ROVER: Introducing A Unified Model To Estimate The Hydraulic Resistance Of Vegetation

[1]Anderson, B.G. , [1]A.W. Western and [1]I.D. Rutherfurd

[1]The University of Melbourne, E-Mail: **b.anderson@unimelb.edu.au**

Keywords: *flow resistance, hydraulics, vegetation, rehabilitation.*

EXTENDED ABSTRACT

The specification of flow resistance is central to both simple and sophisticated hydraulic analyses. Yet it remains encumbered with the greatest level of uncertainty of all hydraulic parameters; despite over a century of field and flume experimentation. The selection of resistance coefficients for natural rivers remains more an empirical art than a matter of implementing robust scientifically verified procedures (Yen, 1991). The complexity and variety of boundary conditions are the principal impediments to developing reliable resistance estimation tools. A range of boundary features contribute to flow resistance and, of these, vegetation is the most potent (Cowan, 1956; Watson, 1987) but the least amenable to theoretical analysis. Plant structures are challenging to describe numerically because of their myriad of shapes, structures, and the mosaic of their distributions along rivers.

This paper describes a new model called ROVER (ROughness of VEgetation in Rivers) that adopts a phenomenological approach to the problem. That is the code was structured around empirical representations of three plant properties thought to be the principal factors that govern vegetation resistance. Dubbed the "D_3 Framework", the properties identified were the Dimension (size and structure), Dynamics (flexibility), and Distribution (around the channel) of plants. This paper briefly introduces both the D3 Framework and provides an overview of the ROVER model.

The utility of the ROVER representations was investigated by calibrating the model to measured vegetation resistance profiles. Strong correlations were achieved, indicating that ROVER has the flexibility to reproduce the shape and features of real vegetation resistance profiles (e.g. Figure 1, the variation of resistance (Manning's n) with depth of flow). To give some insight into this verification process, a case study of one particular module is presented herein. The subject of the case study is of the dynamic process whereby plant leaves and stems adopt a more streamlined position as water pushes against them. Such streamlining can halve the resistance generated by a plant to flow. The result is that plant roughness profiles are not a single curve but a family of curves as shown in Figure 1. ROVER provides a fresh approach to vegetation roughness prediction, based on parsimoniously parameterised curves of depth-varying roughness. It is hoped that the development of ROVER nudges roughness prediction along the continuum towards a more robust scientific method by diminishing some of the existing uncertainty associated with the art

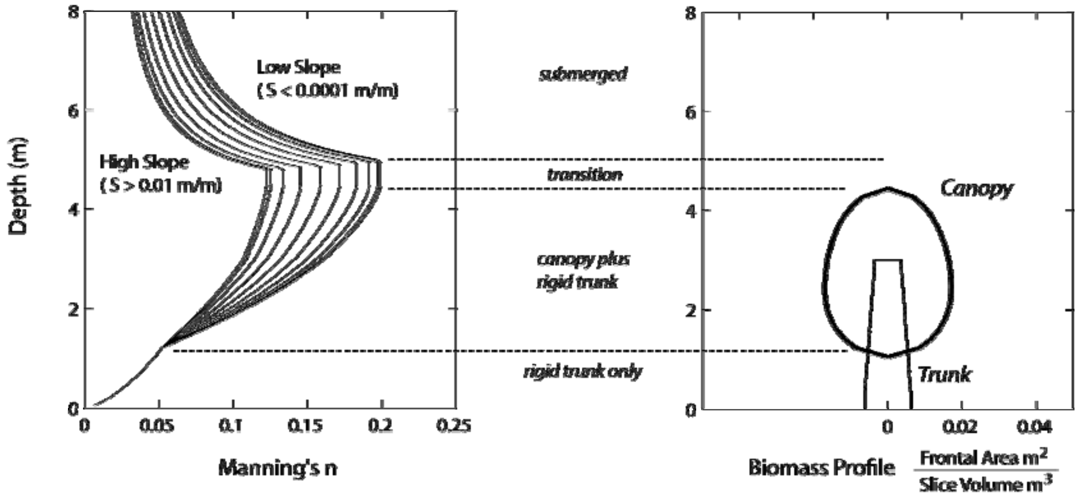

Figure 1 Sample ROVER roughness profiles for a tree constructed from trunk and canopy characteristics.

