An analysis of the influence of riparian vegetation on the propagation of flood waves.

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Abstract: Over the last 200 years, streams throughout Australia have been channelised to increase their hydraulic conveyance, and so reduce flood peaks and durations. One of the main channelisation activities has been to remove large woody debris (LWD) and bank vegetation. Ironically, the major stream rehabilitation activity in Australia, and in many countries, over the last two decades, has been to revegetate the riparian zone and to reinstate LWD. Yet there has been no consideration of the flood implications of returning much of this in-channel and floodplain roughness. This abstract describes a modelling study that quantifies the effects of catchment-scale riparian revegetation on the shape of a flood hydrograph and the speed at which it propagates down river reaches of varying slope and cross-section. A one-dimensional flow-routing model (FLDWAV) is used to solve the fully dynamic formulation of the Saint-Venant equations. The hydraulic properties of a range of riparian assemblages are computed using a model of vegetative resistance similar to HMODEL2 proposed by Darby (1999). This model computes Manning's 'n' as a function of flow depth based on parameters describing the dimensions and distribution of plants in the riparian zone and on the geometry of the cross-section. This study demonstrates that channel roughness, and hence riparian condition, is a significant determinant of wave celerity, hydrograph dispersion and skewness. The impact of roughness is moderated by the magnitude of the hydrograph (peak discharge), with smaller magnitude floods being more sensitive than larger floods.

Keywords: *floods; flood waves; 1d flow-routing; flow resistance; riparian vegetation; large woody debris*

1. INTRODUCTION

Revegetating riparian zones and returning large wood to stream channels are widely practiced river rehabilitation techniques (e.g. Gippel 1999). These modifications reduce channel conveyance by acting as additional resistance elements in the main channel and on the flood plain. A major aim of traditional river management practices, such as stream cleaning and channelisation is to minimise flood risk by maximising conveyance so that over-bank events occur less frequently. However, this is true only if the series of reach inflow hydrographs remains unchanged. We argue that in order to assess the impact of broad-scale rehabilitation works, an understanding of the sensitivity of inflow hydrographs to changes in upstream vegetation condition is required.

Previous numerical investigations demonstrate that increased channel roughness attenuates the peak discharge at the catchment outlet and delays the arrival of the hydrograph peak (Wolff and Burges 1994, Woltemade and Potter 1994, Rutherfurd, et al. 1996). Sensitivity to channel network roughness was examined in these studies by perturbing the value of the roughness coefficient (e.g. Manning's n) around a mean value. These results are applicable to rivers where the value of resistance can be considered constant with stage, albeit with different values assigned for in-channel and floodplain roughness. Such an assumption is not valid for vegetated waterways where roughness changes with stage. This investigation extends previous studies by exploring the case of flow resistance that varies with depth according to different vegetation scenarios. The following questions are addressed: does vegetal roughness appreciably change the celerity and dispersion of flood waves; does the impact of vegetation vary with hydrograph size or with the relative size of vegetation compared to the channel; and what do these results mean in the context of river rehabilitation?

2. METHODOLOGY

Flood waves were routed with a one-dimensional, unsteady flow model down a reach comprising a main channel with flood plains on either side (Figure 1). In this paper we report results for four similarly shaped hydrographs routed under four different flow resistance conditions. To introduce the effect of vegetal roughness an algorithm was developed to estimate the depth variation of Manning's n for both the main channel and on the floodplain. The vegetation present in the riparian zone is defined using two simple properties:

canopy height and foliage density, and by the variation of these properties across the cross-section. The basis for this algorithm and its operation is described in more detail later.

Flow calculations were performed using NWS FldWav (Fread and Lewis 1998) down a 50 km reach for a period of at least 100 hours (longer if necessary to ensure discharge returns to the base flow value). The routing model was set up to output discharge and stage data every 1km at 3 minute intervals (0.05hrs). The output hydrographs were fitted to a three parameter relationship based on the gamma distribution, giving a succinct summary of their evolution. This analysis is detailed in a subsequent section.

2.1. Numerical Flow Routing Model

The flood routing model chosen for this work is *NWS FldWav*, developed by the United States National Weather Service (Fread and Lewis 1998). The main FldWav routine implements an implicit finite-difference solution to the one-dimensional, fully-dynamic form of the Saint Venant equations. The code was developed specifically for flood simulation and has a well validated one-dimensional representation of the physics of coupled channel and floodplain flow (Wolff and Burges 1994), making it ideal for this study. In addition the code can be implemented within a shell, allowing sensitivity analyses to be batch run. Finally, FldWav is open source software, with the code and documentation freely available over the internet, which facilitates the incorporation of alternate roughness models (http://www.nws.noaa.gov/oh/hrl/rvrmech/ fldwav1.htm).

