GENERALISING MANNINGS N FOR HIGH PERFORMANCE ROADSIDE VEGETATED SWALE DRAINS AND FILTER STRIPS

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ABSTRACT

Road Controlling Authorities (RCA) are putting high focus on improving the sustainability of the roadside environment. There is a recognized need to ensure storm water quality as well as quantity objectives are met. RCA's often have conflicting constraints and yet there is a need to achieve a balanced and robust design. Austroads and other international RCA have promulgated guides on acceptable swale and filter strip design practice with these commonly allowing greater than fully submerged vegetation flow depths for the quality storm event. In New Zealand there is a desire to raise the bar with treatment performance and require the quality storm event to be accommodated within the vegetation height or under 'just submerged' conditions. This paper reviews the recent hydraulic data collected for vegetated swales and using a case study of a typical swale drain calibrates the data against the SCS TP61 Manning 'n' relationship. Tests for method robustness are undertaken and reported. The paper concludes the method provides a robust and simple method for determining Manning 'n' for designing high performance roadside vegetated swale drains and filter strips and recommends more physical modeling be undertaken to extend the information available.

KEYWORDS

Filter strips, hydraulic resistance, Manning's equation, retardance curves, roughness, swale drains

PRESENTER PROFILE

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1 INTRODUCTION

Managing storm water within the road corridor is vitally important for ensuring the road assets and road user safety performance targets are met. Stormwater occurs within the road corridor from many sources including direct rainfall, groundwater sources and most importantly from adjacent catchments intercepted as a result of road construction. Historically the storm water management principles have been:

- Collect the storm water positively in a cost effective manner

- Convey the storm water using drainage components that are cost effective and limit risk to the road, road users and adjacent property owners

- Discharge storm water using cost effective moderate risk structures

- Minimize impacts on the affected storm water systems

Design for the existing storm water systems has hence focused on determining peak discharges (Rational Method), conveyance and flow capacity of the various drainage components (Manning's equation) and controlling scour/erosion by limiting flow velocity or boundary shear stress.

The current focus on sustainability has forced a change in the storm water management principles. Internationally Road Controlling Authorities (RCA) have taken up this new management approach, determined the performance requirements and promulgated that to the industry via guides and manuals. While the initial focus of this work is new designs in time there will be a need to evaluate the compliance of existing asset within road networks to ensure the RCA performance requirements are met.

The new storm water management requirements are placing different demands on the road networks with additional land (for storage or treatment devices) and the introduction of new asset (requiring different operation and maintenance regimes) being the most significant. For the bulk of the roadside drains and vegetated batters there is the added demand of ensuring discharged storm water is of acceptable quality.

Early assessments of road runoff quality requirements indicated that historic design practices were appropriate. In recent times the industry has determined that the existing storm water drainage may not provide adequate discharge quality standards and hence has developed a specific water quality storm event for system design and set specific hydraulic criteria for that event to ensure the required performance targets are met. To meet the 'higher treatment performance' requirements shallow flow depths are specified requiring non-submerged vegetation flow conditions to be assessed and going beyond industry accepted design data used over the last 50 years.

This paper focuses on roadside swale drains (SD) and filter strips (FS) for which the specified design flow depth is just at submergence and half the vegetation height respectively. The study has recognized the trend to consider the vegetated hydraulic component has a rigid and fixed boundary which can be represented by a single valued Manning's 'n' roughness, with 0.25 for SD and 0.35 for FS commonly adopted. This approach does not follow the fundamentals of Manning flow resistance and limits the applicability of the 'design procedure' to evaluating the hydraulic performance of existing vegetated drains and vegetated batters and hence limits the evaluation of these existing systems for compliance to the target treatment performance requirements. It is desirable there is a strong linkage between model predicted performance and prototype performance. The study undertakes a review of international research, calibration analysis of ARC research to produce an n - VR relationship specific to vegetated roadside SD and FS that is more general in its application to the hydraulic assessment of these drainage components that is suitable for design or evaluation purposes and more closely aligns with prototype hydraulic parameters.