1. INTRODUCTION

In 1776 a hydraulic engineer named DuBuat stated that one of the major problems facing the field of hydraulics was 'to estimate the velocity of a river of which one knows the width, the depth and the slope' (Bray, 1982). Two hundred years later, and engineers and scientists are still searching for a satisfactory solution. The problem in essence is to quantify the amount of resistance that a fluid flow experiences. In a uniformly shaped channel flow resistance is generally dominated by friction with the boundary surface (Chow, 1959; Yen, 1991). However, as well as having a rough and often mobile boundary surface, resistance in natural river channels also arises as the fluid follows the twisting path of a meandering stream, at points where the flow expands, via the turbulence generated at tributary confluences, and in passing around and through vegetation (Bathurst, 1997). In fact, the later mechanism, vegetation roughness, can be the dominant source of resistance in open channels.

For hydraulic computations the total energy dissipated by all sources is usually combined into a single-valued parameter called a stream roughness coefficient. Roughness coefficients come in three flavours, they are the Chezy **C**, the Manning **n**, and the Darcy-Weisbach **f**. Each is essentially interchangeable with the others, and for this work Manning's **n** was selected. Manning's equation (1) defines the coefficient '**n**' to empirically relate flow velocity to the flow depth (as per hydraulic radius, R) and channel slope (S).

$$V = \frac{1}{\mathbf{n}} R^{2/3} \sqrt{S} \qquad (1)$$

The roughness coefficient is a critical parameter in numerical hydraulic calculations, but is commonly associated with error margins of 20% or greater (Bathurst, 2002; Davidian, 1984). Improved methods of roughness estimation therefore have great potential to improve the accuracy of hydraulic calculations, improve the design of engineering structures and river rehabilitation works, and contribute to better targeted flood management efforts. The estimation of vegetation roughness is becoming increasingly important since the revegetation of riparian corridors is now the most common mode of river rehabilitation practiced in Australia. A recent international investigation (Bernhardt et al., 2005) estimated that investment in such activities is approaching $US1 billion per annum in the United States. In rehabilitated streams it may be that vegetation roughness is in fact the dominant source of flow resistance, overwhelming even boundary resistance (Sand-Jensen and Pedersen, 1999; Watson, 1987). The leverage of vegetation can be discerned by comparing the roughness of channels with and without vegetation. Chow's (1959) often cited table of roughness values shows that channels without vegetation exhibit Manning's n values in the range 0.02 - 0.04, while the equivalent values for channels with vegetation is 0.03 - 0.08, and in some cases up to 0.15. This data demonstrates that roughness coefficients are indeed highly sensitive to the presence of vegetation, and with revegetation projects proliferating throughout Australian catchments, accurate prediction of vegetation roughness is becoming increasingly important.

Generally it is necessary to estimate the value of the roughness parameter for a particular situation and a wide range of methods are available for this purpose (Duncan and Smart, 1999; Ladson et al., 2003). However, while the contribution of vegetation to flow resistance is known to be the important component in many streams, few vegetation roughness estimation techniques are available, and those that are lack generality (i.e. they do not facilitate prediction for a range of plant types) and are backed by limited field verification and testing. Particular exceptions do exist, for example detailed estimation procedures are available for grass-lined channels thanks to decades of investigation by Kouwen (1988). The central problem is that while a great many vegetation resistance studies have been published (see review in Anderson, 2005), the understanding encapsulated in these works has not been successfully formed into a robust estimation procedure. To address this deficiency a new model called ROVER (Roughness Of VEgetation in Rivers) was developed.

