CHAPTER 5

Managing the effects of riparian vegetation on flooding

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Summary

- The major effect of removing riparian vegetation and wood from streams has been the changes in channel form (widening, deepening and straightening) that have occurred. It is important to consider that we are returning vegetation to a channel system that now has a much larger flow capacity.
- The major hydrological effect of returning vegetation to streams is via its influence on roughness and flow resistance.
- Revegetating riparian zones, or adding large wood to stream channels, increases the stage of floods at a cross-section and reach scale, although in many cases the effects are likely to be small. The effect will be greatest where the vegetation is planted across the full width of a floodplain.
- Adding or removing large wood (snags) in streams has little effect on the height and duration of large floods.
- At catchment scale, the cumulative effect of riparian revegetation is to increase flood stage and duration in headwater streams (where flooding is usually not a problem anyway), but decrease flood stage in larger streams, further downstream, where flooding may in the past have been a problem (local-scale versus network-scale effects).
- Although the effect of riparian vegetation on flooding is modest in comparison to the effects of dams and river regulation, it should be considered in planning major revegetation works. The effect is largely positive for downstream catchments, where riparian vegetation will reduce the depth of flooding. The decreased flow depth comes at the cost of slightly longer flood durations.
- Riparian revegetation should be seen as a catchment scale tool that can have a beneficial effect on flooding in lowland areas. Whilst flow regulation and landuse change affect the amount of water available in floods (magnitude and frequency), riparian vegetation affects the velocity of the flood wave delivered to the stream. All of these interacting aspects need to be considered together.

5.1 Flooding issues

Large pieces of wood (snags), and riparian vegetation growing within a watercourse, have been considered to block channels, and slow down flood flow, thereby increasing flood height. As a result, for the last 150 years people have been removing vegetation from stream bed and banks in order to reduce flood risk for adjoining landuses. At present, however, replanting native riparian vegetation is the single most common stream rehabilitation activity in Australia. Nearly 80% of all stream restoration projects involve riparian revegetation, and many involve returning wood to the stream bed.

This turnaround in management approach has meant that, in the life-time of many landholders, they have seen publicly-sponsored efforts to drain swamps, to remove wood from streams, and to clear riparian vegetation. Now they see publicly-sponsored efforts to reverse this work: to replant riparian vegetation and return snags to rivers (Erskine & Webb 2003). Since much of the rationale for removing vegetation was related to flooding and drainage, it should not come as a surprise when landholders ask whether returning riparian vegetation will also lead to a return of historical flood levels. In fact, many landholders resist efforts at riparian revegetation on the grounds that it will increase flooding problems. Are they right to do so? This chapter

A well vegetated upland riparian zone. Photo Ian Rutherford.

reviews recent scientific assessments of the hydraulic and hydrological consequences of revegetating riparian zones, and of returning snags to streams. These consequences in turn have effects on flood magnitude (i.e. height or stage), and flood duration. For waterway managers, this chapter addresses the following types of issues that they might encounter:

1. A farmer will not give us permission to revegetate his stream because he is concerned that his property will be flooded. What can I say to the farmer, is this a risk?
2. If we replant a 5 metre strip of vegetation along the banks of all 1st and 2nd order streams in this 1000 km^2 catchment, what will be the effect on flood levels in the catchment as a whole?
3. If we revegetate 3 kilometres of the banks of this riparian zone, what will be the effect on flood level?

5.2 What is flooding?

Before we can discuss the effect of vegetation on flooding, we need to define what flooding is. A flood occurs when water goes over the top of a stream bank and out of the channel. The flood can also be described as a hydrograph (Figure 5.1), with a rising discharge limb, a peak, and a falling limb.

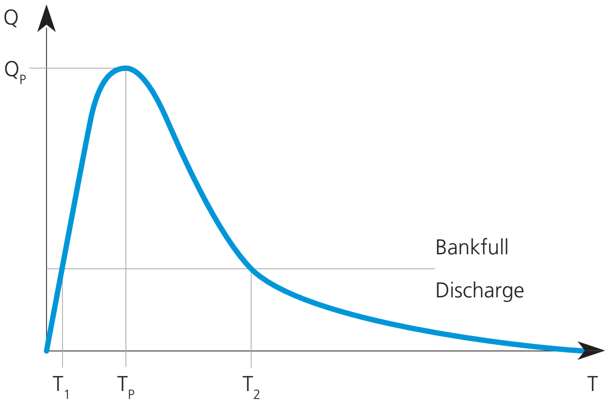

Figure 5.1. A typical hydrograph showing the change in discharge (Q) with time (T).

Catchment flood characteristics may be quantified using a variety of metrics. For this chapter interest lies in the properties of the flood hydrograph defined by the following variables shown on Figure 5.1:

~ Peak (Q_P),
~ Time to peak (T_P),
~ Duration ($T_2 - T_1$).

Other simple metrics include:

~ Flow velocity (main channel, floodplain),
~ Over-bank location,
~ Flood frequency.

A degraded lowland riparian zone. Photo Roger Charlton.

The peak of a flood. This shows that the flow out onto the floodplain can be a very slow moving pool. Photo Ian Rutherfurd.

The 'size' (or magnitude) of a flood can be measured by three related properties of the flow; the stage (or height) of the water surface[1] the duration of the flood (defined as the period of time that it is overbank), and the frequency of the flood (being how often a particular flood can be expected in a period of time). Thus, a natural floodplain could be expected to be flooded every year or two. The frequency of this flood would be 'annual' or 1–2 years recurrence interval. The stage would be defined as, for example, a "5 metre stage on the Jonesville gauge". The duration of the annual flood could vary from a few days over bank, to perhaps a week, before the water falls back within the channel. In small tributaries the hydrograph can rise and fall in hours, in large, low-land rivers, the floodplains, under natural conditions, could have stayed flooded for weeks or months.

The amount of water in a flood (the discharge) is a product of the cross-sectional area of the flow, multiplied by the velocity of the flow. The faster the velocity, the smaller the cross-sectional area, and so the lower the stage of the flood. If the flow is blocked, the velocity falls and the stage rises. A flood should be thought of as a wave of water passing down a channel, getting larger as it goes because new tributaries contribute water to the wave. Standing at one point, an observer sees the river rise and fall. This wave tends to slow down as it moves downstream, this means that the wave spreads out, or 'attenuates'. The wave contains the same amount of water, but as it slows down, the elevation of the peak of the wave (amplitude) rises, and the duration (or length) of the wave increases.

Another important influence on the size of the wave is the presence 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.

Engineers and land holders have worked to clear, straighten and de-snag channels in order to reduce the flow resistance that would slow the flood flow and attenuate the peak. The aim of all of these 'channelisation' works has been to increase the velocity of the flood wave, decrease its height, and encourage it to pass through as quickly as possible (Brookes 1988, Mason et al. 1990, Shankman & Pugh 1992). Our research question is: does **revegetation** influence the size of the flood wave?

What makes up riparian vegetation in the context of flooding?

Riparian vegetation affects flow by coming into contact with the flowing water. Thus, vegetation growing in different parts of the cross-section interact with different flows. In the bed of the channel are the submerged macrophytes (such as reeds), and the woody pieces, that interact with all flows. As we move up the stream banks the plants are accustomed to less and less inundation. Hydrophytes give way to grass, bushes and trees up the face of the stream bank. Above the top of the bank, vegetation only interacts with annual floods.

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[1] Note that 'stage' refers to the height of the water relative to some reference point, usually 'gauge zero'.

A flood wave moving down Snapes Creek in Gippsland. This photo is taken near the peak of the flood, which will return within the banks within about 12 hours. Photo Ian Rutherfurd.