2   ROADSIDE SWALE DRAIN AND FILTER STRIP DESIGN

Roadside drainage design in New Zealand is required to be in accordance with the Highway Surface Drainage: Design Guide for Highways with a Positive Collection System (Oakden, 1977). The philosophy of the guide is positive collection and conveyance of storm water. It is recognized that all sources of water need to be quantified and the effects of the storm water managed accordingly. The guide has no specific reference to vegetated swale drains. In practice Henderson, 1966 has been used for designing swale drains with this method based on the retardance curves of Chow 1959 and the USDA-SCS-TP61, and limiting flow velocity to ensure drain scour was limited. With the

publication of HEC 15 the design procedure changed to use effective boundary shear stress to limit scour potential but the hydraulic analysis is still based on a Mannings n determined using the appropriate retardance curve.

The New Zealand Transport Agency (NZTA and its predecessors Transit New Zealand and National Roads Board) have standardized vegetation control specifications which set limits on acceptability of grass height on shoulders, batters and within storm water channels in the road reserve. The specification differentiates between manicured vegetation for urban or rest areas and that required for control of vegetation along typical rural highways. While mechanical control of grass is typical Agricultural and Non-chemical control is used for kerb and channel and roadside swale drains, limiting the treated width to approximately 1.0m. The target grass length range is set at 25 to 200mm on shoulders to 0.5m behind marker posts. For the remainder of the shoulder and on batters the target range is 25 to 300mm. It is expected the average grass length would be in the range of 100 to 200mm.

In 2001 Austroads published the guide "Road runoff and drainage: Environmental impacts and management options" which introduced the environmental and biodiversity focus. It drew road designer attention to the need to ensure road run-off and drainage minimized impacts on aquatic and terrestrial ecosystems by limiting changes to water quality, water quantity and water flow paths.

While the Auckland Regional Council (ARC) has had storm water management design guidelines (including Technical Publication 10 – TP10) from the early 1990's (reflecting the introduction of the Resource Management Act) the large urban problems have taken some time to be sufficiently significant for other regional councils and Road Controlling Authorities (RCA) to take up the requirements. Recently NZTA has promulgated its own storm water management guide to the industry.

3   THEORETICAL BACKGROUND AND PRIOR RESEARCH

3.1   GENERAL

Many studies have been undertaken on flow resistance in open channels with a variety of linings being studied. A description of the typical flow resistance in an open channel is achieved by balancing retarding shear flow at the boundary with the propulsive force of the weight of water flowing down the slope (Henderson, 1966). It is recognized the boundary shear stress in an open channel is non-uniform due to the existence of the free surface and the distribution varies depending on the cross sectional shape and secondary flows.

Traditional open channel flow assumes the flow depth is large relative to the boundary roughness and the boundary is rigid. While there are several equations for open channel flow hydraulics Manning's equation is that most commonly used and forms the basis of this paper. It is recognized that the Manning's equation has greatest validity under fully turbulent flow conditions and with a rigid boundary.

For SD and FS with vegetated boundaries the boundary is only apparently rigid when the flow depth is large. When the flow depth approximates the thickness of the boundary and the boundary is not rigid (such as a grassed boundary) then any empirical method applied (e.g. Darcy's Law for flow through a media or Manning's equation for flow in an open channel) needs to be carefully considered. It has been accepted by the industry that SD and FS hydraulic analysis can be represented by the Manning's equation for the full range of flow conditions. Ree (1949) identified three distinct flow regimes that become apparent when the flow

resistance for a given vegetated channel is plotted against depth or discharge. The regimes are (1) low flow with the flow depth within the bent vegetation height, (2) intermediate flow when the flow depth is at or just above submergence and (3) high flow when the flow depth is well above the bent vegetation height.

This paper addresses the flow resistance for the full range of flow regimes.

