Abstract

Traditional approaches to flood management have often conflicted with what is now regarded as being best practice for river and catchment management focused on ecological and water quality outcomes. Maximising the extent of riparian vegetation, including in-channel vegetation, has long been recognised as critical for improving aquatic ecosystem complexity and diversity, and for stabilising channels, and thereby reducing erosion. The conventional wisdom amongst floodplain managers has been that optimal flood mitigation is best achieved through having the channel network designed to be as hydraulically efficient as possible, and typically this has meant clearing in-channel vegetation, straightening and armouring channels. However, it has long been appreciated that these types of activities can lead to increased channel instability, thereby threatening assets, and are deleterious to many ecosystem processes within the river channel network. There is also increasing evidence that by not accounting for the geomorphic feedbacks between in-channel vegetation and channel stability or catchment scale flood wave dynamics, that vegetation removal or suppression (intentional or otherwise) can lead to increased downstream flooding and a cascade of unintended consequences. It has also become increasingly apparent that across government there are policies focused on different aspects of river and floodplain management that can sometimes conflict, and when viewed collectively are unnecessarily complicated. In this paper, based on work in the Hunter Valley, we propose a simplified unifying framework for viewing all aspects of river and floodplain management through the lens of the maximisation of in-channel woody vegetation. By maximising in-channel (ideally native) woody vegetation four complementary objectives can be achieved:

I. Minimising channel erosion, thereby protecting riparian land and reducing sources of sediment to the downstream waterbodies.
II. Maximising sediment deposition and nutrient retention within the channel network, improving downstream water quality and reduced “leakiness” of ecological pathways (e.g. carbon and nitrogen cycling).
III. Maximising ecosystem functioning through increased habitat complexity (e.g. increased woody debris; low flow pool habitat availability)
IV. Minimising flooding in the lower catchment, through increasing-channel roughness in upstream channels with reduced flood celerity in key tributaries.
Riparian Vegetation Management as a Unifying River management Framework.

Introduction
Catchment, river and flood management are complex policy areas for various levels of government, which often result in a myriad of overlapping and sometimes contradictory policy frameworks. In a recent review of the management of unregulated rivers in the Hunter (Brooks., et al., 2016; Kemp et al., 2017) it became apparent that, despite a daunting array of policy and management frameworks, most management objectives could be practically achieved through a focus on the management of riparian vegetation. We concluded, therefore, that by maximising in-channel (ideally native) woody vegetation four complementary objectives can be achieved:

I. Minimising channel erosion, thereby protecting riparian land and reducing sources of sediment to the downstream waterbodies.

II. Maximising sediment deposition and nutrient retention within the channel network, improving downstream water quality and reduced "leakiness" of ecological pathways (e.g. carbon and nitrogen cycling).

III. Maximising ecosystem functioning through increased habitat complexity (e.g. increased woody debris; low flow pool habitat availability)

IV. Minimising flooding in the lower catchment, through increasing-channel roughness in upstream channels with reduced flood celerity in key tributaries.

In this paper, we review evidence underpinning these conclusions, along with knowledge gaps, associated with the role that riparian vegetation plays, and could play, as a flood management tool in the Hunter. The evidence underpinning the first three aspects is less controversial than that surrounding the role of vegetation as a flood management tool, and will not be the primary focus of this paper. For a recent review see Kemp et al. (2017).

