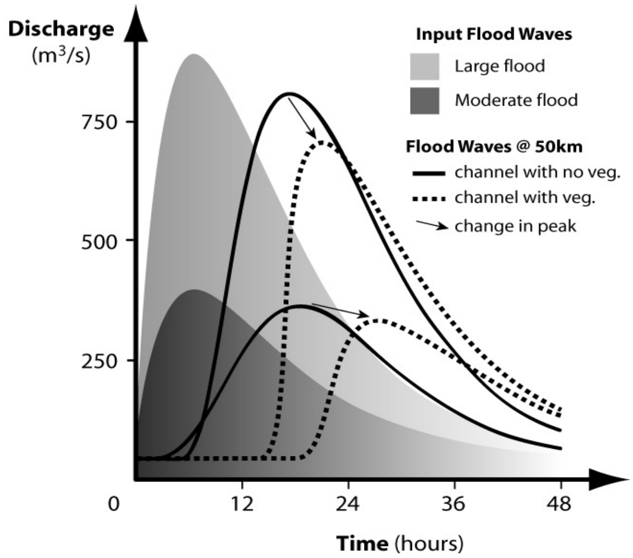

Figure 3 Numerical routing of two flood waves down a 50 km reach, with and without vegetation.

These results confirm that in channels of higher roughness the hydrograph arrives later and that the peak flow is attenuated more than for channels cleared of vegetation. Furthermore, the response to large floods differed from small floods with smaller attenuation of the peak observed in the case of the small flood. It was found that the principal changes could be described by two flood routing parameters: the wave speed and a dispersion coefficient. The wave speed describes the speed at which the discharge peak moves downstream and the dispersion coefficient quantifies the attenuation of the peak discharge and, more generally, the spreading out of the flood wave. My experiments show that the effect of vegetation on a travelling wave may be profound. Dense vegetation can slow the wave speed in some cases from running pace, 8 km/hr, to closer to a walk, 3 km/hr. These slow-moving flood waves also disperse more than their fast moving counterparts.

So, so far I have developed a new model to calculate the local resistance effect on flood stage at a cross-section, then I have quantified how it attenuates floods along a single reach of river. Next I needed to evaluate the gross impact of the change in these flood routing parameters on the hydrograph generated by an entire stream network. To do this, a second, large-scale numerical model was required.

Problem 3: Evaluating the trade-off for a whole catchment

The detailed simulations along the 50km reaches showed that the effect of vegetation on flood routing primarily causes variations in wave speed and the dispersion coefficient. This allowed me to use a much simpler set of equations and required only a small amount of input data to route flood waves down entire channel networks. By varying only the wave speed, the dispersion coefficient this simple model predicts the difference between the size of a flood wave generated by channel networks with and without riparian vegetation. The model is generic, in that it can be applied to any network of channels. To demonstrate the potential impact of a whole-of-catchment revegetation project, I have chosen a set of simulations using the channel network of the upper Murrumbidgee River (above Wagga Wagga, see Figure 4a).

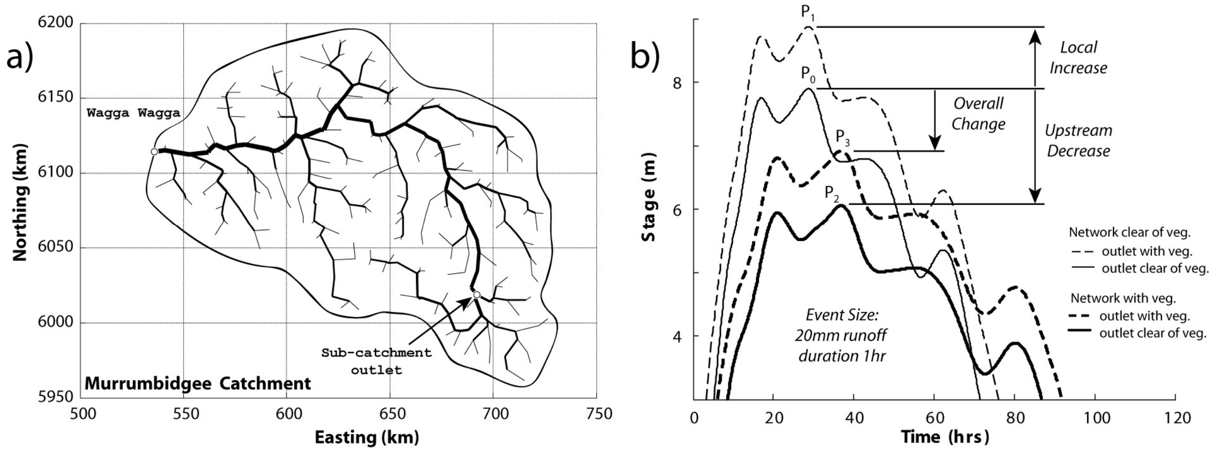

Figure 4 a) Channel network of the upper Murrumbidgee; and b) stage hydrographs at Wagga Wagga comparing the relative importance of local and upstream vegetation condition.