3.2   FLOW RESISTANCE AND BOUNDARY LAYER EFFECTS

The predominance of research to date has been focused on the intermediate to high flow regimes. For these flow conditions the flow resistance of an open channel is dominated by viscous and pressure drag over the wetted perimeter. For a vegetated channel the drag can be considered to have three components (USDA Handbook 667, 1987), these are: (1) the sum of viscous drag on the soil surface and the pressure drag on the soil particles (soil roughness), (2) pressure drag associated with large non-vegetal boundary or form roughness and (3) drag on the vegetal elements (vegetal roughness). Interaction of the boundary with the flow field causes the boundary roughness of the grass lined channel to become a function of the flow conditions.

Classical boundary layer theory suggests that when the flow depth is very shallow laminar flow conditions can be expected to develop. As stated by Streeter and Wylie the laminar flow equation $f = 64/\mathbf{Re}$ (where f = Darcy Weisbach friction factor and $\mathbf{Re}$ = Reynolds Number) applies to all roughnesses as the head loss in laminar flow is independent of boundary roughness.

For open channel flow it can be readily found that Manning's n and the Darcy Weisbach friction factor are related by n being a function of ($f^{1/2} R^{1/6}$). Hence for laminar flow we find that n is a function of $\{R^{1/6} (VR)^{-1/2}\}$, because $\mathbf{Re}$ is a function of VR (where V = mean flow velocity and R = hydraulic radius of the section). With this relationship it becomes a relatively easy task to undertake a sensitivity of the flow conditions to determine the laminar flow relationship with roughness (Manning's n) and this can be plotted on an n-VR graph.

Following boundary layer theory it is predicted that as the flow depth increases a transition from laminar to turbulent flow is expected. The flow conditions that would occur through the transition cannot readily be predicted and are likely to follow trends observed by Nikuradse's when testing sand roughened pipe. Testing would be required to define this transition for a vegetated boundary in an open drain.

3.3   PRIOR RESEARCH

As has been noted above considerable research has been undertaken into vegetated drain hydraulics, not only the shallow swale type but also the large flow depth wetland or marsh type. The hydraulic characteristics of these are different as reported by Ree (1949).

While it is recognized Manning's n is not as stable as f (Darcy Weisbach friction factor) with flow regime, usually represented by $\mathbf{Re}$ Reynolds Number, it has been shown that for the intermediate flow regime and for given cover and boundary conditions Manning's n can be expressed as a function of VR. This study shows that with care this relationship can be extended to the low flow regime.

Traditional resistance to flow in vegetated channels, when the flow depth is greater than or equal to submergence (occurring when the bent height of the

grass is submerged, i.e. intermediate to high flows), is well described by the Manning's equation. It has been found that Manning's n is dependent on a retardance factor described by the vegetation characteristics including height, thickness and density and the parameter VR (Chow, 1959, Henderson, 1966 and USDA SCS-TP61, 1966).

The industry accepts the method of hydraulic analysis for intermediate to high flow regimes. When a low flow regime exists there is less certainty in the hydraulic modeling.

In order to refine the ARC TP 10 and improve understanding of the usefulness of vegetated swales for treating urban and road runoff Michael Larcombe was engaged to undertake research specifically to investigate the contaminant removal and hydraulic performance of swale drains. This work, reported in 2003, forms the basis of this study. In this study and assuming Manning's equation is appropriate the reported discharges and flow depths have been back analysed to confirm the V and R terms so that the n-VR relationship could be developed. The analysis focused on the 150mm grass height as that was most relevant to roadside swale drains. In completing this analysis it was found that with the minimum reported 1% slope Manning's n was a maximum and as the slope increased to the maximum reported of 5% there was greater departure from the 1% slope n-VR relationship. In Figure 1 the 1% slope n-VR relationship has been plotted as Option 1.