The Role of Riparian Vegetation
There is now abundant scientific evidence demonstrating that the maximisation of in-channel and riparian vegetation can help to achieve the first three of the objectives outlined above. In the Hunter, where riparian vegetation regrowth has occurred in some tributaries as much by happenstance as by design, there is anecdotal and some robust scientific evidence of its associated benefits to channel stability, post-flood channel recovery, increased baseflow, the persistence of pools, and improved water quality and ecological function. As graphically demonstrated in Figure 1, the channel of Wollombi Brook was largely devoid of riparian vegetation in the 1960s, and at this time channel and bank erosion was a major problem throughout the Hunter, delivering considerable volumes of sediment to the lowland reaches of the Hunter River and Newcastle Harbour. By the early 2000s, this situation had changed dramatically, as extensive natural vegetation regeneration has very effectively stabilised the channel. As is evident from the images, the large “Pasha Bulker” flood of June 2007 caused very little channel erosion, resulting if anything in sediment deposition within the channel (David Outhet, pers. Comm., 2007). Also apparent from the set of images is the considerable degree of in-channel roughness associated with the mass of in-channel vegetation. In the remainder of this paper we explore the implications of all of this extra roughness on flood behavior.
Figure 1. Sequence of photographs taken from the Warkworth bridge over the Wollombi Brook, in 1967, Feb and June 2007, showing the dramatic increase in riparian vegetation over four decades, and the associated improvement in channel stability and in-stream ecosystem diversity.
The role of riparian vegetation in flood mitigation

Local Context of Flooding in the Hunter

The last thirty years have seen an abeyance in catastrophic flooding in the Lower Hunter, partly owing to episodes of drought and protection offered by reservoirs upstream. Despite this, the threat of flooding remains high, particularly for population centres at Maitland and surrounding agricultural land (Figure 2). Glenbawn Dam and Lake St Clair (Figure 2), which together regulate some 1600 km$^2$ or 7% of the total Hunter catchment, offer modest protection against flooding in the lower Hunter, but large areas of the catchment remain unregulated. In the lower Hunter, flood control works including levees were constructed after the destructive flood in 1955, which in Maitland alone killed 24 people and inundated 2180 houses (WMA Water, 2015). However, the levees do not protect against floods on the scale of 1955 or even lower floods, and dams at spillways upstream of Maitland were overtopped in 1991, 1997 and 2007. Singleton is located almost entirely on the floodplain of the lower Hunter River. Its flood protection levees are designed to accommodate floods at the 1955 flood level (14.31 m) (Paterson Consultants, 2012), but residential buildings are required to be 0.48 m higher to allow for climate change effects on flood levels. It is noteworthy that the flood height in June 2007 was 13.35 m, which was the second highest recorded stage since gauge recordings commenced in 1913. Model results of flooding in Wollombi Brook (BMT WBM, 2016) noted inundation of the township of Broke by floods with average return intervals of more than 100 yr, with considerable flooding extent downstream of Brickmans Bridge (stn. 210135, Figure 2). However, the model was sensitive to channel roughness (Manning’s n parameter), particularly in areas upstream of Brickmans Bridge. This represents the actual sensitivity of floods in the Wollombi, among other things, to changes in floodplain and in-channel vegetation, and sediment transport conditions that result in a change in channel dimensions. An increase of 1.0 m was recommended to Flood Planning Levels and Flood Planning Areas in this part of Wollombi Brook (BMT WMB, 2016).

Figure 2 Hunter catchment showing places discussed in text.
**Flood Attenuation**

Attenuation is the natural dissipation of a flood wave in a downstream direction. It produces a downstream decrease in peak flow velocity and flood stage, and an increase in flood duration. The degree of attenuation increases with drainage area, sinuosity, and overbank flooding, which increases the storage of flood waters and slows the celerity or speed of the flood wave. Celerity is defined as the distance travelled divided by the peak to peak travel time with units of velocity in m s\(^{-1}\). Riparian vegetation, particularly forest, that is established both within the channel and on the floodplain is a substantial component of channel roughness (Acrement and Schneider, 1989) and increases flood attenuation. Attenuation may be counterbalanced to some extent with tributary inflows downstream. In the Hunter, a historical reduction in the attenuation of flood peaks has resulted from historical attempts to reduce flow resistance through channel clearing and desnagging, channel straightening, and the construction of levees. These interventions combined with indirect feedback effects and land use change resulted in bank and bed erosion and the creation of enlarged, incised channels in the Upper Hunter, which isolated the channel from its floodplain except during severe floods. In the Lower Hunter, sand liberated by channel erosion upstream was deposited in the channel bed, raising bed levels by up to 2 m and increasing flood frequencies at Maitland and Singleton.