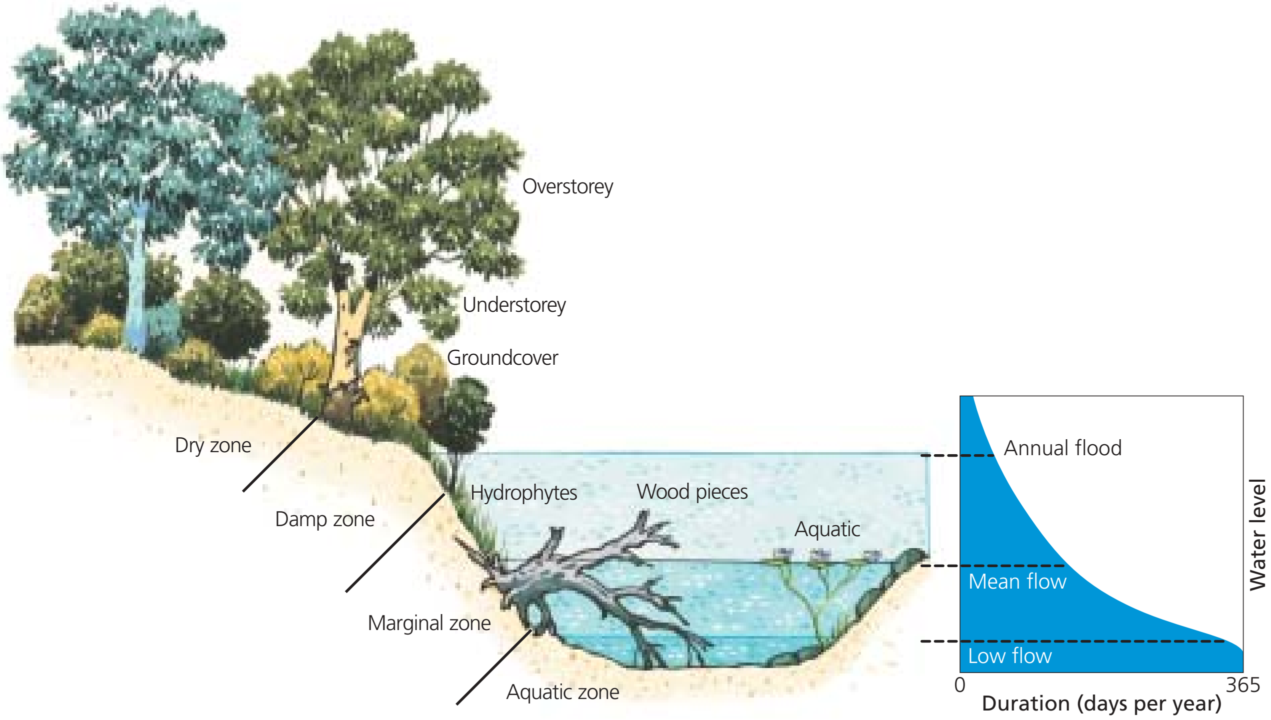


Figure 5.2. Schematic example of riparian vegetation and its interaction with flow. Illustration Paul Lennon.

5.3 What effects can vegetation have on flooding?

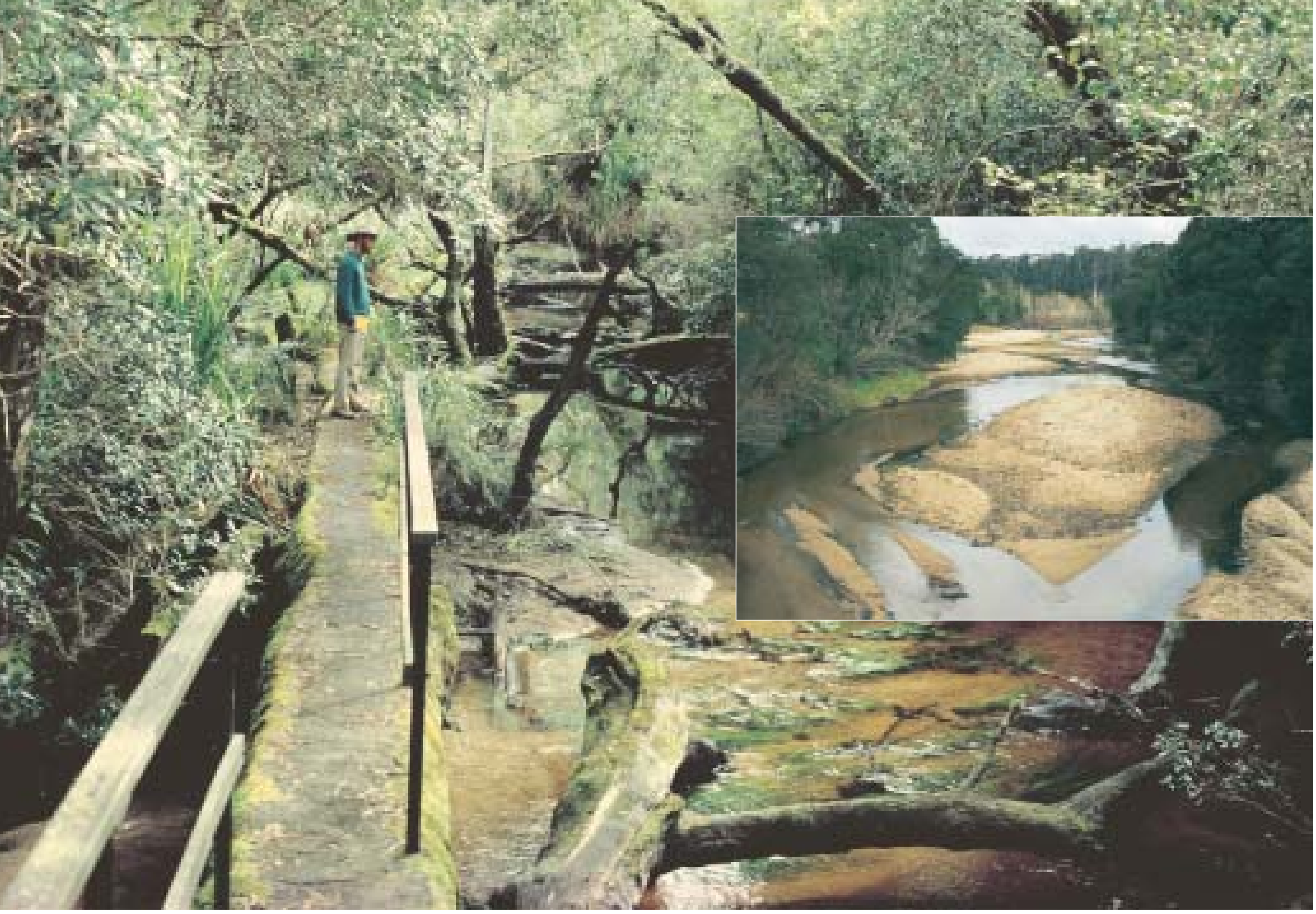
Vegetation can affect flooding in three ways: by affecting the shape and size of the stream channel (geomorphology), by altering the amount of water reaching the stream channel (hydrology), and by altering the resistance to flow (hydraulics).

Geomorphic effects of removing vegetation

When vegetation (including large woody pieces) has been removed from Australian stream channels, there are numerous reports of major changes in channel form. Such changes have included gullying, bed-deepening, and widening. There is no question that the consequences of removing vegetation on channel morphology are at least as important for flooding as are the direct effects on flow. Morphological changes to the cross-section of channels, and extension of the drainage network by gullies, alter the hydraulics and hydrology producing changes in flow and in floods.

A good example of this effect in Australia, is a comparative study by Brooks et al. (1999a, 1999b, 2003) comparing the Thurra and Cann Rivers in eastern Victoria. The contemporary condition of the Cann River differs profoundly from that which has prevailed for thousands of years, while the adjacent and undisturbed, well-vegetated Thurra system has remained relatively stable. The researchers traced a channel metamorphosis that has resulted in a 700% increase in channel capacity and 150-fold rise in the rate of lateral channel migration, changes that are attributed to clearing riparian vegetation and removing large woody pieces from the channel.

Left: Removing vegetation from the bank and catchment has led to widening and deepening. Right: Gullying triggered by catchment and riparian clearing. Both photos Roger Charlton.



Research by Andrew Brooks has demonstrated that the Cann River (inset) originally had the same form as the adjacent Thurra River, but widened and deepened in response to channelisation and riparian clearing. Photos Andrew Brooks.

Wood in streams has the potential to significantly and sometimes systematically shape channel processes across a wide range of scales (Montgomery & Piegay 2003). For example, as well as providing a direct physical barrier to flow, it affects channel form by:

~ creating steps in the longitudinal profile (Harmon et al. 1987, Keller & Swanson 1979, Marston 1982, Webb & Erskine 2003);

~ moderating sediment storage and scour within channels:
  - underpinning the forming of bars and benches (Malanson & Butler 1990, Webb & Erskine 2001),
  - regulating bedload transport (Beschta 1979, Fetherston et al. 1995), and
  - causing localised scour (Abbe & Montgomery 1996, Marsh et al. 2001).

~ contributing to the formation of pools (Buffington et al. 2002, Marsh et al. 1999, Robison & Beschta 1990, Webb & Erskine 2003) which improves habitat through the provision of cover (Hortle & Lake 1983, Richmond & Fausch 1995);

~ enhancing overbank deposition of fines, reported as the dominant deposition process on floodplains by Gurnell and Gregory (1981).

In recent years, research and experience have shown the beneficial effects of riparian vegetation on the stability of stream banks and the role of in-channel vegetation and wood in controlling bed grade and erosion. The important contribution of both to maintaining habitat complexity and biodiversity have also been accepted. This new knowledge underpins the current emphasis on reversing past clearing to improve the condition of many streams and rivers.

In this chapter we are not concerned with the effects of removing vegetation, but with the consequences of returning it. In most cases, riparian vegetation and wood is being returned to streams that have already altered the form of their channel. It is important to emphasise that revegetating streams will not simply reverse the effect of clearing the streams, returning them to their 'pre-European' form. Instead, we are considering the effects of returning vegetation to already altered channels.

Hydrological effects of riparian vegetation

Vegetation can have numerous impacts on the amount of rainfall that becomes runoff, and enters streams (Table 5.1). Although riparian zones make up only a small percentage of the total area of a catchment, they can make up a large percentage of the land adjoining first-order streams which is the main source of runoff. Overall, the main effect of riparian vegetation on hydrology (i.e. the amount of water entering streams) is on base flow rather than on flooding. Thus, the remainder of this chapter deals with the hydraulic effect of vegetation on flow resistance.