Figure 1:   Proposed n-VR relationship
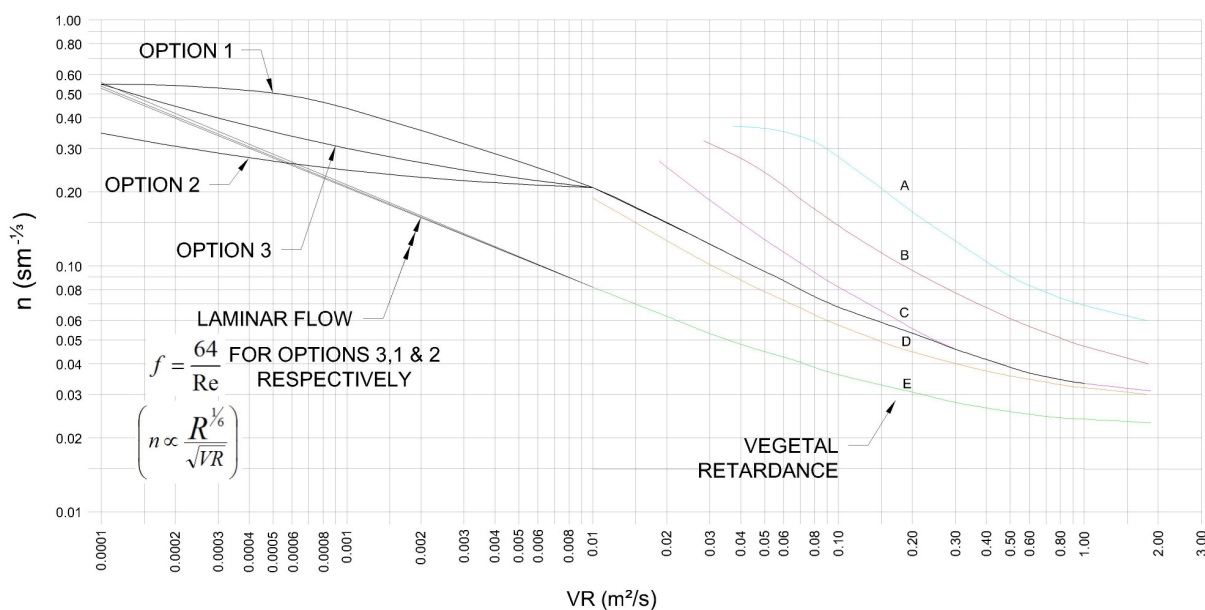
Tsihrintzis and Madiedo (2000) undertook a comprehensive review of research by others into marsh and swale drain flow and generated an n-VR graph of the compiled data. That graph has been schematically reproduced as Figure 2. The research data included in Figure 2 has been critically examined to ensure data that is relevant to SD and FS can be utilized. It is found that the data from research by Chen (1976) and Wu et al (1990) is most relevant. With typical NZTA roadside mowing specifications and typical NZ roadside vegetation a design retardance curve between Curve C and D (refer to Figure 1) is considered most relevant for flows above submergence, i.e. VR greater than or equal to 0.01m^2/s.