Research conducted elsewhere in the world has shown that well vegetated riverine corridors may reduce flood severity at the catchment scale by slowing down the passage of flood flows, restoring the connection between the channel and its floodplain, particularly in the upstream reaches, and increasing the temporary storage of flood waters (Lane, 2017). Restoration strategies that increase channel and floodplain roughness have the potential to decrease both the celerity of the flood wave downstream and the peak flood discharge.

Preliminary results on the extent to which woody vegetation has increased in the riparian zone of rivers in coastal valleys of NSW, and in particular in the Hunter Valley, over at least the last three decades. The positive effect this increase has had on flood wave celerity are reported in Brooks et al. (2016), Cohen et al. (in review) and Fryirs et al. (in press). This work will provide the foundations upon which further research can be undertaken on these topics. A summary of recent changes on Wollombi Brook (Cohen et al., in review) is outlined below.

Analyses of change over time in downstream flood wave propagation for Wollombi Brook since the 1980s strongly suggest that the regrowth of woody riparian vegetation has had a substantial and measurable effect on flood wave travel times and hydrograph shapes through reductions in the rates of flood event rise and fall (Cohen et al., in review). This analysis focused on Wollombi Brook because:

1. Wollombi Brook in particular and the Hunter catchment generally showed some of the most active regrowth of riparian vegetation in a statewide analysis of NSW main-stem rivers;
2. Wollombi Brook has three gauging stations with continuously recorded water level data concurrently available at all three stations from the 1980s onwards.

Gauged streamflow records provide information about large floods in November 1984, June 1989, April 2008, September 2008, February 2013 and April 2015. The 2007 event could not be used for the analysis because downstream tributaries peaked before the
upstream ones, due to the movement of the rain cell. Detailed spatial information is available for precipitation, wave, wind and streamflow levels for the more recent floods, including the April 2015 “Super Storm”, which was generated by an intense low-pressure system known as an East Coast Low. Catchment precipitation for the six days during and after the storm is shown in Figure 3. Figure 4 plots flood hydrographs against time for six flood events with peak stages of 4.5 – 10 m between 1984 and 2015 over 54 km of channel length. Figure 4a-d shows that flood travel times have increased threefold, from 301 – 501 minutes for events in the 1980s (Figure 3a-b), to 903-1665 minutes post-2000 (Figure 3c-g). This equates to a threefold decrease in flood wave velocities from 1.81 - 3.01 m/s in the 1980s to 0.53 - 0.98 m/s, for events post-2000 (Cohen et al., in review). It is significant that the 2007, 2013 and 2015 events have the slowest flood travel times and celerities despite being the first, second and third largest of the seven assessed events. Increasing flood magnitudes should result in decreasing flood travel times because of decreasing relative roughness (Anderson et al., 2006), but this is not observed for Wollombi Brook. This suggests that channel relative roughness has continued to increase through time since the 1980s for all flood stages up to 11.4 m that are recorded at the Wollombi Brook Brickmans Bridge (210135) gauging station.

![Figure 3](image-url) Precipitation over Wollombi Brook at Warkworth during the April 2015 ‘Super Storm’
Figure 4. Wollombi Brook examples of flood wave celerity and hydrograph shape changes for six flood events in 1984, 1989, 2007, 2008, 2013 and 2015. Note the substantial reduction in travel times and wave celerities since the 1980s, and that the post-2000s larger floods also have lower velocities and travel times than the smaller 1980s floods. Note that the blue line (A) = station 210135 and is the most upstream station; red line (B) = station 210028; green line (C) = 210004 and is the most downstream station.