Table 5.1. Hydrological impacts of vegetation.

Role of vegetation	Mechanism
Physical impacts	
1. Interaction with overbank flow by stems, branches and leaves generating turbulence and limiting rilling and rain splash	*Quick flow **
2. Flow diversion by log jams	*Quick flow **
3. Change due to litter in the infiltration rate of flood waters and rainfall	*Infiltration*
4. Increase in turbulence as a consequence of root exposure	*Quick flow **
5. Increase of substrate macroporosity by roots which prevents slaking	*Infiltration*
6. Increase of the capillary fringe by fine roots	*Infiltration*
7. Stemflow — the concentration of rainfall by leaves, branches and stems	*Interception*
8. Condensation of atmospheric water and interception of dew by leaves	*Interception*
Physiologic processes	
1. Hydraulic lift, uptake of water from deep soil layers	*Soil moisture*
2. Hydraulic redistribution, lateral water flow to support root growth in dry soil zones which also limits soil moisture fluctuations, reducing desiccation	*Soil moisture and infiltration*
3. Water storage in large roots	*(Storage)*
4. Water storage in the stem	*(Storage)*
5. Water storage in branches and leaves	*(Storage)*
6. Evapotranspiration	*Soil moisture*

* These processes also have significant hydraulic implications.

Resistance effects of riparian vegetation at a cross-section and a reach

The scientific literature contains a number of excellent reviews on the topic of fluvial resistance; most recently works by Bathurst (1993) and Yen (1991). However, most of the work on the resistance effects of vegetation are based on studies of small vegetation elements. What is missing is a way of representing the effects of all plants, small and large. Dawson and Charlton (1987) list some of the factors that influence the magnitude of resistance offered by a plant or stand of plants:

~ the height of vegetation relative to the depth of flow,
~ plant characteristics such as stem diameter, leaf size, surface texture and specific gravity which vary with the age of the plant and often the season,
~ flexibility of the stems or the whole plant stand (e.g. in the case of a reed bank),
~ orientation of stems within the plant and their areal density,
~ degree of stem compaction with increasing flow velocity and the associated change in stand permeability,
~ distribution of individual plants within a stand, their frequency and dispersion pattern,
~ orientation of the plant with respect to the local flow direction.

Vegetation affects flood velocity, and so flood stage, in three ways:

1. by directly occupying space in the channel cross-section, and so reducing capacity,
2. by using energy in the flow (such as by vibrating), and
3. (the most important effect) is to block flow and reduce velocity.

Stream with flow close to bankfull. Note the flow in the canopy of the trees on the right side of the photo. Photo Ian Prosser.

The way to think about the effect of vegetation is in terms of 'backwater' curves. Behind each piece of vegetation that blocks the flow, the water level rises slightly as the velocity slows. This raised water level then slows the water immediately upstream, which also rises, which raises the water level upstream, and so on. The result is a curve of slower, higher, water extending upstream from the blockage. The larger the blockage by the vegetation, the higher and longer is the backwater curve. The lower the slope of the channel, the further upstream the backwater effect will extend (Figure 5.3).

A backwater curve is essentially a form of water storage. If velocity is slowed at one point, then the water will not be delivered downstream so quickly. The water that is already downstream will drain away, and so the water level will drop. Thus, slowing a flood wave will increase the depth and duration of that flood wave upstream, and the storage will produce a fall in the downstream hydrograph. The effect of vegetation is essentially a balance between slowing of the floodwave by local roughness (leading to a local rise in flood stage and increased storage) versus slowing of the flood wave as it propagates through the network (leading to a lower peak downstream, but longer duration).

The way to think about the hydraulic effect of vegetation is to consider four scales of effect:

1. the local backwater effect of a single plant and a small group of plants, then
2. to combine all of the effects of the backwaters from many plant communities at a given cross-section, then
3. combine the effect over a series of cross-sections, at a reach, and
4. finally consider the attenuation of a flood wave as it passes through the whole catchment (see Figure 5.4).

Reeds (macrophytes) provide high resistance to flow until they lie down, when they can actually reduce resistance. Photo Guy Roth.

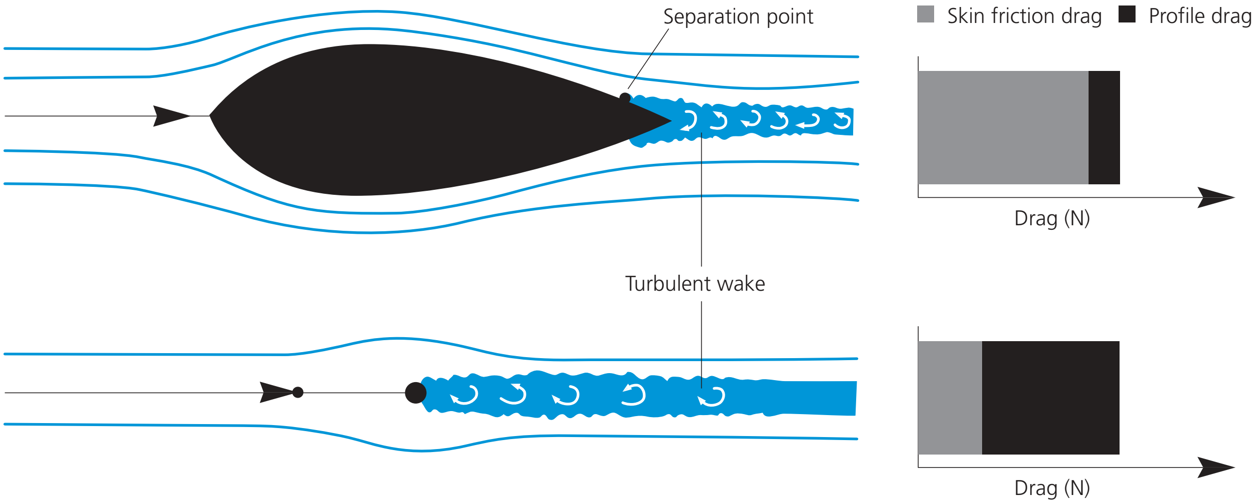
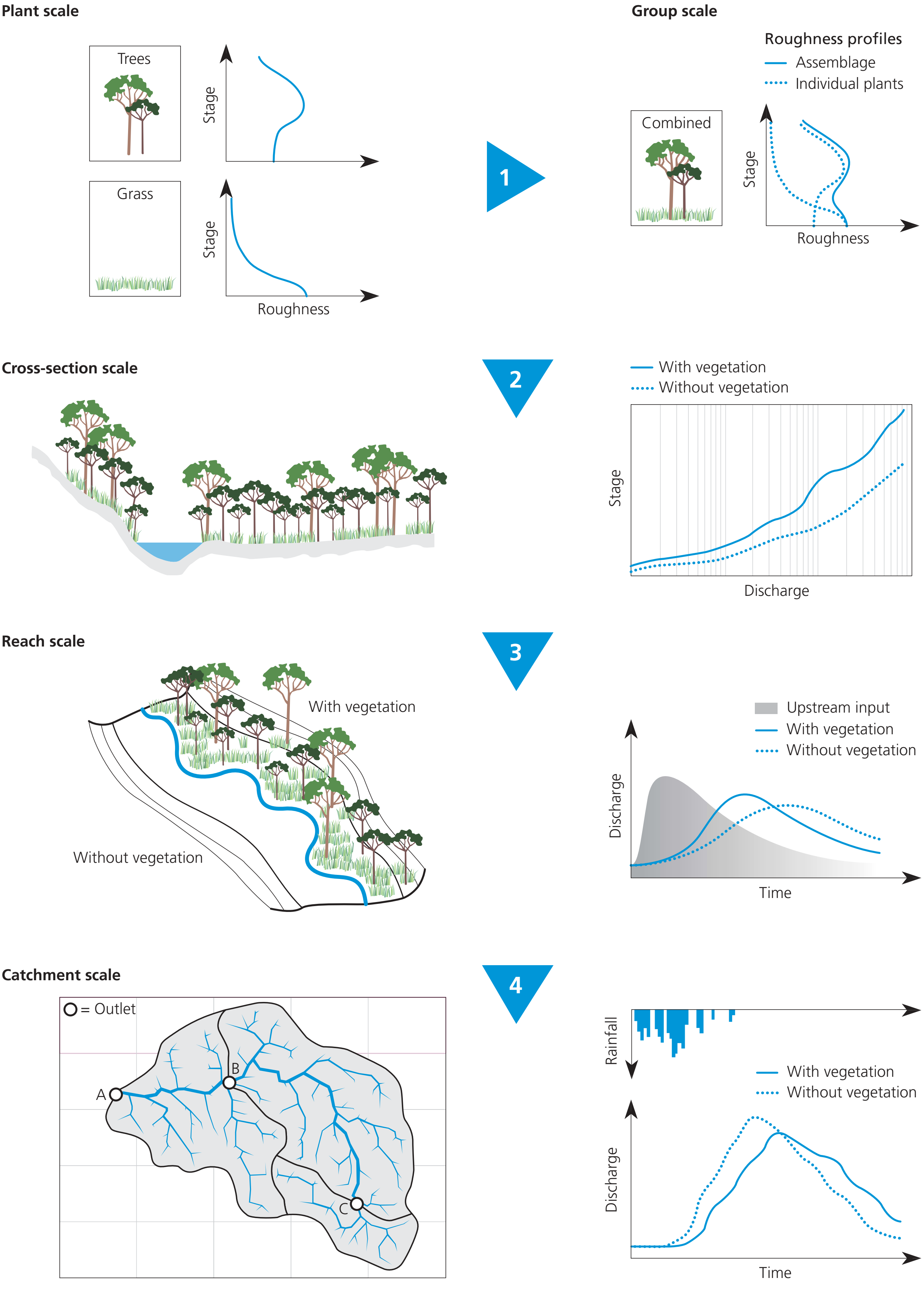


Figure 5.3. Comparison of the drag of streamlined and cylindrical obstructions (adapted from Vennard & Street 1982, p. 97). Vegetation produces 'drag' on the flow. Two very different sized objects can produce the same amount of drag due to its two components skin friction (i.e. the length of contact with the water) and profile drag (which is a description of how 'streamlined' the object is).