The channel cross-section and inflow hydrograph specifications are identical to those used by Wolff and Burges (1994), and represent a medium sized North American river. These were adopted as their test matrix was applicable to this study and running identical geometric and inflow boundary conditions facilitated validation of numerical output and allowed direct comparison of our results with their published data. The following sections briefly describe the channel and hydrograph specifications.

2.2. Channel Cross-Section Geometry

The channel cross-section is essentially a double trapezoid cross-section, with a small side-slope (0.001 m/m) on the floodplains. Figure 1 shows a schematic of the cross-section, and lists the geometric values that define the section size (the bankfull discharge listed is based on the no vegetation Manning's n of 0.043 which is defined later). A constant valley slope of 0.001 (1 m/km) and zero sinuosity complete the reach definition. A much wider array of cross-section characteristics will be considered in future work.

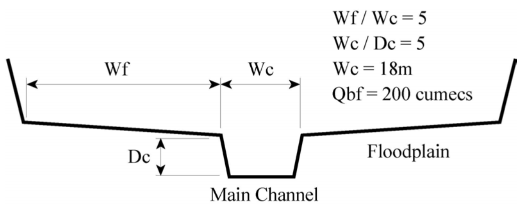

Figure 1. Cross-section schematic with dimensions.

2.3. Hydrograph Definition

Wolff and Burges (1994) use a two parameter (α, β) gamma-distribution to define the shape of their inflow hydrographs. The α and β parameters determine the variance and skew of the distribution, with values of $\alpha = 5$ and $\beta = 0.5$ giving hydrographs with steeper rising than falling limbs. The gamma-distribution is scaled to the desired peak discharge (Q_P) with a base-flow (Q_B) component giving the analytic function in (1), with $\Gamma(\alpha)$ representing the standard gamma function (e.g. http://mathworld.wolfram.com/GammaDistribution.html)

$$Q(t) = \frac{Q_P - Q_B}{\beta^{\alpha}\,\Gamma(\alpha)}\, t^{(\alpha - 1)}\, e^{(-t/\beta)} + Q_B \qquad (1)$$

Four inflow hydrographs were defined with peak discharge values shown in Table 1. Wolff and Burges (1994) computed these values for each return period listed assuming an extreme value type I flood frequency distribution. They also assumed a baseflow discharge of 40 cumecs. Entering these parameter values into (1) gives the four inflow hydrographs shown in Figure 2.

Table 1. Peak discharge and estimated return periods for the inflow hydrograph series.

Peak Discharge (cumecs)	Return Period (yrs)
295	2
504	10
722	50
816	100

2.4. Analysis of Output Hydrographs

The FldWav flow calculations yield discharge hydrographs at each 1km river station. A non-linear data fitting algorithm was employed to fit a gamma distribution identical to Equation 1 to the computed hydrographs, but with $t = t + C.x$ (where C is a parameter representing wave speed and x is the distance of the station downstream). Thus, the curve fitting procedure reduced the output to a three parameter description of wave form evolution, facilitating comparison between the roughness cases on the basis of wave speed (celerity), dispersion, and skew.

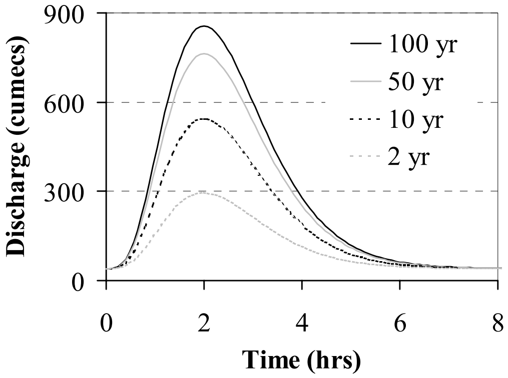

Figure 2. Input hydrographs designated by return interval.

3. VEGETAL RESISTANCE MODEL

Field and laboratory studies show that the hydraulic resistance offered by particular plants, or plant communities, vary with their size and constituent elements, particularly the density of foliage and the branch structure (Jarvela 2002). Many plants respond dynamically to increased flow velocity, with the flexure of stems and branches, and streamlining of leaves, dramatically reducing the effective drag coefficient of the plant (Kouwen and Fathi-Moghadam 2000). Within a fully featured riparian zone, where groundcover, understory shrubs and overstory trees are all present, the resulting resistance profile is highly complex. However, the main features of the roughness profile are the vertical extent and density of biomass, moderated by any dynamic response (Anderson, et al. 2001).