2. THE ROVER MODEL

Review of vegetation roughness characteristics

Model development was based on a comprehensive review of field and laboratory studies into the resistance characteristics of vegetation species including: grasses; aquatic vegetation; macrophytes; bushes/scrub; trees; and large woody debris (Anderson, 2005). The magnitude of the roughness coefficient depends principally on the density and stiffness of the plant structures. A rule of thumb is that vegetation resistance becomes significant when the density of foliage and stems exceeds around 10% of the flow cross-sectional area (e.g. Gippel, 1995). Stem flexibility is also important, and vegetation roughness may decline by more than 50% as flow velocity increases and stems adopt more streamlined orientations (Fathi-Moghadam and Kouwen, 1997). Furthermore, as flow depth increases to submerge the plants, flow roughness declines rapidly with a layer of unobstructed (and hence low resistance) flow developing above the vegetation canopy (Gippel, 1995; Wu et al., 1999). Therefore, in contrast to boundary friction which can be defined with reasonable accuracy by a constant value of Manning's n, the roughness of vegetation is sensitive both to flow depth and, for flexible plants, to velocity as well.

D_3 *Framework*

An approach was sought in which that vegetation of all types could be defined within a common numerical framework. Three generic properties were identified as being the most important drivers of vegetation roughness, these being:

- *Dimensions:* physical size (height, width and breadth) and space filling (stem density).
- *Dynamics:* attenuation of roughness as fluid pressure causes postural change in flexible stems/foliage.
- *Distribution:* the location of the plant with respect to cross-section or reach geometry.

Dubbed the D_3 framework, these three categories of plant properties provide the ROVER backbone. The numerical representation of vegetation is then based on defining the characteristics of individual plants, which revolves around dealing with the first two ***D***'s (*Dimension* and *Dynamics*). *Dimension* parameters define the initial shape of the Manning's n versus flow depth curves, also called plant scale roughness profiles (Figure 2). The roughness profiles may then be modified by *Dynamic* correction coefficients designed to simulate plant flexibility. Then *Distribution* (the third ***D***), is central in upscaling from plant- to community-scale (Figure 2, arrow #1), and to estimate the contribution of vegetation to cross-section roughness (Figure 2, arrow #2). ROVER models are built in three stages: firstly parameter values are defined that specialise the generic equations for plant roughness profiles; secondly algorithms are enacted that compute multi-species community curves from the constituent individual profiles; and thirdly a stage-discharge curve is calculated from the distribution of communities around a cross-section.

A full description of the model is beyond the scope of this paper (see Anderson, 2005). Instead, the remainder of the paper introduces one novel model component: the *Dynamics* module. First, a conceptual model of the dynamic behaviour is introduced, then the numerical model with key equations. This numerical description was tested against the resistance characteristics of flexible saplings measured by Fathi-Moghadam and Kouwen (1997). The conceptual model is phenomenological, in that it attempts only to reproduce observed behaviour using empirical curves. The core objective was to reproduce the variability in roughness shown by the measured data using a parsimonious algorithm.