Figure 5.4. Conceptual diagram of the effect of riparian vegetation on discharge at the scale of a plant, a cross-section, a reach, and a catchment. Figure redrawn from diagram provided by Brett Anderson.



A comment on compound channels

Before we discuss the effect of vegetation on hydraulic resistance, it is important to mention compound channels. Riparian vegetation occurs at the interface between the channel and the floodplain. Even without vegetation, this is a complicated hydraulic environment, with the high velocity flows in the channel interacting with the low velocity flows on the floodplain. One of the key effects of riparian vegetation is to alter the hydraulic relationship between the floodplain and the channel.

There are excellent reviews of compound channel hydraulics by Knight and Shiono (1996), and Helmio (2002). As the floodplains of a compound channel are inundated, the conveyance of the floodplains is initially small by comparison with that of the main channel. Consequently, the flow velocity on the floodplains is much lower than in the main channel. The velocity difference results in a zone of turbulence at the interface between the two flows, often described as a vertical shear layer. Extensive three dimensional mixing of main-channel and flood plain flows produces a momentum transfer across the interface leading to velocity reduction in the main channel. The penetration is reduced as riparian vegetation density increases, which in turn, further reduces the velocity in the main-channel (Naot et al. 1996).

The relative effect of riparian vegetation on momentum transfer depends a great deal on whether the stream is straight or sinuous. For example, Burkham (1976) shows that flow resistance is low where the channel is straight and parallel to the floodplain, but high where the channel meanders across the floodplain. In his analysis of three floods down the Gila River in Arizona, Burkham (1976) observed that roughness (Manning's *n*) (definition in box below) decreased by an average of 30% where floodplain trees were cleared. Thus, in relative terms, revegetating the riparian zone of a straight stream will have more effect on flooding than it will on a meandering stream.

The effect of individual plants on roughness

The effect of vegetation on roughness varies dramatically with flow depth. For example, when we consider grasses, at low flows the water flows through and around the grass, and the grass will provide maximum resistance to flow. As the depth of flow increases, the grass will be submerged, then it will probably be pushed down by the flow, which will reduce the resistance. This is because:

- the volume density of stems/foliage (collectively called biomass) is the primary determinant of the magnitude of flow roughness for plants,
- plant flexibility causes streamlining of stems/leaves under flow pressure that may reduce flow resistance by over 50% (where flow pressure is either energy or velocity driven by channel slope),
- vegetation roughness profiles exhibit distinct characteristics over two different depth ranges. The ranges are defined by whether the plant is emergent or submerged.

What is 'roughness'?

If you have ever tried to work out discharge, flow depth or channel dimensions to carry a particular flow, you have probably needed to estimate a roughness coefficient, the most common being Manning's *n*. Simply put, the amount of water that can pass a particular cross-section depends on the slope of the reach, the area of the channel, and the resistance to flow in the channel. These variables are embodied in Manning's equation (see below) in which, Q is discharge, A is the cross-sectional area, S is slope, R is hydraulic radius (area divided by wetted perimeter) and the resistance is lumped into a single coefficient, Manning's *n*.

$$Q = \frac{AR^{2/3}S^{1/2}}{n}$$

Although this formula has been criticised, it remains the standard method for estimating flow velocity and discharge in ungauged sites. Thus, Manning's *n* is a key parameter in water resources work, including floodplain management, stream restoration, and the design of hydraulic structures.

Manning's *n* typically ranges from 0.01 in smooth concrete channels with no obstructions to 0.10 in streams with large amounts of large woody pieces and vegetation that impedes flow. Rarely, values as high as 0.2 have been used. We will use *n* as a surrogate measure for resistance in streams associated with vegetation.

Stream roughness coefficient tables have been developed for vegetation in Australian rivers and can be found under tools and techniques on the rivers website — www.rivers.gov.au

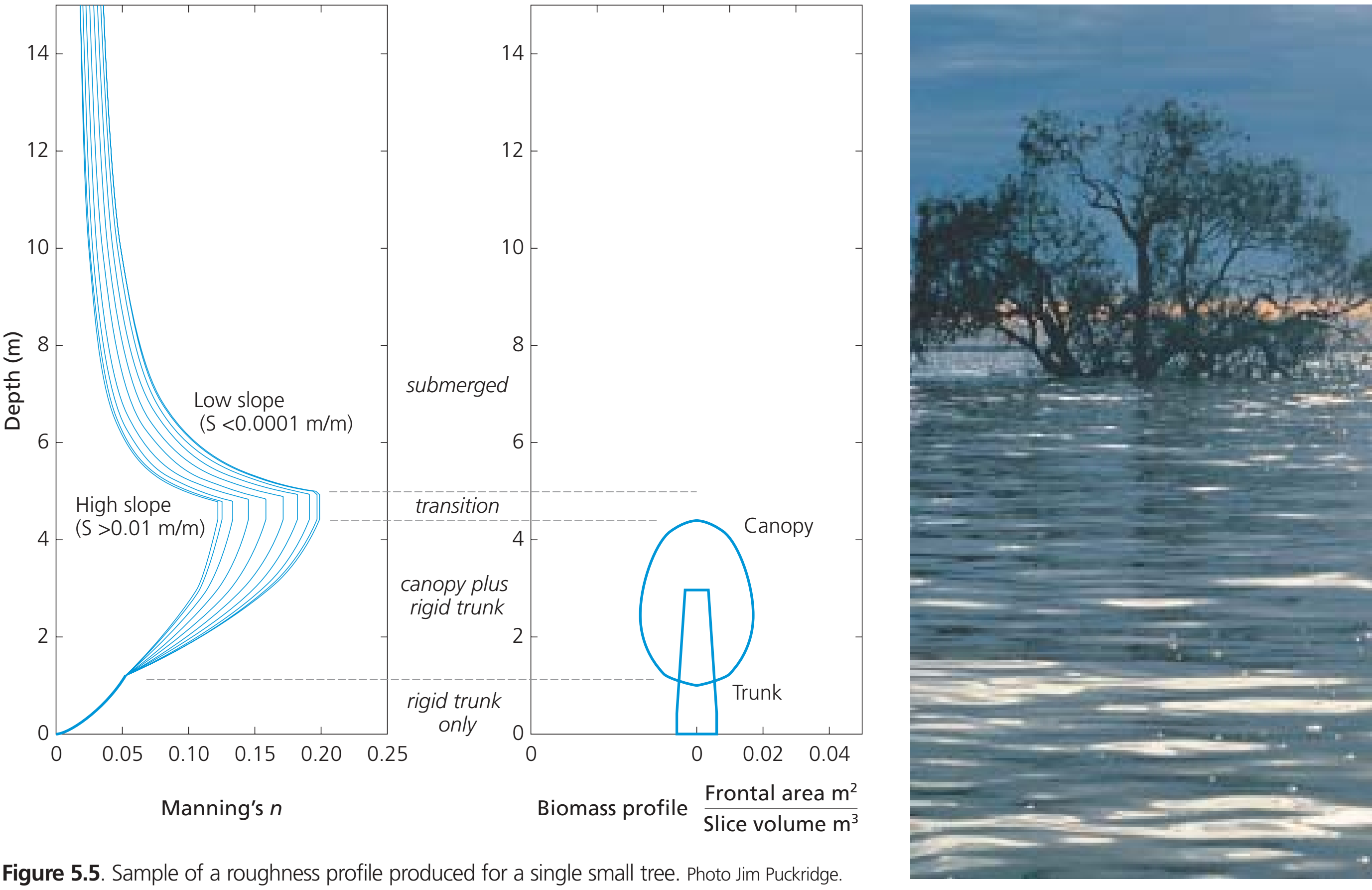


Figure 5.5. Sample of a roughness profile produced for a single small tree. Photo Jim Puckridge.