Two existing models calculate depth varying resistance at a cross-section. (Darby and Thorne 1996) developed HMODEL2, an algorithm to predict stage-discharge curves for sand or gravel bed channels, of arbitrary cross-section, with flexible or non-flexible vegetation distributed at discrete lateral locations. Independent testing has shown this model to be of limited use in natural river environments where vegetation properties diverge from the profiles offered in HMODEL2 because the model does not account for roughness variations in the longitudinal direction (Thomas 2003). Early results from a recently published model by Helmio (2002) are promising, but this model is still under development and has yet to be validated against field or flume data. Given the lack of a suitable existing model, a simple parametric vegetal resistance model was developed.

Our model defines a local flow resistance profile (Manning's n variation with flow depth) defined by two vegetation parameters: canopy height and foliage density. For this study the simple profile shown in Figure 3 was used. For flow depths less than the canopy height, a constant value of Manning's n is assumed. The value of the coefficient is chosen with reference to published literature (Chow 1959, Arcement and Schneider 1989) and assigned to the variable "foliage density". As the plants become submerged (flow depth > canopy height) the roughness coefficient declines towards a value equivalent to the no-vegetation value (Wilson and Horritt 2002). The rate of decline is determined using Keulegan's logarithmic equation (Sturm 2001) with canopy height substituted for the sand-grain roughness parameter. Thus, assuming the shape function in Figure 3, local flow resistance is a two-parameter model.

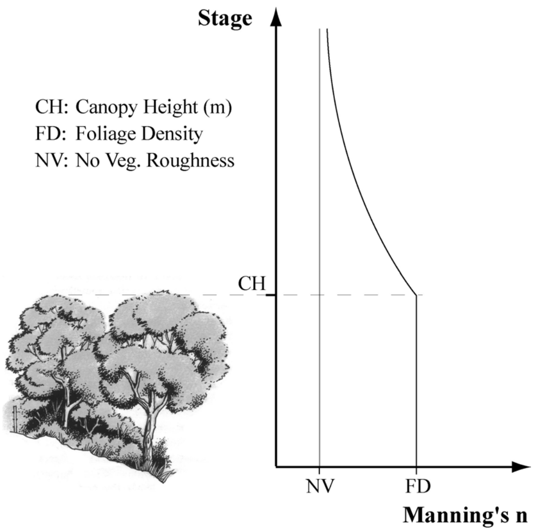

Figure 3. Shape function for the variation of vegetal roughness with flow stage.

The net section resistance is computed for the main channel and floodplains by integrating the contributions of each local profile across the cross-section. Integration is achieved by taking a weighted average of the local resistance profiles at a series of horizontal slices through the section. This weighted average approach is consistent with the findings of recent field studies that show that the percentage of the wetted perimeter covered by vegetation is strongly related to the roughness increment caused by vegetation (Coon 1998, Phillips and Ingersoll 1998). Such a relationship is also suggested by (Kouwen and Fathi-Moghadam 2000).

The simple model has the following properties:

- variable resistance, by virtue of the foliage density and roughness shape function;
- finite vertical scale, specified by the canopy height; and
- sensitivity to channel geometry via the integration of local roughness profiles.

This model is not as complex as existing algorithms, but we argue that the model captures the primary drivers of vegetal resistance.

In this paper, results are presented for four vegetation scenarios based on canopy heights (CH) of 0m (no vegetation), 0.5m, 1.5m, and 3.0m. A base Manning's n value of 0.043 was selected for the unvegetated (NV) cross-section by applying the empirical relationship of Dingman and Sharma (1997) at bankfull stage. The foliage density coefficient was set at 0.15, which corresponds to the suggested maximum roughness coefficient for natural channels with heavy stands of timber and underbrush in (Chow 1959). Figure 4 shows the roughness profiles computed for the main channel and floodplain under each vegetation scenario.

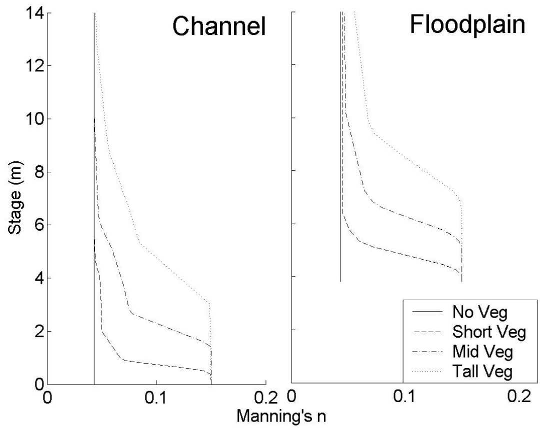

Figure 4. Main channel and floodplain roughness profiles for each test scenario.