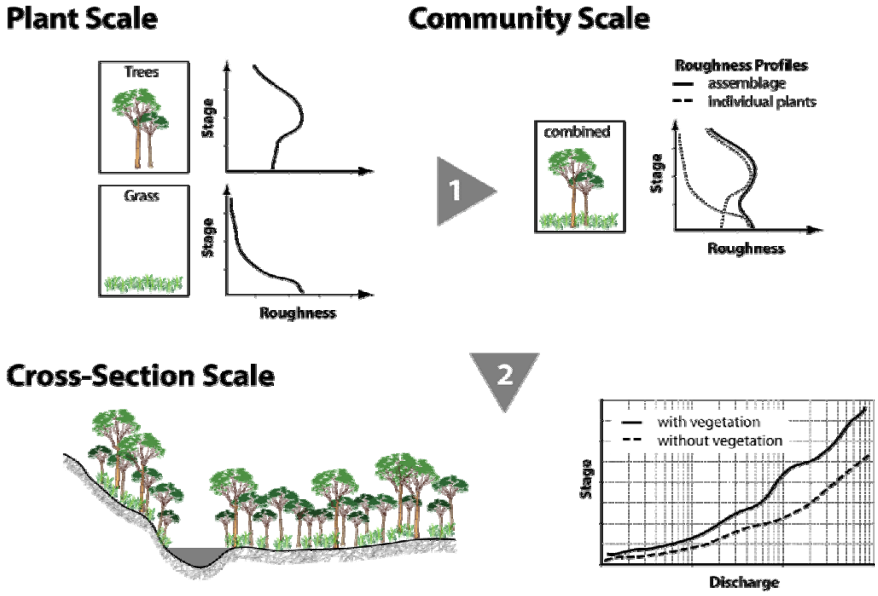

Figure 2. Structure of the ROVER model: plant-scale roughness profiles are defined then combined to provide a community profile. The distribution of plant communities around the cross-section then allows for estimation of the stage-discharge relationship.

3. ROVER DYNAMICS MODULE

The degree of streamlining of a plant is constrained by the stiffness of the stems and foliage and driven by the pressure that is applied by the flow on the plant. Existing vegetation models quantify flow pressure either as a shear stress (e.g. Kouwen's (1988) algorithm for grasses uses boundary shear stress) or via mean flow velocity (e.g. Fathi-Moghadam and Kouwen (1997) model of saplings). While both formulations succeed in defining dynamic vegetation resistance, by defining resistance as a function of a flow property they demand an iterative solution scheme. To simplify the implementation of ROVER the degree of flexure was defined according to channel longitudinal slope.

Kouwen and Unny (1973) identify three different 'states' that flexible roughness elements adopt under changing flow conditions. These states, defined as plant *posture*, they called erect, waving and prone (Figure 3, top). Kouwen and Unny observed that, at low discharge, the simulated flexible stems remained upright and were un-deflected by flow pressure. As discharge was increased, the stems began waving and became visibly deflected. At higher discharges again, the stems were maximally deflected and ceased to wave, lying prone against the bed.

In this description postural change is related to discharge, which is effectively a surrogate parameter for the drag force applied by water to the flexible stems. Theoretically, the magnitude of the drag force depends on the square of the local velocity (V_l) seen by the stem (i.e. the dynamic pressure: $\frac{1}{2}\rho V_l^2$) . However, attempting to solve for the drag force explicitly presents two main difficulties. First, drag force also depends on the drag coefficient of the stem, the magnitude of which varies as the stem flexes. Second, the determination of local velocity is non-trivial. The velocity at a particular stem varies according to where it is in the stand, and therefore on the flexure of neighbouring, upstream stems.

Hence, developing a theoretical formulation based on local velocity and a velocity-dependent drag coefficient rapidly becomes very complex, much more complex than can be discerned from the available information. Instead, an empirical model of the behaviour was sought. In place of velocity, channel slope was selected to indicate the amount of flow pressure applied to plant stems. Slope is a key parameter in flow resistance formulations (e.g. Manning's equation), thus it is a logical substitute to velocity, given a physically-based model is impractical.

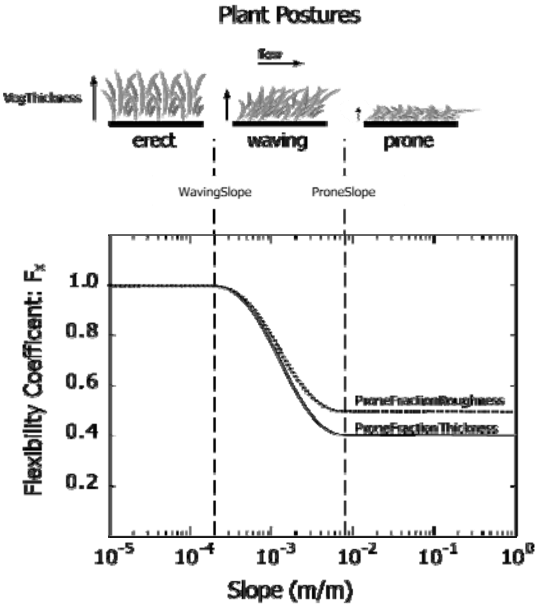

Figure 3. Schematic showing the relationship between the slope-based flexibility model (graph) and the behaviour of a grass sward (top).