Roughness effects of vegetation communities

Vegetated channels have consistently higher roughness than equivalent channels (i.e. channels of the same size and shape) without vegetation. Although we can use a roughness of 0.05 as a general estimate for vegetated channels, the roughness effect varies with stream slope, stage and discharge. The usual effect is for the roughness to decline as the bed of the stream is drowned out, then the roughness reaches a maximum as the grass, and the canopies of bushes intersect the flow. The general rule of thumb is that the **lower** the slope of the stream, the greater the roughness effect of the vegetation.

Roughness effects of large wood in streams

A comprehensive review of the literature regarding the physical significance of wood in streams was completed by Gippel et al. (1992). With regard to the hydraulic significance of wood, this review, and the associated and subsequent experimental and field results (Gippel 1995, Gippel et al. 1996a, Gippel et al. 1992, Gippel et al. 1996b, Shields & Gippel 1995), represents the seminal work in the area. In the next sections we summarise this work. Table 5.2, for example, illustrates that clearing timber out of streams always reduces roughness, but the amount varies greatly. In large channels, such as the Murray River below the Hume Dam, removing the snags produced only a small decrease in roughness (0.037 to 0.033), whereas in the Deep Fork River in Oklahoma clearing reduced roughness from 0.15 to 0.04. This means that removing snags may have only a limited effect on flooding but, as described earlier, have a major effect on channel depth, width, and on loss of aquatic habitat.

The hydraulic effect of adding large wood in streams

Millions of logs have been removed from Australian streams to reduce flooding (Erskine & Webb 2003). We are interested now in the flood consequences of putting logs back into streams. In this section large wood will be referred to as snags. Snags have a small, to insignificant, effect on the frequency or duration of large floods (i.e. perhaps greater than the 20 year flood). However, snags can increase the duration of smaller floods (i.e. the length of time that floods are on the floodplain). By 'smaller' floods we mean the 1 to 2 year events. Clearly, the larger the snag in relation to the size of the stream, the greater the effect, so a given snag will have a relatively greater effect on a smaller channel. In general, snags will **not** affect even small floods when:

Table 5.2. Field measurements of the roughness due to wood in streams (expanded after Gippel et al. 1992). Australian rivers in blue.

Source	Site and treatment	Roughness (Mannings *n*)	
		obstructed	cleared
*Kikkawa et al. (1975)	Channelised reach of Gono River, Hiroshima (*n* estimated)	0.040	0.035
*Shields and Nunnally (1984)	De-snagged U.S. rivers and streams	0.050–0.045	0.045–0.035
*Gregory et al. (1985)	Clearance of debris dams in Highland Water, Hampshire (low flow measures)	0.516	0.292
*Taylor and Barclay (1985)	De-snagged reach of the Deep Fork River, Oklahoma (*n* estimated)	0.150	0.040
Shields et al. (2001)	Cleared and snag-obstructed reaches of the South Fork Obion River, Tennessee	0.053	0.043
*S.R.W.S.C. (1981)[1]	Clear and snag-obstructed reaches of the Wannon River, Victoria	0.079	0.036
*Binnie and Partners (1981)	Channel clearing, Ovens River, Victoria	0.045	0.035
*M.D.B.C. (unpublished)[2]	De-snagging of River Murray, Hume to Yarrawonga (*n* computed by model)	0.037	0.033
Gippel (1999)	Clear and snag-obstructed reaches of the Edward River, Victoria	0.130–0.056	0.060–0.050

* Sourced from Gippel et al. (1992). (1) S.R.W.S.C. State Rivers and Water Supply Commission. (2) M.D.B.C. Murray-Darling Basin Commission.

~ The projected area of the snag is less than 10% of the area of the cross-section. The 'projected' area is the area of the snag in a two-dimensional cross-section across the stream. A log needs to be very large to occupy 10% of the cross-section of a third order or higher stream.

~ The snag is angled at 40° to the flow (i.e. with the upstream end of the log against the bank).

~ The snag is submerged in a backwater at higher flows. That is, the level of the flood could be hydraulically controlled by some feature downstream. For example, a bridge crossing downstream may constrict the flood

Left: Large wood in the bed of the Campaspe River. Replacing wood at these densities would probably not lead to an increase in bankfull flood stage. Photo Ian Rutherfurd. Right: Typical natural loads of timber in a stream. Photo Simon Treadwell.

flow. This constriction will then produce a backwater upstream. If a log falls within that backwater, then it will have no hydraulic effect on flow at all during that flood. As the flood level falls, however, the log will eventually produce its own shorter backwater. The same principle applies to a backwater produced by a log: if another log falls within that backwater, it will have no hydraulic effect on flow. A rule of thumb for this effect is that a log that is five to six log diameters upstream of another log of similar (or larger) size, will not affect flood level, because it will be within the backwater of the existing log.

- Several snags in line will not produce any more afflux than a single snag, so long as each piece is located within two times the diameter of the next piece up or downstream. Thus, up to six pieces can be placed parallel to each other in a line. In general, any piece of wood will add little extra afflux (i.e. rise in water level) if it is placed within four log diameters of the next piece.

Chris Gippel has measured the effect of removing logs in several situations. The following three examples illustrate that removing even dense piles of logs in a large stream does not produce dramatic change in water level at bankfull flow.

- In a 30 metre wide channel, 2 metres deep, a log 20 metres long and 1 metre in diameter (i.e. blocking one third of the channel area), in a flow of 1.5 m s^{-1}, causes a 5% increase in water surface elevation (100 millimetres).
- Seven LWD accumulations were removed from the Tumut River (40 metres wide, 2.5 metres deep) and the effects on flow conveyance measured (Shields & Gippel 1995). Removing the snags reduced upstream water surface level by about 0.2 metres, and increased conveyance by about 20% at bankfull flow. The afflux (i.e. the backwater effect) extended for about 3 kilometres upstream. The effect on major floods would be negligible.
- Removing 96 items of woody debris from the channel of the Lower Thomson River did not produce a measurable effect on the height of bankfull flow.

This new understanding explains why removing one or even several pieces of wood from a stream in most situations has a negligible effect on local flooding, either in height or duration. However, there is plenty of evidence of the negative effects of removing wood, including channel deepening and widening, loss of aquatic habitat, and infilling of pools that are essential refugia over summer low flows. Unless a hydraulic survey shows that removing wood will result in significant reduction in flood effects, it is best to 'let sleeping logs lie'.

5.4 Quantifying the effects of vegetation and wood on reach scale hydraulics

Our research has also examined the hydraulic (flood) effect of revegetating a reach of river. Fread (1991) conducted numerical tests using a one-dimensional flow routing simulation on a lowland river where a segment of the reach was assigned either an elevated or depressed roughness coefficient (±20%). The results of his trials are shown in Figure 5.6 for elevated roughness, which demonstrates substantial changes in stage (maximum deviation of 0.6 metres over a base of 6 metres, a change of around 10%). These model results are also supported by the work of Romanowicz et al. (1996), who showed that reach flow characteristics are most changed by conditions at a flow constriction, and least affected by average roughness over, for instance, the floodplain. Thus, local regions of high roughness extending continuously in a direction at right angles to flow can act as substantial flow controls.

Representing the reach scale effect of revegetating streams of different size

The following examples show the hydraulic effect of revegetating the riparian zones of typical small, medium and large rural streams. The variables that control the effect of the vegetation are described in Table 5.3.

Developing a model of vegetation resistance

After reviewing over 200 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 then three factors that moderate the impact of vegetation: 2) free space; 3) flexibility and 4) flow depth. We developed a numerical model

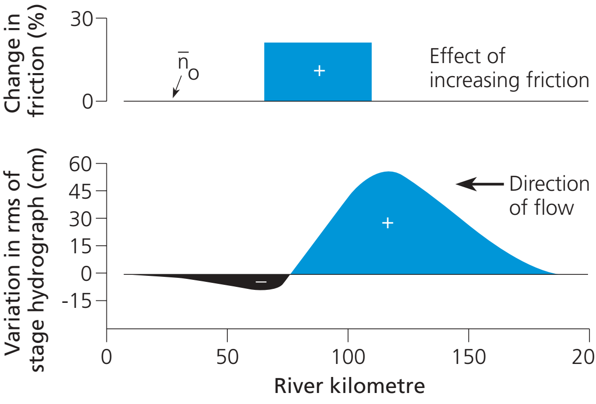


Figure 5.6. Sensitivity of stage to a discrete zone of increased roughness (after Fread 1991, p. 430).

Table 5.3. Variables that control the effect of vegetation on stream roughness and stage. The second column shows the effect of the variable on vegetation roughness.

Variable	Effect on hydraulics	Direction of change
Cross-sectional area of the channel	The bigger the channel, the smaller the relative effect of the vegetation	Bigger cross section = smaller blockage
Position of vegetation on the boundary	The lower in the cross section, the greater the effect	The lower the vegetation on the bank = higher the stage
Density of vegetation across the channel	Greater density of vegetation provides greater resistance	Greater the density = higher stage
Density of vegetation along the stream	Generally, the greater the density of the vegetation along the banks the greater the flow resistance	Greater planting density along the banks = higher stage
Length of bank vegetated	The backwater will extend from the upstream end of a clump of vegetation	Longer vegetated zone = longer flood effect
Slope of the channel	Everything else being equal, the lower the slope, the greater the relative effect of vegetation on roughness	Greater slope = less roughness effect

(ROVER — **R**esistance **o**f **V**egetation in **R**ivers) that represents these vegetation characteristics in a hydraulic model. This model allows us to estimate the effect of vegetation on flood stage. Table 5.4 provides some more detail on each mechanism, and gives an indication of the size of the impact.