The changes depicted in Figure 4 show a halving of flood wave celerity in Wollombi Brook from the 1980s to the 2000s, with the reducing trend continuing into the 2010s. Not only has flood wave celerity been drastically reduced to consistently around 0.5-0.98
ms⁻¹ from 1.8 - 3.0 ms⁻¹ in the 1980s, the nature of the hydrographs themselves appear to have transformed. In the 1984 and 1989 events, flood hydrographs show pronounced peakedness with rapid rising and declining limbs at the Bulga (210028) and Warkworth (210004) gauging stations (Figure 4a, b). This stands in contrast to the Bulga (210028) and Warkworth (210004) hydrographs from 2008, 2013 and 2015, which have gradually rising and receding limbs at these middle and lower catchment gauging stations (Figure 4e-g). Although this pattern cannot be expected to occur across all east coast river systems that vary substantially in channel size, slope and relative roughness from vegetation regrowth, it highlights the potentially large changes that in-channel vegetation can have on channel erosive capacity as indicated by flood wave celerities, and the changing nature of flood travel times in catchments up to 2,000 km² in size. This is in keeping with modelled impacts of increasing vegetation density in channel networks (Anderson et al., 2006) and has important implications for the prediction of flood peak arrival times to the lower end of catchments.

Cohen et al. (in review) confine their analyses to flood stage because of uncertainties in high flow ratings and discharge estimates for the Wollombi Brook gauging stations. Significant uncertainties remain unresolved in the Wollombi Brook discharge records.

Fryirs et al. (in press) presented a comparison of travel times and celerities for the 1977 and 2007 flood events for the Hunter River at Singleton and Greta. For the much larger Hunter River (16,400 km² at Singleton), travel times and celerities for these two exceptionally large flood events that rose to gauge heights of 14.01 m and 14.14 m, respectively, differed by only 10%. Again for the Hunter River, rating table uncertainties for high flow events currently preclude analyses based on discharge. Peak discharge for the 1971 event is estimated as 462,000 MLd⁻¹ in contrast to 193,000 MLd⁻¹ for the 2007 event, probably because the 2007 event does not include "breakaway flow out of Doughboy Hollow" (Anthony Belcher pers. comm. 31/07/2017).

Will Natural Flood Management work on a catchment the size of the Hunter? Attenuation effects generally decrease with increasing catchment size. Significant attenuation of floods has been observed after rehabilitation on small catchments in the UK (Byers 2011; McLean et al., 2013; Jacobson et al., 2015; Clilverd, 2016; Dixon et al. 2016; Lane 2017; Metcalfe et al., 2017). Intermediate size catchments have been studied in the US by Woltemade and Potter (1994 - 700 km²) and Jacobson et al. (2015). Lane (2017) argues that unambiguous evidence of effective flood attenuation is not yet available even in small catchments (Patinson and Lane, 2012). But circumstantial evidence of the link between vegetation and flood hydrology is available for the Hunter over timescales from a few decades (this report) to centuries (e.g. Hoyle et al., 2008). In large catchments, the hydrological response to climate and land use change becomes increasingly hard to detect owing to large variations in land cover (Bloschl et al., 2007).

If the primary objective in the Hunter is to reduce flood peaks on the lowland floodplains, particularly in the vicinity of the two main towns, Singleton and Maitland, the tantalizing evidence from the Wollombi, and the more circumspect evidence from the Hunter mainstem, raises a number of questions that we currently don’t have answers for. In particular, we need to establish what is the theoretical potential attenuation in tributary catchments with different catchment areas, slopes and relative flood magnitudes? Is there greater attenuation achieved by re-vegetating lower gradient reaches than higher gradient reaches? Should some tributaries be left unchanged, so that tributary peaks are kept in a non-synchronous state?
Can we quantify the likely effects on flood frequency, duration, intensity and peak heights?
The link between riparian zone management and flood risk is specific to each catchment and even to each flood (Patinson and Lane, 2012). Attenuation depends on the structure of the drainage basin, and the relative influence of restored tributaries. The concept remains to be tested in hydrologically variable catchments such as many of the perennial streams in eastern Australia.