The *Dynamics* module in ROVER defines 'multipliers' that adjust both roughness and (where required) plant thickness to mimic these plant postures. The resistance of plants that are erect or prone is constant, effectively plants are inflexible in these posture. Flows are sluggish at very low channel slopes, and do not generate sufficient pressure to bend plant stems until a lower slope threshold is reached (*WavingSlope*). At high slopes, a second threshold is reached (*ProneSlope*) where the flow has sufficient energy to fully compress and maximally streamline the flexible stems, meaning that there is no capacity for further flexure at higher slopes. A cosine function was selected to represent the transition between these postures (i.e. the waving posture) as it provides a gradual departure from the erect state and a similarly smooth entry into the prone state (which seemed physically realistic). Flexibility coefficients (*F*) were defined as piecewise continuous function (2) based on the constant parameters: *WavingSlope (W)*; *ProneSlope (P)*; and *ProneFraction* (*α*).

$$F = \begin{cases} 1 & S < W \\ 1 - (1-\alpha)\dfrac{(\cos(S') + 1)}{2} & W < S < P \\ \alpha & P < S \end{cases} \qquad (2)$$

where *S'* is an auxiliary variable that varies over the interval [π 2π] computed using (3):

$$S' = \pi + \frac{\pi\,(\log_{10}(S) - \log_{10}(W))}{\log_{10}(P) - \log_{10}(W)} \qquad (3)$$

Thus, the *Dynamics* module requires three parameters to simulate roughness reduction as a result of stem flexure, and a fourth (*ProneFractionThickness*) if stand height also changes.

4. CASE STUDY: FLEXIBLE SAPLINGS

"Individual pine and cedar tree saplings and branches were used to model the resistance to flow in a water flume for nonsubmerged and nonrigid vegetation to determine the amount that streamlining decreases the drag coefficient and reduces the momentum absorbing area." (Fathi-Moghadam and Kouwen 1997, p.51)

Fathi-Moghadam and Kouwen (1997) report roughness profiles (Manning's n versus flow depth) and the associated vertical distribution of leaf area per unit volume for pine and cedar saplings (Figure 4). Roughness profiles were reported for pine (Figure 5) and cedar (Figure 6) in the form of families of curves plotted at constant values of flow speed, with isovels from 0.1m/s up to 0.9m/s. The measured data (solid lines) show that Manning's n declines to about half the low-flow-speed value as velocity increases by almost a factor of ten. The aim was to reproduce these characteristics by calibrating the ROVER model.

An initial roughness profile was computed for pine and cedar (i.e. without flexibility) in ROVER by treating them as canopy structures. A canopy structure requires the following input: a biomass profile (Figure 4); a canopy-average drag coefficient (set at a fixed value of 1.0); and an exponent to vary roughness with flow depth (set to default value of ⅔). This leaves only the three dynamic model parameters to be calibrated.

Fathi-Moghadam and Kouwen (1997) report the variation in roughness due to flexibility as a function of changes in flow velocity. However, the proposed dynamic module in ROVER is driven by channel slope rather than velocity. A relationship between velocity and slope was therefore sought. As a first approximation the effective slope was assumed to be related to the square of velocity ($S = \mathbf{a}V^2$), as per Manning's equation (1). The constant of proportionality (**a**) was assigned a constant value of 0.011 (based on the flume slope = 0.004, and an intermediate value of $V^2 = 0.6^2 = 0.36$). This relationship was used to transform each measured isovel (Figures 5 and 6) into constant-slope curves. Consequently, at a given channel slope the flexibility correction applied by ROVER does not impact on the depth variation of the roughness profile. Instead the flexibility coefficient acts only to scale the magnitude of the roughness coefficient when slope changes.