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 is 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 (snags).

How will planting riparian vegetation affect flood height in a long reach?

A local rise in flood stage at one point will lead to a decrease in flood stage downstream due to storage. 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 breaks new ground by considering vegetation resistance as a property that varies with flow depth, and changing the resistance increment according to channel

Table 5.4. 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 to 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

Rules of thumb for the effect of vegetation on floods levels

Flood levels at a cross-section

1. If vegetation does not block more than 10% of the cross-sectional area, it will probably have little effect on stage. This is why vegetation has more effect on small streams than large ones.
2. If the stream has a width/depth ratio greater than 17, vegetation is unlikely to have any affect on flooding because the cross-section is too wide and shallow (Masterman & Thorne 1992).
3. Vegetation in the bed has more influence on flow than does vegetation on the top of the bank.
4. If the vegetation lies down during a flood, then it probably has little effect on the flood stage.

Flood levels at catchment scale

5. In what sort of catchment types will flood stage be most affected by riparian revegetation? The answer is where the catchment:
    a. is long and thin in shape,
    b. has a high drainage density, and
    c. has a short, steep headwaters section, and then a long low-gradient section.

Photo John Dowe.

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 50 kilometre 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 5.7 shows the results for four typical simulations. Floods of two different sizes were injected at the top of the reach; a large flood (light blue shading) and a moderate flood (dark blue shading). The two events were routed down an identical 50 kilometre reach, once with dense vegetation flanking the channel (dotted lines) and then with no vegetation present (solid lines).

Figure 5.8 (overleaf) shows flood hydrographs for three different cross-section shapes. The input hydrograph is the solid line, and the dotted line is the same hydrograph when it has travelled 10 kilometres further downstream. Note that in this simulation, vegetation delays the peak by between 5 and 10 hours, depending on the shape of the cross-section. The wider and shallower the cross-section, the greater the attenuation due to vegetation. Note too, that the effect of the vegetation is much less with a large input discharge.

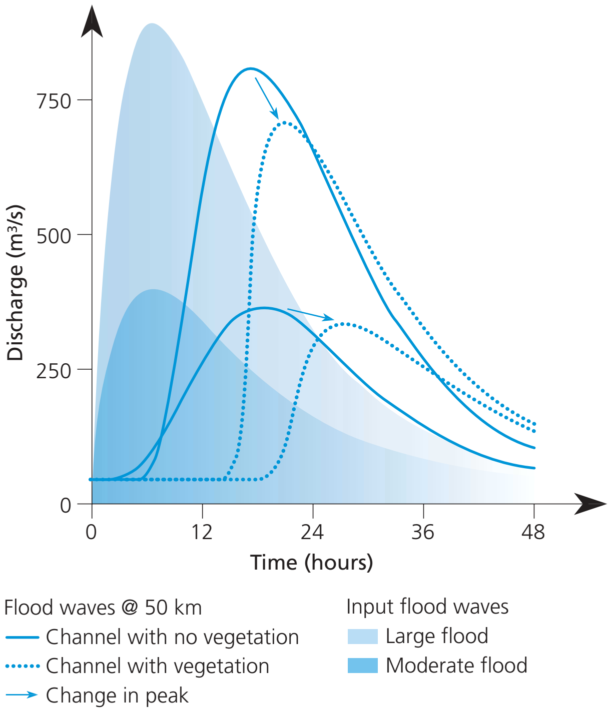


Figure 5.7. Numerical routing of two flood waves down a 50 kilometre reach, with and without vegetation. Source: Brett Anderson (unpublished thesis).

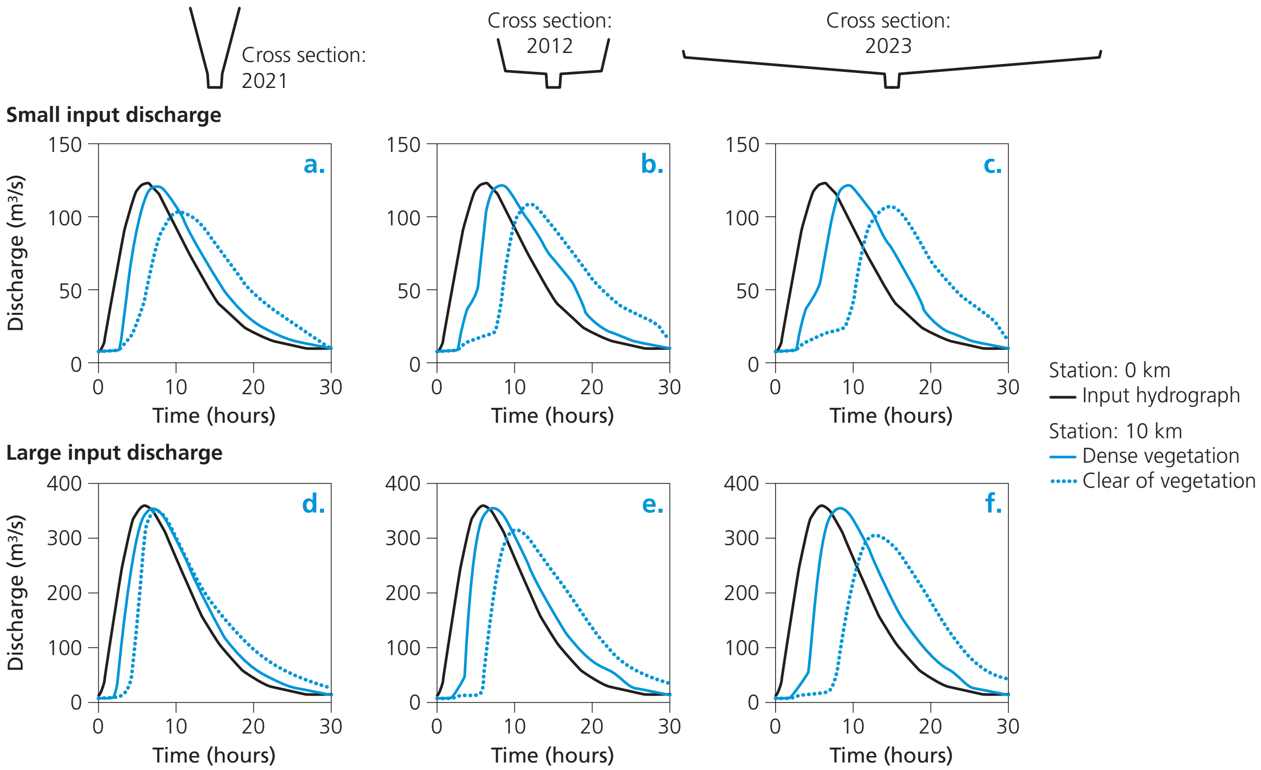


Figure 5.8. Sample of simulated waves computed for different channel shapes, showing the input hydrograph and hydrographs at the 10 kilometre station for channels with vegetation, and clear of vegetation. Source: Brett Anderson (unpublished thesis).

These results confirm that, in channels of higher roughness, the flood arrives later and that the peak flow is attenuated when compared to 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. The effect of vegetation on a travelling flood wave can be profound. Dense vegetation can slow the wave speed in some cases from running pace, 8 kilometres/hour, to closer to a walk, 3 kilometres/hour. These slow-moving flood waves also disperse more than their fast moving counterparts.

Figure 5.8 demonstrates the effect of channel dimensions and discharge size on the reach scale attenuation effect. These results show:

1. small discharges are relatively more attenuated than are large discharges (compare a and d),
2. for large discharges, the flood wave is slowed more in channels with wide floodplains (compare d and f).

So far, we have developed a new model to calculate the local resistance effect on flood stage at a cross-section, then we have quantified how it attenuates floods along a single reach of river. Next, we need 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 is required. This is the Murrumbidgee model that we describe next.

Photo Ian Rutherfurd.