What scale of intervention is required? What length of channel requires re-vegetation to achieve an acceptable level of flood mitigation, and which tributaries should be prioritised? The establishment of riparian vegetation in a large catchment, where the riparian forest might represent <5% of the catchment area, is unlikely to produce a measurable reduction in runoff. Attenuation effects will be enhanced where broad floodplains or terraces are more frequently inundated. In steep, headwater locations with gradients exceeding 1 in 50 (0.0205) attenuation does not occur because kinematic waves do not develop (Henderson, 1966). Hence, the scale of floodplain and channel restoration may need to be larger than is currently practised in most catchments, where restoration projects have been started (Sholtes and Doyle, 2011).

How effective is vegetation in attenuating moderate floods compared to large floods? Flood wave celerity is partly dependent upon stage, reaching a peak in most rivers around bankfull stage with a second maximum achieved with significant inundation of the floodplain (Knight and Shiono, 1996). Intense (i.e. flashier) floods with a higher peak to volume ratio tend to attenuate more owing to floodplain storage (Woltemade and Potter, 1994). Comparisons need to be made on floods with similar times to peak, noting the return interval of the event. This should be tackled using the empirical evidence as well as by modelling approaches. Modelling of synthetic reaches with HEC-RAS suggests that vegetation is most effective on floods of moderate magnitude with return periods of between 2 and 50 yr (Anderson et al., 2006; Sholtes and Doyle, 2011). Greater effectiveness is achieved if a connection can be re-established between the channel and the floodplain in mid and upstream reaches (Woltemade and Potter, 1994; Sholtes and Doyle, 2011; Rak et al., 2016).

What is the variability of storm tracks across the catchment, and what type of storms are most important in flood generation? How does this interact with the tributary network, and which tributaries should be prioritised for restoration? What is the effect of antecedent conditions on the effectiveness of flow attenuation and runoff generation? All things being equal, storms that move downstream towards the catchment outlet would result in a greater peak flow than storms tracking towards the headwater region of the catchment. Increased vegetation cover in the catchment as distinct from increased riparian vegetation would lead to a decrease in streamflow, including a reduction in surface runoff during flood events. However, catchment vegetation and land-use have a diminishing effect on the flood magnitude during extreme events with ARI >50-100 years.

What is the effectiveness of restoration of various Hunter tributaries on downstream attenuation at Maitland and Singleton? This question concerns the whole of catchment flood routing. Rehabilitation on a reach changes the timing of flood peaks, but also the potential for flood convergence downstream, as peaks delayed in upstream reaches may coincide, or be out of phase with, peaks from tributaries located further downstream.
Many of the measures of flood routing rely upon desynchronising runoff-generating areas or tributaries to reduce this concentration. Slowing the flow in all tributaries may produce a peak flood in the lower reaches that remain synchronised. Historically, the most catastrophic floods in the lower Hunter have arisen from the convergence of floods in the Upper Hunter and Goulburn rivers, and also convergence in the Lower Hunter and Wollombi Brook. Hence, delaying peaks from the Wollombi should have a measurable effect on lower Hunter peaks.