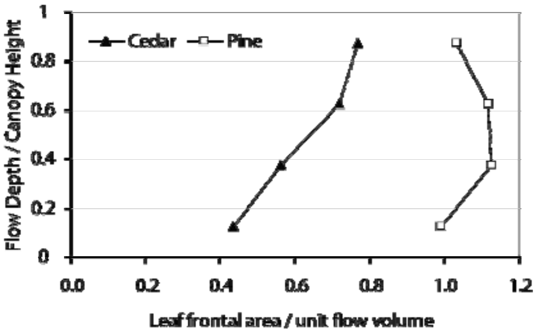

Figure 4 Average biomass profiles for the cedar and pine models tested in the flume by Fathi-Moghadam and Kouwen (1997). Note: canopy height ~0.35m.

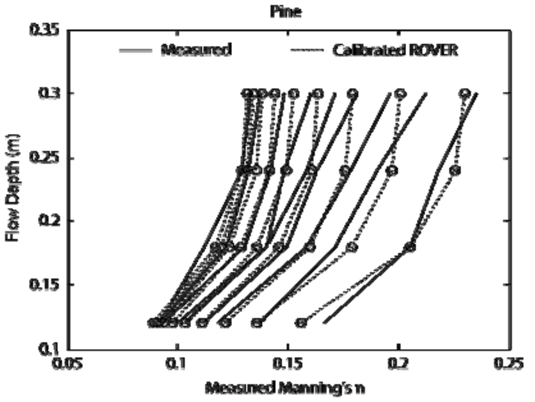

Figure 5 Measured and modelled flow resistance (Manning's n) versus flow depth isovels. Flow velocity of left-most curve is 0.9m/s, decreasing in 0.1m/s increments down to 0.1m/s at right.

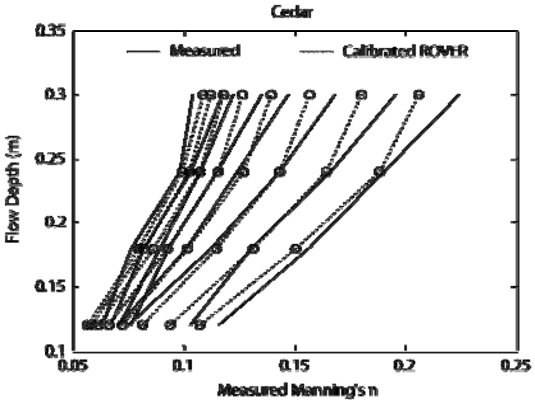

Figure 6 Measured and modelled flow resistance (Manning's n) versus flow depth isovels. Flow velocity of left-most curve is 0.9m/s, decreasing in 0.1m/s increments down to 0.1m/s at right.

5. RESULTS AND DISCUSSION

The subroutine that computes canopy roughness (including flexibility) was configured so as to report the error between predicted roughness and the measured value for each data point in the cedar and then the pine data sets. A non-linear optimisation routine was configured to search for parameter values that minimised both the mean and maximum error values. Optimised parameter values and the associated flexibility curves are shown in Figure 7. Modelled versus measured roughness values for the pine and cedar cases are plotted in Figure 8.

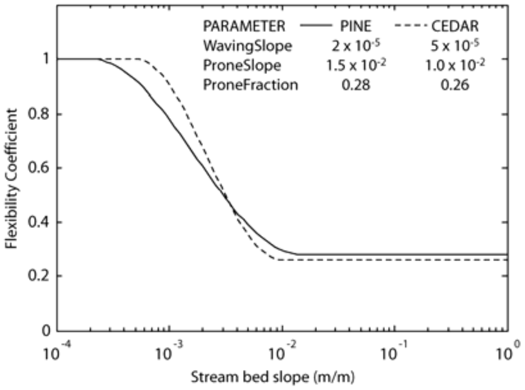

Figure 7 Optimised ROVER flexibility function plots and parameters for pine and cedar.