5.5 What will be the effect of revegetation on flooding at the scale of a whole catchment

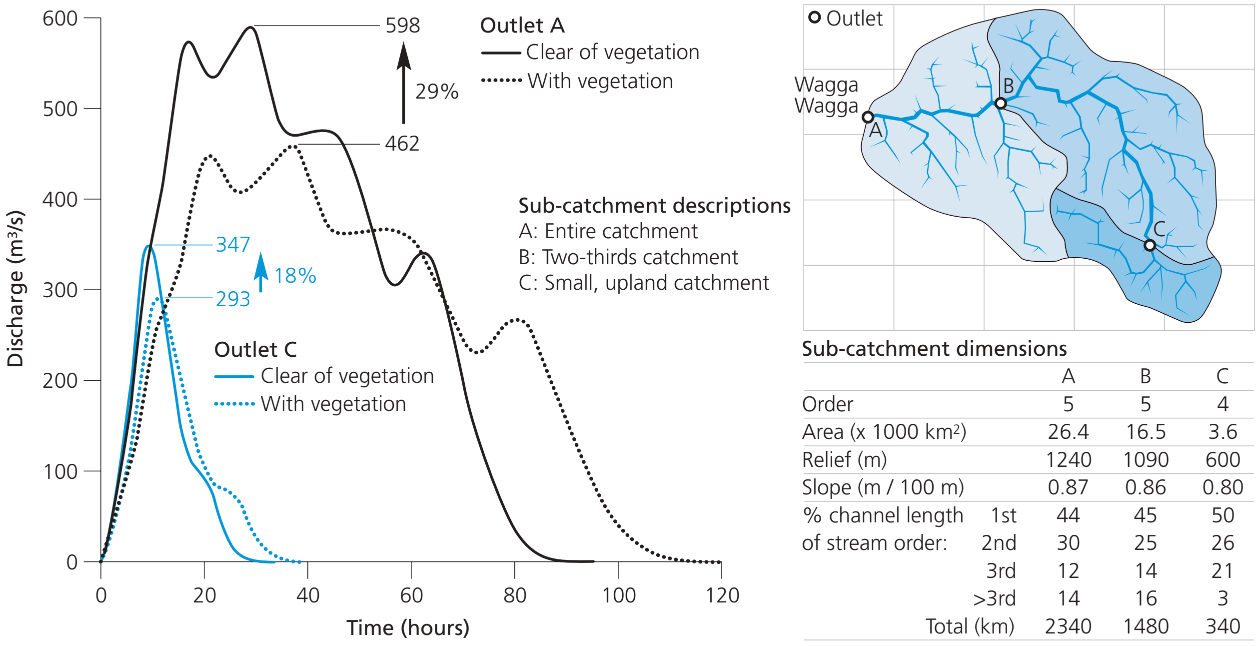
The detailed simulations along the 50 kilometre reaches (previous) showed that the effect of vegetation on flood routing primarily causes variations in wave speed and in the dispersion coefficient. Thus, by varying only the wave speed and the dispersion coefficient we can predict the difference between 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, we have chosen a set of simulations using the channel network of the upper Murrumbidgee River above Wagga Wagga.

Revegetating the entire riparian zone of the Murrumbidgee River has a considerable effect on the size and timing of the flood peak reaching different outlets (Figure 5.9). At outlet C (the upstream site) the peak is attenuated by 18%, at the larger outlet A, the peak is attenuated by 29%.

Two models of the upper Murrumbidgee catchment were generated, one with vegetation and one without. Rainfall events ranging in intensity (millimetres/hour) and duration (hours) were routed through each channel network, giving two different flood hydrographs at Wagga Wagga; we will refer to these as the inflow hydrographs. Figure 5.10 (overleaf) 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 8.0 metres down to just 6.1 metres.

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 5.10b 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 1.0 metre. Hence, or 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 8.0 metres to 6.9 metres). 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.

Perhaps more important than the effect on discharge, is the effect on stage shown in Figure 5.10d. This illustrates the combined effect of cross-section roughness, and network attenuation. At the upstream



Sub-catchment dimensions

	A	B	C
Order	5	5	4
Area (x 1000 km^2)	26.4	16.5	3.6
Relief (m)	1240	1090	600
Slope (m / 100 m)	0.87	0.86	0.80
% channel length of stream order: 1st	44	45	50
2nd	30	25	26
3rd	12	14	21
>3rd	14	16	3
Total (km)	2340	1480	340

Figure 5.9. Effect of revegetation on discharge at two stations (upstream and downstream) of the Murrumbidgee, for two recurrence interval flows. The lumpy character of the hydrograph is a product of different tributary inputs (modelled for 20 millimetres rainfall for 1 hour duration).

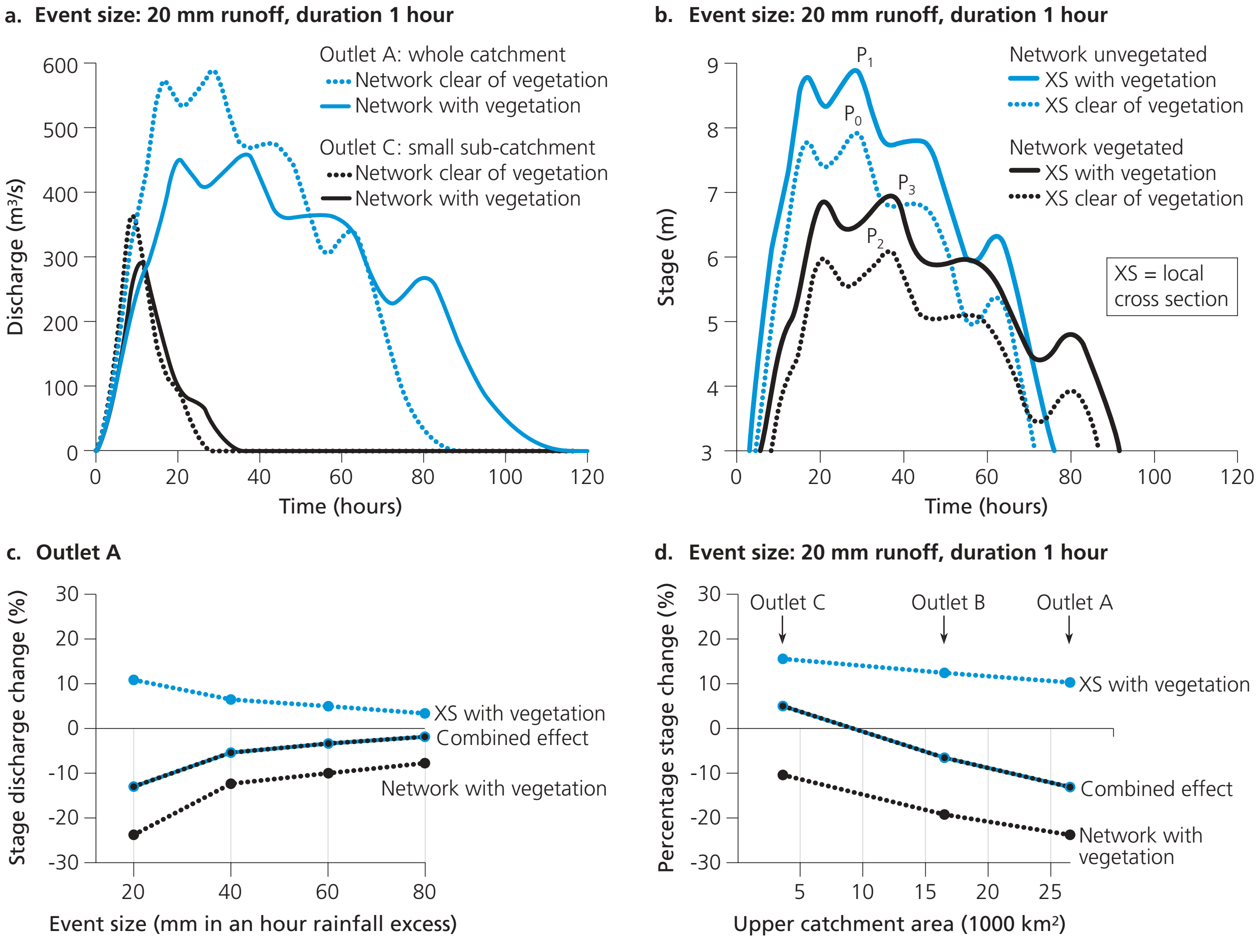


Figure 5.10. a) and b) Stage hydrographs at Wagga Wagga comparing the relative importance of local and upstream vegetation condition. c) Percentage stage change at Wagga Wagga (Outlet A) for a given event size. d) Percentage stage change down the catchment (from outlet C to A) with the addition of riparian vegetation.

outlet, the combined effect of cross-section resistance and network attenuation is to increase the stage of a given flood when vegetation is added. By contrast, attenuation of the flood wave downstream means that outlets B and C both show a decreased stage for the same recurrence interval flood. That is, the effect of riparian vegetation is to decrease flood depth at downstream sites. In this model example, the stage falls by about 10% at the downstream outlet C. Thus, the effect of the riparian vegetation is to slightly increase the depth of flooding in catchments less than a few thousand square kilometres, and decrease the depth of flooding in larger catchments. The other consequence of decreasing flood depth is that flood duration must increase to compensate.

You will also note, from Figure 5.10c that the size of this effect decreases with the size of the flood or storm event. Stage is 20% higher at the upstream catchment outlet for a 20 millimetres per hour storm, but this effect disappears with an 80 millimetres per hour storm. Thus, the effect will be most marked at small and moderate sized floods.

5.6 Implications for riparian revegetation

The effect of revegetating the riparian zone on flooding can be seen in the differences 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, demonstrating 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 total riparian revegetation could be changes in peak depth and overbank duration in the order of 10% to 20%.