Can we quantify the effects of vegetation and form roughness? How does the resistance component from vegetation change with stage? How does roughness vary with vegetation structure and species? How does it change the flow field in the river corridor? Models of flow resistance offered by stiff vegetation (i.e. trees) show that it increases with flow depth and water velocity, although there is a maximum roughness for each vegetation type depending on the discharge, cross-sectional area and channel slope (Anderson et al., 2006; Hoyle et al., 2012). Channel roughness is therefore dependent upon flood stage and vegetation type (leaf density and type, stand density, flexibility). The effects of flexible vegetation are harder to measure, with larger differences in roughness of different species, flexibility and leaf type, but flexible vegetation generally provides lower resistance to flow. Roughness owing to vegetation is often incorporated into the Manning equation (Hammer and Kadlec, 1986; Pearlstine et al., 1985), but there are often additional dynamic components from complex reciprocal adjustments between flow and vegetation (Knight and Shiono, 1996; Wilson et al., 2003). Secondary effects can lead to the creation of stable bars, modifying the bed morphology and channel cross-section. Vegetation may also increase velocities in some parts of the channel depending on flow depth and bank cohesion, and redirect flow towards less vegetated areas, promoting incision and meander migration (Tsujimoto, 1999; Bennett et al., 2002; Järvelä, 2002). Additional roughness may then be generated by the transition in planform from braided or wandering to meandering (Davies and Gibling, 2010). In the Hunter, the critical issue is the channel cross-sectional area and the extent to which vegetation can increase roughness, and to a lesser extent, the resulting channel capacity for overbank flow.

What is the likely time lag between revegetation and an effective reduction in flood severity downstream? Increasing floodplain roughness by planting or allowing regrowth of riparian forest probably represents the most cost-effective method of modifying flood routing, but the full benefits of revegetation may take years to establish.

Way forward to resolving the potential for using vegetation and a flood management tool.
A thorough analysis of the effect of riparian vegetation on flood hydrology requires a combination of evidence from historical observations within the period of reliable streamflow records and modelled evidence based on Hunter and synthetic river reaches. These two strands of study need to be supported by smaller studies of vegetation dynamics and roughness effects to better understand the various components of the distinctive hydrology of the Hunter catchment, its riparian ecology, and floodplain dynamics. Combining these approaches will provide different insights into catchment processes and timescales. It is important to note that modelling approaches are not independent of the field analysis since models of catchment/reach response to changes in riparian condition are heavily dependent upon empirical measures of hydraulic roughness created by riparian forest and wood debris. Without accurate estimates, and
an understanding of processes and the evolution of channels in the Hunter, the
information derived from catchment models is of limited value.

Quantifying the recent impacts of riparian vegetation on flood hydrology in the Hunter River Basin

There is a general appreciation of the value of riparian vegetation on channel and floodplain for increasing the resistance to flow, but quantitative evidence of its effectiveness on flood hydrology have so far been lacking especially for large catchments (Lane, 2017). This is partly because there has been insufficient research to establish causal links between Natural Flood Management and its downstream effects (Dadson et al., 2017). Long-term information from streamflow records is required because major floods are reasonably infrequent, and studies need to include hydrological data from more than one event to establish the existence of a consistent change in hydrology. It is important that prospective studies establish proper experimental controls and collect accurate baseline data. In the Hunter, a full appraisal of the effectiveness of riparian vegetation requires examination of the recent hydrological effect of vegetation change at stations from tributaries elsewhere in the basin to test the trends evident here. As such, further insights can be gained into flood routing in reaches with complex histories, trajectories of change, and with different sediment and vegetation characteristics. However, this requires accurate measurement of high water levels and accurate high-stage ratings. Accurate ratings at high flow stages are often problematic owing to difficulties gauging flood flows. In the Hunter and elsewhere in New South Wales, there has been a systematic effort by WaterNSW to improve the high flow end of rating curves that were often poorly constrained by historical streamflow gaugings undertaken at minor to moderate flood flow stages. Since the breaking of the Millennium Drought in 2010, these efforts have substantially improved in-channel flow estimates for recent floods, although considerable uncertainties remain as to how, or whether, to apply recent data to backwards revisions of historical rating curves, especially where discharges were estimated by extrapolation from lower flow gaugings, and where significant changes to channel cross-sectional form has occurred.