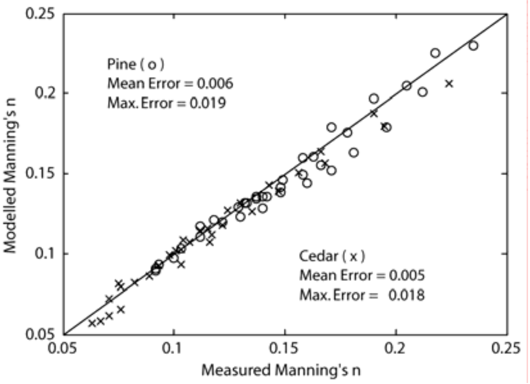

Figure 8 Comparison of modelled and measured roughness values.

Visual inspection of the modelled and measured curves in Figures 5 and 6 suggest a good calibration was achieved. The model fit is confirmed by the comparison presented in Figure 7, in which measured Manning's n does not diverge significantly from modelled Manning's n at any point across the range of roughness values. Indeed, the mean and maximum errors are quite low, being around 3% and 10% of the reported roughness coefficient range.

The modelled curves in Figures 5 and 6 do show more curvature than the measured equivalents. Curvature arises in the equations by virtue of an increase in hydraulic radius ($R^{2/3}$) and the shape of biomass profiles (Figure 4). The divergence is consistently large for the case where the flow is both deep and slow. The model overestimates the decrease in roughness due to flexibility at these points. The maximum flow depth is near the top of the vegetation. It may be that additional roughness is generated as the flow begins to transition from the highly obstructed plant zone to one with no resistance elements. Indeed, such a resistance rise has been observed in other plant roughness experiments (e.g. Wu et al., 1999).

The calibrated flexibility coefficient curves presented in Figure 7 show that pine and cedar have only slightly different dynamic parameters. The calibration suggests that the deflection of cedar leaves commences later than for pine, has a narrower waving slope range, and in the 'prone' posture cedar leaves are slightly more streamlined than is the case for pine. However, if an identical slope model is used, taking intermediate values for each of the three parameters, only a small amount of additional error is incurred (mean error increases by 0.0015 for pine, by 0.0005 for cedar and the maximum error increases to 0.021 for both species, a very small net change of 0.003).

The calibration of the flexibility model controls the spacing of the isovel roughness profiles; however calibration has no impact on the shape of the vertical variation. This is controlled by the un-calibrated parameters, most particularly the biomass distributions. It is the difference in biomass that causes the Manning's n for pine to be higher than that predicted for cedar, i.e. the range of Manning's n values in Figure 5 is shifted to the right compared to the range in Figure 6. Also, whereas the biomass profile for pine is roughly uniform, the frontal area for cedar increases by over 40% as the depth of submergence increases from 0.1 to 0.9. The effect of this is evident in the more angled gradient of the roughness profiles predicted for cedar by comparison with those for pine. The merit of explicitly including the biomass profiles is clearly evident in these results.

6. CONCLUSION

The roughness of vegetation is a significant, possibly dominant, component of flow resistance in streams and rivers. With hundreds of millions of natural resource management dollars being invested in transforming stream corridors from efficient drains to rich and vital ecosystems, it is becoming more critical to predict the hydraulic impact of channels hosting variegated and dense plant communities. The work described in this paper opens one path toward addressing this need. Firstly the complex and dynamic features that drive the interaction of plant structures and flowing water are reduced to a set of primary drivers and a numerical framework developed in which these are defined and combined at successively larger scales. All this culminates in the ROVER model, one element of which was described briefly in this paper (the Dynamic Module). The development of ROVER relies heavily on limited sources of quantitative vegetation resistance data, and is version 1 of what is hoped to be a step forwards towards a reliable procedure for predicting the hydraulic impact of vegetation on rivers. As we continue to take positive steps to protect Australia's precious water assets by replanting great swathes of stream networks, numerical models such as ROVER will be increasingly called on to assist with making decisions to manage the changing flow environment.