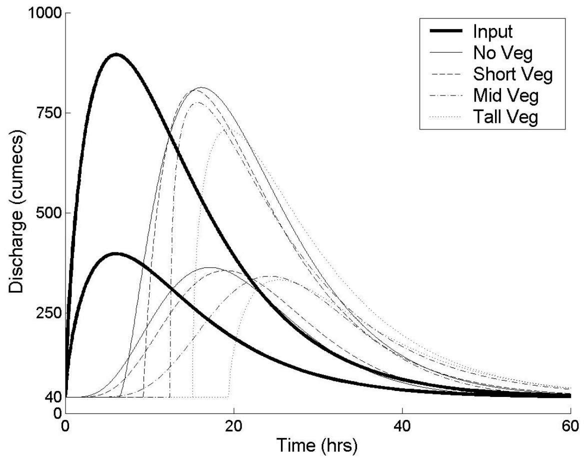

Figure 5. Selected input hydrographs (2yr and 100yr ARI) and the corresponding fitted hydrographs at 60km downstream for each vegetation scenario.

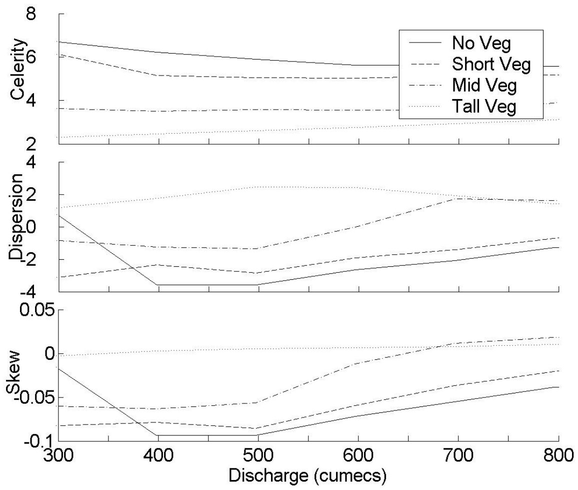

Figure 6. Wave celerity, dispersion coefficient and average changes in skew for hydrographs with peak discharges from 300 to 800 cumecs.

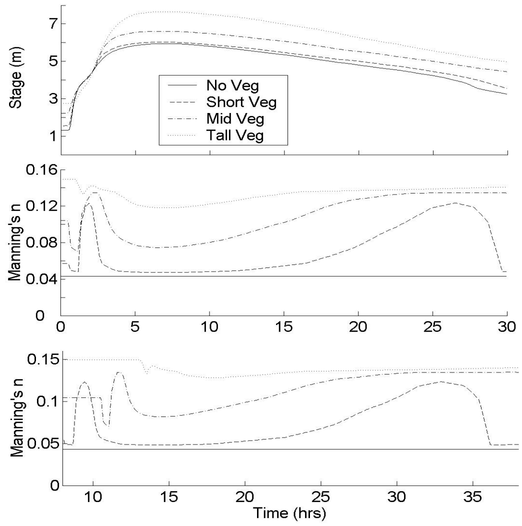

Figure 7. Sample variation of input stage vs time for the 50yr ARI inflow hydrograph (top); corresponding variation of Manning's n at 0km (middle) and 50km (lower) for each veg.

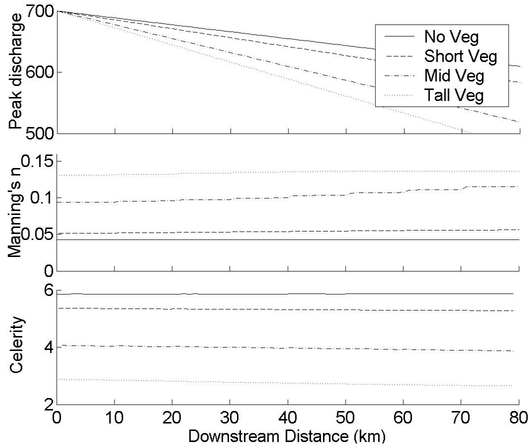

Figure 8. Downstream peak discharge attenuation (50yr ARI inflow) with roughness (middle axes) and wave celerity

4. RESULTS AND DISCUSSION

The impact of vegetal roughness on hydrographs of different sizes is clearly demonstrated by the results in Figure 5. This figure shows the shape of a small and a large flood (2yr and 100yr ARI) after 60km of routing under the four roughness scenarios. Differences in arrival times, peak discharge attenuation and hydrograph shape are evident. Arrival time indicates the wave speed and changes seem more pronounced for the small flood hydrograph. Attenuation of peak discharge varies also, but is more substantial in the case of the larger flood. The steepness of the rising limb varies, with the smaller flood flattening out considerably under all but the 'Tall Veg' scenario. The changes in the hydrographs of Figure 5 are quantified by curve-fit parameters: wave celerity, dispersion coefficient and the rate of change of skew. Figure 6 shows the average values of each parameter, and shows the variation of the parameter over the range of peak discharges tested.