Figure 2: Research data compiled by Tsihrintzis and Madiedo (2000) and presented schematically in n-VR graph.
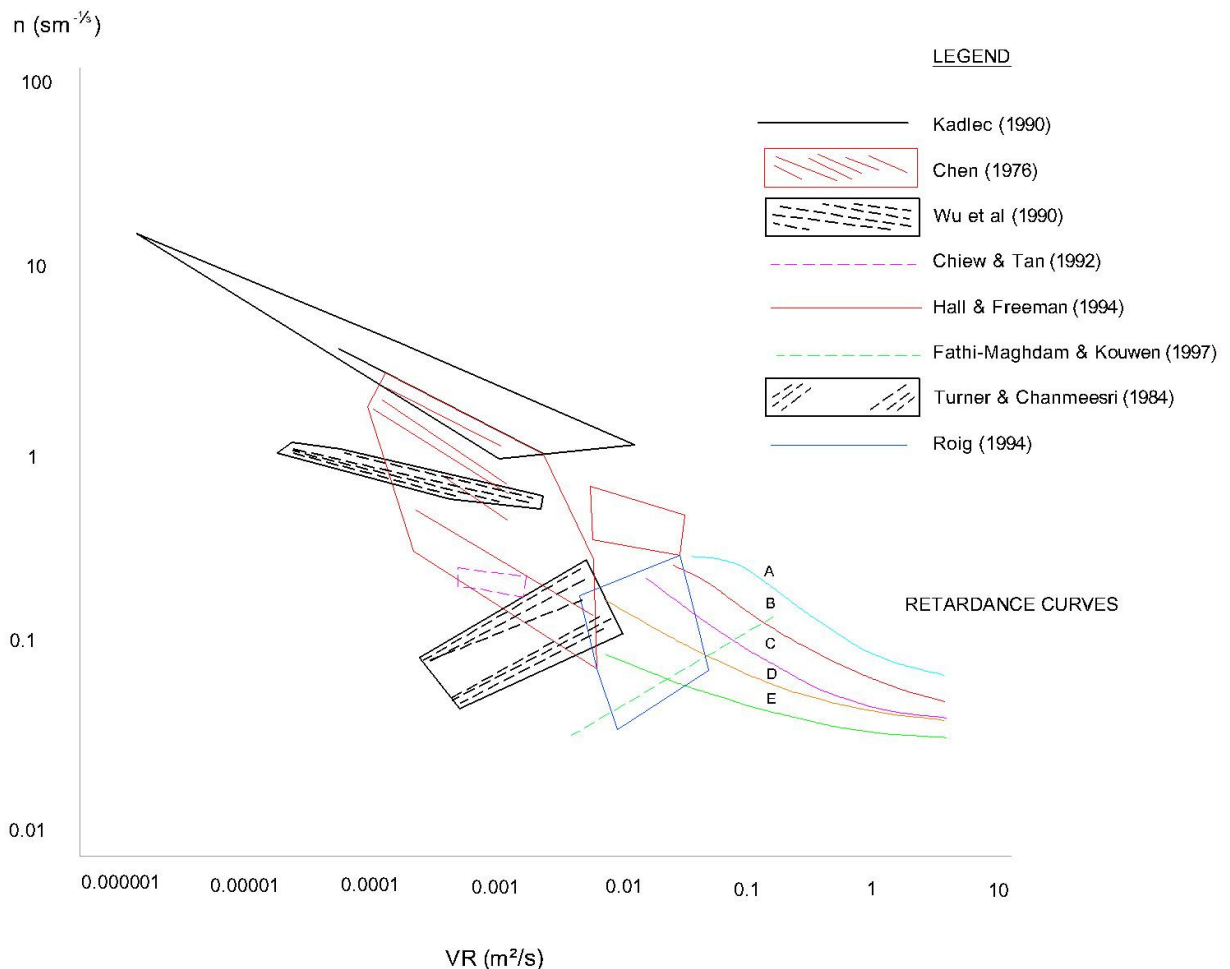
Figure 2 shows two significant differences between the Chen and Wu et al research data, they are; (1) Chen shows that drain slope is a significant factor (broad spread of the trend lines) whereas Wu et al show that drain slope is not significant (close grouping of the trend lines) and (2) the significant difference in trend line slope with Chen data relatively steep whereas Wu et al trend lines have relatively flat grades. It is interesting to note that both researchers report decreasing n with increasing VR and this is at variance to the trend suggested in USDA Handbook 667 (1987) that under low flow conditions Manning's n will tend to increase with increasing depth or discharge. The USDA Handbook 667 (1987) assertion is based on the assumption that the flow velocity within the grassed boundary is constant. Examination of the Larcombe (2003) field data clearly shows this assumption is incorrect (refer to Figure 6 in this paper).