7. ACKNOWLEDGMENTS

This work was part of the PhD research of the first author who is supported by an APA scholarship at the University of Melbourne, by the Riparian Lands Program of Land and Water Australia, and by the Cooperative Research Centre for Catchment Hydrology.

8. REFERENCES

Anderson, B.G., 2005. On the impact of riparian vegetation on catchment scale flooding characteristics. PhD Thesis, University of Melbourne.

Bathurst, J.C., 1997. Environmental River Flow Hydraulics. In: C.R. Thorne, R.D. Hey and M.D. Newson (Editors), Applied Fluvial Geomorphology for River Engineering and Management. John Wiley & Sons Ltd., Chichester.

Bathurst, J.C., 2002. At-a-site variation and minimum flow resistance for mountain rivers. Journal of Hydrology, 269(1-2): 11-26.

Bernhardt, E.S. et al., 2005. ECOLOGY: Synthesizing U.S. River Restoration Efforts. Science, 308(5722): 636-637.

Bray, D.I., 1982. Flow Resistance in Gravel-bed Rivers. In: R.D. Hey, J.C. Bathurst and C.R. Thorne (Editors), Gravel-bed Rivers. John Wiley & Sons Ltd, pp. 109-137.

Chow, V.T., 1959. Open channel hydraulics. McGraw Hill, New York.

Cowan, W.L., 1956. Estimating Hydraulic Roughness Coefficients. Agricultural Engineering, 37(7): 473-475.

Davidian, J., 1984. Computation of water-surface profiles in open channels: U.S. Geological Survey Techiques of Water-Resources Investigations, Book 3. United States Government Printing Office, Washington.

Duncan, M. and Smart, G., 1999. Flow Resistance: An overview of formulae for alluvial channel flow estimation, National Institute of Water and Atmospheric Research Institute Ltd, Napier, New Zealand.

Fathi-Moghadam, M. and Kouwen, N., 1997. Nonrigid, nonsubmerged, vegetative roughness on floodplains. Journal of Hydraulic Engineering-ASCE, 123(1): 51-57.

Gippel, C.J., 1995. Environmental hydraulics of large woody debris in streams and rivers. Journal of Environmental Engineering(May): 338-395.

Kouwen, N., 1988. Field estimation of the biomechanical properties of grass. Journal of Hydraulic Research, 26(5): 559-568.

Kouwen, N. and Unny, T.E., 1973. Flexible roughness in open channels. Journal of the Hydraulics Division, ASCE, 99: 713-728.

Ladson, A.R., Lang, S., Anderson, B.G. and Rutherfurd, I.D., 2003. An Australian Guide to Stream Roughness Coefficients, 28th Hydrology and Water Resources Symposium. The Institution of Engineers, Australia, Wollongong, NSW, Australia.

Sand-Jensen, K. and Pedersen, O., 1999. Velocity gradients and turbulence around macrophyte stands in streams. Freshwater Biology, 42: 315-328.

Watson, D., 1987. Hydraulic effects of aquatic weeds in U.K. rivers. Regulated Rivers: Research & Management, 1: 211-277.

Wu, F.C., Shen, H.W. and Chou, Y.J., 1999. Variation of Roughness Coefficients for Unsubmerged and Submerged Vegetation. Journal of Hydraulic Engineering, 125(9): 934-942.

Yen, B.C., 1991. Hydraulic resistance in open channels. In: B.C. Yen (Editor), Channel Flow Resistance: Centennial of Manning's Formula. Water Resources Publications, Littleton, Colorado, U.S.A., pp. 1-135.