What are the impacts of riparian vegetation on flooding relative to other impacts?

It is important to put this result into perspective. The effect of riparian revegetation on flooding in the streams of south-east 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. Figure 5.11 shows that large dams in Victoria have reduced the frequency of the natural 1 year Average Return Interval (ARI) flood to 2 to 15 years, and the natural five year ARI flood to 6 to 100 years. By contrast, the effect of returning riparian vegetation would be to alter the duration and timing of the flood rather than in dramatic changes in its recurrence interval.

Research by the former Cooperative Research Centre for Catchment Hydrology has demonstrated the effect of landuse change on hydrology. The main focus of this work has been on catchment water yield, rather than on flood magnitude, frequency and duration. Reforestation and pine plantations are able to halve water yield from a catchment. Similarly, revegetating the pasture Glendu catchment in New Zealand with pines, led to a halving in peak monthly runoff per hectare, suggesting a major impact on the size of floods (Fahey & Jackson 1997) (Figure 5.12). At catchment scale the effect of landuse change (e.g. reforestation) would have a more substantial effect on the depth and duration of flooding (i.e. the amount of water in a flood), whereas the effect of riparian vegetation is to alter the timing of the delivery of that flood.

Over coming decades, it is likely that catchment reforestation will be combined with riparian revegetation. The effect will be to reduce discharge (due to landuse effects) and to slow the downstream passage of flood peaks. The total effect could be substantially reduced flood levels in the long, lowland sections of streams. Having said this, the effect will almost certainly be mediated by the continuing effect of dams along the path of large, regulated streams.

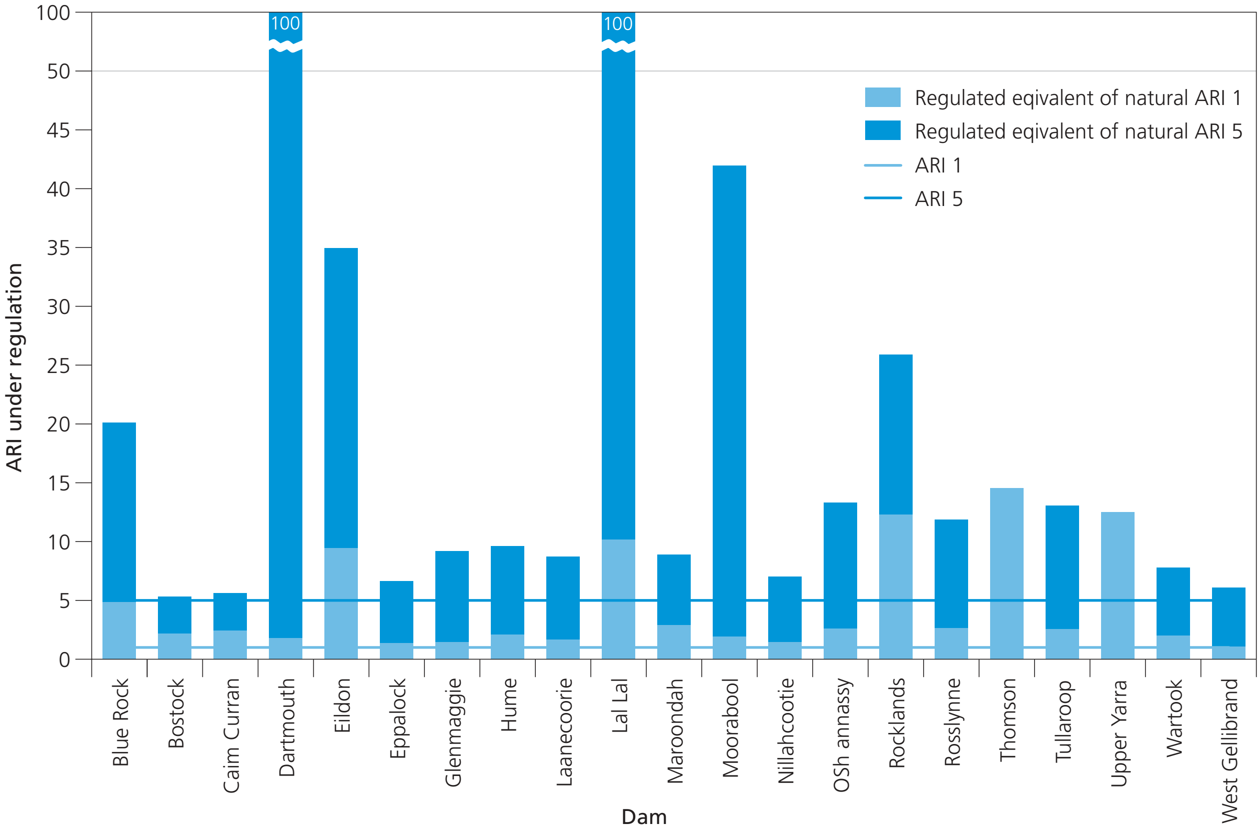


Figure 5.11. Change in the average recurrence interval of the natural (pre-regulation) 1 and 5 year floods in Victorian catchments with large dams. Data from an unpublished Master of Science thesis by Deb Woods, University of Melbourne, former Cooperative Research Centre for Catchment Hydrology.

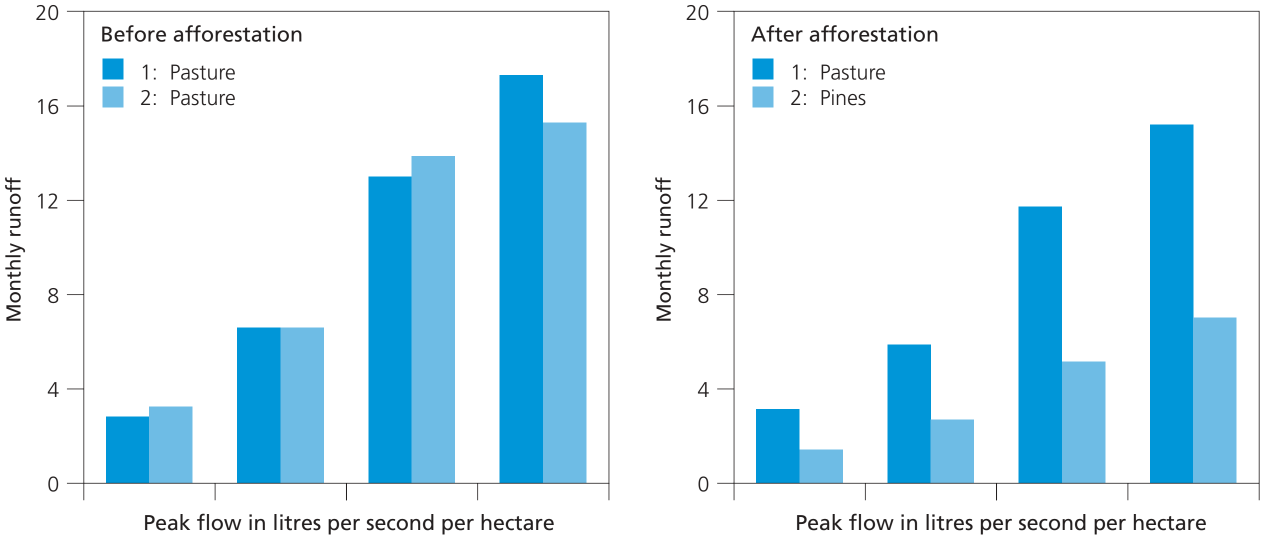


Figure 5.12. Peak monthly runoff per hectare after revegetating the pasture Glendu catchment in NZ with pines (from Fahey and Jackson, 1997).

Principles for managing the effects of riparian vegetation on flooding

To summarise:

~ The major effect of returning vegetation to streams will be through its influence on roughness and flow resistance. Adding or removing large wood (snags) in streams has a very little effect on floods above bankfull capacity.

~ Revegetating riparian zones, or adding large wood to stream channels, will increase the stage of floods at a local reach scale, although in many cases the effects are likely to be small. The effect will be greatest where the vegetation is planted across the full width of a floodplain. But, the effect of increasing flood level at one site is to hold back the flood-waters so that the downstream flood stage will be lower.

~ At catchment scale, the cumulative effect of riparian revegetation is to increase flood stage and duration in headwater streams (where flooding is usually not a problem anyway), but decrease flood stage in larger streams, further downstream, where flooding has in the past often been a major problem.

~ Although the effect of riparian vegetation on flooding is modest in comparison to the effects of dams and regulation, it should be considered in planning major revegetation works. However, the effect is largely positive for downstream catchments, where riparian vegetation will reduce the depth of flooding. The decreased flow depth comes at the cost of slightly longer flood durations at these lower depths.

~ Riparian revegetation should be seen as a catchment scale tool that can have a beneficial effect on flooding in lowland areas. Whilst flow regulation and landuse change affect the amount of water available in floods (magnitude and frequency), riparian vegetation affects the velocity of the flood wave delivered to the stream. All of these interacting aspects need to be considered together when planning changes in catchment land use, including revegetation.

A flood interacting with riparian vegetation. Photo Ian Rutherfurd.

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