The author has not had the opportunity to discuss these differences with the respective researchers but considers the main difference between Chen and Wu et al is the way in which the collected data has been analysed. Wu et al has reduced the data so the characteristics of the section of rough boundary are clearly reported rather than using average flow conditions. The Wu et al data reduction method is considered to generate data that can be more readily used by designers using Manning's equation and hence is considered more relevant to this study. Unfortunately the Wu et al research used relatively stiff horse hair to represent the vegetated boundary. In this study it is considered the roughness would be higher than that expected from flexible vegetation. When the Wu et al data is considered 'compressed' to a single trend line and the Manning's n

reduced to allow for the relative stiffness it can be seen the data correlates well with the Retardance Curve C/D at submergence, i.e. at a VR approximately equal to 0.01m²/s, and matches the ARC data at submergence. While the Wu et al data becomes 'linked' it provides a 'cusp' discontinuity in the relationship as shown by the Option 2 curve on Figure 1.

Recent research has focused on better defining the velocity profile across vegetated channels. Some researchers are using this information to develop more sophisticated hydraulic analysis methods to shift away from the empirical Manning's equation method. USDA Handbook 667 provides a discussion on the apparent behavior of the velocity profile as the flow depth increases from non-submerged (low flow) to a fully submerged (high flow) regime, noting that under low flow conditions the flow velocity is essentially constant. Carollo et al (2002) provides good research data on velocity profiles and while the summary shows that all test runs were undertaken with a flow depth to bent vegetation height ratio of greater than 1.6 (indicating intermediate/high flow regimes) it was reported that the velocity profile within the height of the vegetation is not constant but shows an increasing vertical velocity gradient. It is noted that in prototype swale drains the low flow is commonly observed to channelize, with the flow path dependent on small variations in vegetation stiffness and root growth. These effects have not been reported in the research papers indicating either the effect did not arise or the sampling of the velocity profile was not sufficiently comprehensive to identify it. The variation in the velocity profile is indicated schematically in Figure 3 assuming uniform flow velocity occurs within the shear less zone.

Figure 3: Velocity profile for varying flow depth.
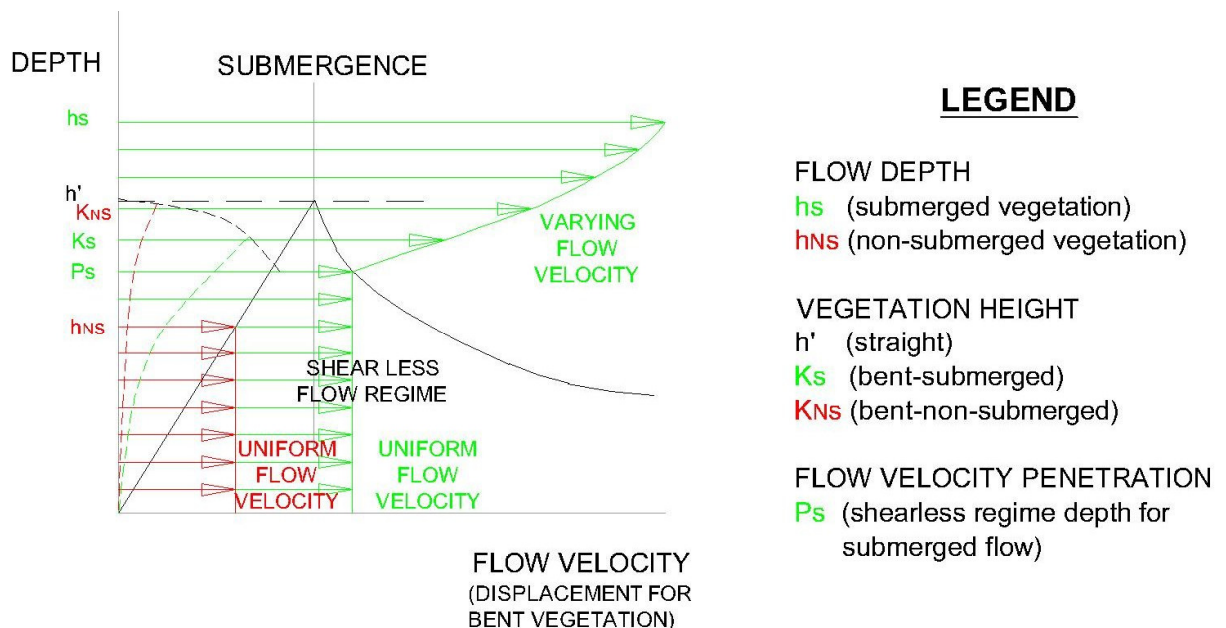
4 OBSERVATIONS AND DEVELOPMENT OF A DESIGN RELATIONSHIP