The Wollombi Brook analysis should be extended to other areas of the Hunter that have experienced differences in the spatial extent and degree of vegetation change, using the Pages River as a control catchment, albeit accounting for the differences in sediment type and channel slope. A comparison of recent flood hydrographs in different Hunter tributaries might shed light on regional variations in flood type (arrival time, peak discharge/flood water yield), and the effect of planform type (straight, meandering), density and type of riparian vegetation (cleared, restored), and type of channel-floodplain-terrace morphology, valley width, sediment type. Hydrological trends identified in Wollombi Brook and other Hunter tributaries need to be compared to rivers elsewhere in coastal NSW that have experienced recent changes in the density of riparian vegetation as part of a broader meta-analysis. In the NSW south and central coasts, there are statistically significant declines in total annual discharge since the early 1990s, but the same trend is not evident in the northern NSW coast. Although not all catchments have suitable pairs or larger numbers of trunk stream gauging stations suitable for such analyses, it may be possible to formulate and test a hypothesis that significant regrowth of riparian vegetation can be detected at single gauging stations through changes over time in the shape, rate of rise and rate of fall in time series records of flood events. The practicality of exploring such a hypothesis across SE Australia could be tested by examining trends in hydrograph shapes at key Wollombi Brook and Hunter catchment sites where evidence from paired gauging stations for flood attenuation is strong.
Objective measures of the effectiveness of riparian vegetation need to be chosen. For example, reductions in peak discharge, peak velocities and flood wave celerity, together with quantitative measures of the downstream effectiveness of this change in populous areas. Ideally, measures chosen should resonate with the local rural and urban communities.

**Catchment modelling of riparian vegetation influences on flood attenuation**

Catchment-scale modelling can be used to address a number of questions listed above, including the effectiveness of Natural Flood Management (NFM) in large catchments (Ballard et al., 2012), quantification of the riparian vegetation effect on flood frequency, duration, intensity, scale of restoration required, relative effects of flood stage and intensity, flood routing, and the wider benefits of NFM in the Hunter. The use of relatively simple, ID models such as HEC-RAS (USACE 2008) are attractive because they do not require time-consuming and expensive computations required for the analysis of larger catchments, or the associated difficulties of calibrating models of this scale. Vegetated channels where velocity changes with stage require unsteady hydraulic models. HEC-RAS and all hydrological models can handle any channel shape. HEC-RAS can also differentiate between overbank (or overbench) and in-channel roughness, discharge, velocity. Most importantly, LiDAR data and for bigger channels, bathymetric survey data, are needed to set up a robust 1D, 2D or 3D model. These are based on extensive flume tests but have simplified vegetation zones and are less well verified by field data. Note that 1D models do not explicitly account for 2D and 3D aspects of energy dissipation due to turbulent exchange at the interface of floodplain and channel flows or momentum lost in transverse flows around meander bends. Instead, they compartmentalise channel and floodplain flow, and changes to reach sinuosity is simulated by changing the longitudinal channel length relative to the floodplain length (Sholtes and Doyle, 2011). More complex, 2D models have been used successfully (see review in Corenblit, 2007). Some of these models incorporate sediment transport (e.g. Guan and Liang, 2017), bench accretion (Crosato et al., 2011), or floods (Bertoldi et al., 2014). TUFLOW FV may be serviceable for subcatchments of the Hunter, and has been used to model whole catchments of this scale (BMT WBM, 2015). Simpler, heuristic methods may be used to analyse attenuation of flood flows in various land use and channel change scenarios in small reaches or subcatchments (e.g. Dixon et al., 2016). For flood routing above Maitland, a whole-of-catchment model will be required that at least includes all areas above the tidal zone. A critical outcome of this research should be the recalibration of existing flood models with parameters that incorporate the recent increase in riparian vegetation within the channel and river corridor.