Wave celerity for the low roughness cases is two to three times greater than for the high roughness cases, with the difference in celerity greater for smaller discharge peaks. The dispersion and skew parameters describe the wave shape which are closely related, as evidenced by the similarity in the trajectories plotted. In terms of wave shape, the variation between roughness scenarios is greatest for low and mid-sized flood peaks, suggesting that vegetal roughness is less important for high discharge floods.

Other features to note in Figure 6 include: the high roughness scenario ('Tall veg') exhibits almost zero change in skew and a dispersion coefficient that varies little with peak discharge; the negative rates of skew change (i.e. decreased skewness) shown for the lower roughness scenarios accords with the flattening in the flood hydrographs observed in Figure 5; and finally, the unusual jump in dispersion and skew for the 'No Veg' case at 295 cumecs is thought to be a results of the channel running at close to bankfull discharge and the associated rapid changes in channel geometry and roughness that occur at this point. These data demonstrate that flood waves are sensitive to vegetal roughness and that this sensitivity varies with flood magnitude.

The nature of the vegetal roughness environment experienced by a flood wave is best shown through the temporal evolution of roughness at a cross-section (Figure 7). As the hydrograph passes through a cross-section, roughness is high during the rising and falling limbs, and is at a minimum near the peak stage. The middle and lower axes in Figure 7 show how the roughness variations compare at the 0km and 50km cross-sections along the test reach (note that the hydrograph arrival times vary in the lower plot, hence the resistance curves are offset). Comparison of these plots reveals that the shape of the roughness curves does not vary substantially between the two stations. Therefore, while there is a large variation in the resistance acting along the flood wave, there are only incremental changes at a given point on the wave. For instance, if the resistance at peak discharge starts low it does not change much.

Figure 8 shows the attenuation of discharge peaks for the 50yr ARI inflow case (upper plot). The associated changes in Manning's n at peak stage (middle plot) exhibit some variability, with the 'Mid Veg' scenario changing most dramatically. However these peak roughness changes have no discernable affect on flood wave celerity (lower plot). This suggests that downstream changes due to the varying nature of vegetal roughness are either small, or are not significant enough to slow or accelerate the wave, or both.

5. FUTURE WORK

These results suggest that the large differences in celerity and wave shape between the vegetation scenarios are likely to be driven by the difference in the average roughness value across the wave. Whether this is simply a temporal average or some form of discharge weighted average is the subject of future research. The variability of roughness along the wave seems of secondary importance, although it may be an important modifier of the wave shape, this is also being investigated.

The celerity of flood hydrographs and dispersion coefficients can be predicted using relationships derived from the advection-dispersion form of the Saint Venant equations. We are investigating whether these relationships produce values comparable to the results in this paper. Additional simulations are being run using a broader test matrix which includes variations in foliage density, in valley slope, and in cross-section shape.

6. CONCLUSION

This study demonstrates that channel roughness, and hence riparian condition, is a significant determinant of both wave celerity, hydrograph dispersion and skew. The impact of roughness is moderated by the magnitude of the hydrograph (peak discharge), with smaller magnitude floods more sensitive than larger floods.

The reach scale effect of vegetation shall be applied to the channel network across an entire catchment. The reduced celerity under vegetated conditions found here would be expected to lead to a lengthening of catchment response times and a consequent decrease in peak discharge, which may be more important than the local reduction in bankfull discharge.

The objective of this work was to estimate the sensitivity of hydrograph celerity and wave shape to vegetation condition. The results shown demonstrate considerable sensitivity to both vegetation height and to hydrograph size. We intend to incorporate these results into either a Muskingham-Cunge or Unit Hydrograph routing engine, thus producing a catchment-scale flood routing tool sensitive to vegetation condition. Using this tool, the local and catchment scale impacts can be integrated along the channel network providing an estimate at each point of the net change in flood risk. The results presented in this paper thus represent an important step towards predicting the sensitivity of catchment flood characteristics to broad scale changes in riparian vegetation condition.

7. ACKNOWLEDGMENTS

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