Two models of the upper Murrumbidgee catchment were generated, one with vegetation and one without. Rainfall events ranging in depth (mm/hr) and duration (hrs) were routed through each channel network, giving two different flood hydrographs at Wagga Wagga; we will refer to these as the inflow hydrographs. Figure 4b shows the inflow hydrographs as solid lines, with the lower curve delayed and more highly attenuated as a result of dense vegetation in the upstream network (see 'upstream decrease'). In fact, the additional resistance in the upstream network reduces the peak flow depth at Wagga Wagga from 8.0m down to just 6.1m.

However, this reduction assumes that the channel at Wagga Wagga is clear of vegetation. But if this reach also has dense vegetation, then the local stage will be higher. The dashed lines in Figure 4b show the increase in stage that results when the stage-discharge relationship is adjusted to account for the presence of dense vegetation (see 'local increase'). For this location on the Murrumbidgee, the additional resistance causes the peak flow depth to rise by about one metre. Hence, for this particular flood event at Wagga Wagga, the reintroduction of vegetation both locally, and to all of the upstream channel network, produces a flood with a reduced peak flow depth (down from 8.0m to 6.9m). For this case, the peak of the flood is actually reduced by the presence of dense vegetation through the network despite there being vegetation at Wagga Wagga. In terms of the trade-off, the effect of vegetation on the flood wave produced by the upstream network is larger than the local impact on flow depth.

Of course flow depth is not the only factor to consider. The reduction of the peak comes at the expense of an increase in the overbank duration. Duration in Figure 4b is the difference between the time at the start and end of each curve (as the channel at Wagga Wagga is 3.0m deep). Flood duration in the 'clear of vegetation scenario' (curve with peak: P_0) is 62 hours, while the presence of dense vegetation extends this by almost a day to 82 hours (curve with peak: P_3). Thus under this scenario, if overbank duration is more of a concern than peak depth, then the presence of dense vegetation is undesirable.

Implications for riparian restoration

The effect of revegetating the riparian zone on flooding can be seen as a battle between the local effect, which is to increase flood height, versus the whole of catchment effect, which is to hold back the flood, and so reduce downstream flood height. When the whole catchment is considered the latter effect can be dominant, so that result of this research demonstrates the counter-intuitive conclusion that the introduction of resistance can provide flood protection. The more comprehensive set of results from which this example is drawn, Anderson (2005), shows that the balance of the impact of replanting may fall either way. The relative impact varies depending on where the 'local' cross-section is located in the catchment, the size of the flood event considered, and of course how much of the channel network is replanted and at what density.

The question that sparked this study was whether the reinstatement of riparian vegetation was in fact going to catastrophically increase flood hazard at the scale of large catchments, by undoing over a century of vegetation removal. This research provides a clear answer to this question. Even in a large catchment, the impact of riparian restoration could be changes in peak depth and overbank duration in the order of 10-20%.

It is important to put this result into perspective. The effect of riparian revegetation on flooding in the streams of Southeast Australia will always be dwarfed by the effect of large dams, flood levees, and other major structural changes. These structures and measures provide protection far greater than any changes that might be wrought by riparian restoration at catchment-scale. The fact that in places the restoration actions may result in additional protection can be considered a bonus.

In order to solve this problem I developed and successfully tested ROVER, a completely new approach to estimating the effect of vegetation on channel resistance. I recognised that while the effect of vegetation makes floods worse at a cross-section, this must be balanced against the reduction in the size of the flood wave delivered by a well vegetated upstream channel network. Finally, I applied two different numerical models to quantify the balance between the two counteracting effects.

This research now allows managers to (a) know the absolute scale of effect of riparian vegetation on flooding (b) identify whether they ought to be concerned about the impact of revegetation on flood size in their specific catchment and (c) design where vegetation can be placed to have either the maximum or minimum effect on flood height or duration. The exciting prospect is that we can now see our main tool for river restoration also as a tool for flood management. It is not often in natural resource management that everybody wins!

References

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