**The effect of vegetation on the flow field in the channel and adjacent floodplain.**

The roughness created by riparian vegetation is a critical parameter for flow attenuation, yet measures of vegetation roughness have typically been evaluated by their contribution to total roughness (Curran and Hession, 2013). This fails to distinguish between the relative contributions from geomorphic complexity, and planform effects, and components of roughness such as sediment size. Causes of variation in vegetation roughness are related to vegetation density, type, age, seasonal changes in leaf cover or flexibility, and vegetation succession, all of which can vary with flow depth, across the floodplain and longitudinally (i.e. downriver). There is often a substantial variation in the distribution of plants across a channel and floodplain. Roughness changes more with flow stage in vegetated channels compared with unvegetated channels. Higher flow...
depths tend to submerge shrubs or small trees, and flexible species become increasingly streamlined. This makes it challenging to apply simple flow models. Roughness coefficients for vegetated river corridors are therefore difficult to assess at the regional scale. The compound channel of the main stem Hunter River is unusual in allowing vegetation to grow within the high channel banks, providing the opportunity for significant hydrological effects for flows below flood level.

A number of models for calculating vegetation resistance have been produced (Perucca et al., 2009; Curran and Hessian, 2013), but have limited application outside the specific vegetation communities from which they were generated. Independent modelling of roughness and diffusion coefficients in the Hunter should be tested against field data and reliable streamflow records. The review of roughness coefficients on Australian streams by Anderson et al. (2001) considered the vertical extent and density of vegetation, but any update on this work would be welcomed by Australian geomorphologists and river managers alike. Rutherfurd et al. (2007) catalogue the specific effects of vegetation on roughness, but quantified measures are required. Shape functions of the change in “vegetation” or total roughness with flow stage need to be generated for various Hunter reaches. This should include an analysis of the relative influence of flexibility and density on vegetation roughness of different vegetation communities and species compositions.

The role of complex topography on the floodplain also needs to be considered in vegetation-channel interactions. Where a connection is re-established between channel and floodplain, the pattern of floodplain vegetation and the floodplain geomorphology have a substantial influence on the effectiveness of floodplains to attenuate and store floodwaters. Is the riparian and floodplain forest longitudinally fragmented, and are there backchannels or secondary channels? This is common in compound channel morphologies and in areas like the Hunter that experience high flow variability. These might offer shortcuts for floodwaters that reduces the attenuating effect of vegetation and increases the risk to individual floodplain from high-velocity floodwaters (Tabachhi et al., 2000). On the other hand, certain patterns of riparian forest may increase the confinement of flood flows and increase flood velocities in the main channel, particularly those which create a dense and sharply defined internal edge such as that created by dense, climbing balloon vine within riparian trees (Tabachhi et al., 2000). There are simple, turbulent models that describe the hydraulic interaction between the main channel and the floodplain (e.g. Samuels, 1985). More complex vegetation scenarios are examined in Tabacchi et al. (2000).

Novel methods for estimating roughness parameters have been based on vegetation density using LiDAR and drone surveys (Hoyle et al., 2012; Perignon et al., 2013; Rahman et al., 2013; Guan and Liang, 2017; McMahon et al., 2017) or remote sensing (Forzieri et al., 2012; Mtamba et al., 2015) and terrestrial laser scanning (Jalonen et al., 2015).

**Conclusion**

Preliminary evidence suggests there is a significant benefit to be gained in managing lowland flooding in a catchment like the Hunter through the promotion and management of in-channel and riparian vegetation. It is clear from the review presented here that there is still much to be learnt before we can have the confidence to rely on catchment riparian revegetation as the frontline management tool, but there is increasing evidence that it should undoubtedly be a key part of catchment-scale flood management.
strategies. What we can say with increasing confidence is that the case for removing in-channel vegetation as part of a flood management strategy no longer stacks up. Hence, maximising in-channel riparian vegetation should be a central plank of river management activities that aim to achieve the quadruple bottom line objectives of improving: ecosystem health, water quality, infrastructure protection and flood mitigation.

References