It is clear from the above discussion that the flow characteristics are not simple and vary with flow depth. It is also clear there is not full agreement within the industry on some of the trends and expectations of hydraulic characteristics. This suggests very careful consideration is required before an empirical method of analysis is applied.

Using the expected roadside vegetation conditions, from the review of relevant NZTA specifications, some confidence is gained with the correlation and 'linking' of the expected retardance curve data, the ARC research data reduced using Manning's equation and the reduced research data of Wu et al (1990) at submergence. Clearly there is industry acceptance for flow depths greater than submergence as the proposed n-VR relationship correlates well with the industry accepted retardance curves, fitting as expected between curves C and D. The correlation is poor with flow depths below submergence with the reduced ARC data (Option 1) essentially having the opposite relationship to that reported by Wu et al (Option 2). An aim of this study was to develop a proposed relationship that generalised n for a wide range of flow conditions and hence there is a need to rationalise the Option 1 and 2 curves.

In order to rationalise the design n-VR relationship it is useful to understand the expected flow conditions throughout. It is found that at submergence (VR = 0.01 m^2/s) the flow depth approximates 70 to 100mm, at a VR = 0.001m^2/s the flow depth approximates 30 to 50mm and at a VR = 0.0001m^2/s the flow depth approximates 10 to 30mm depending on the cross section shape and size of the drain. Physically it can be expected that with a VR < 0.0001m^2/s flow boundary conditions are expected to dominate over vegetal roughness and the laminar flow state can be considered. It is recognized that laminar flow conditions will give an upper bound estimate of roughness.

A sensitivity analysis was undertaken initially using the Option 1 and Option 2 relationships to determine the respective laminar flow n-VR relationship. This has been plotted on Figure 1 as an extension of the vegetal retardance Curve E, with intercept point n = 0.08sm$^{-1/3}$ and VR = 0.01m^2/s. This analysis shows that while there are significant differences between the Option 1 and 2 relationships there is remarkable stability in the laminar flow relationship. The intercept with the Option 1 relationship at VR = 0.0001m^2/s was noted and resulted in the Option 3 curve being proposed. The laminar flow relationship for Option 3 was also determined and has been presented in Figure 1. Again there was good correlation with the Option 1 and 2 laminar flow relationships. The Option 3 n-VR relationship is that recommended for roadside swale drain and filter strip design.

It is interesting to note that when the laminar flow curves in Figure 1 are transferred to Figure 2 there is close agreement between the slope of the laminar flow curves and the slope of the Chen (1976) trend lines.

It is desirable the hydraulic model trends closely match that observed and reported from research. The following sections summarise the findings and report the correlation from the analysis undertaken in this study. Before reporting the calibration findings the hydraulic analysis method used needs to be understood and hence is now discussed. The focus of the calibration is to get 'good agreement' between measured discharge and that predicted using the Manning's equation.

The method of analysis for the intermediate to high flow regimes assumes the following:

- Drain longitudinal slope is as constructed in the field

- Drain cross section is as constructed in the field

- The boundary roughness is assumed to have no thickness, hence

- The cross sectional area is based on the constructed cross section and observed or measured flow depth (no reduction is made for the vegetation)

- The wetted perimeter is based on the constructed cross section and observed or measured flow depth. A rigid and fixed boundary is assumed for model purposes

- Boundary roughness is determined from the appropriate retardance curve (n-VR relationship) taking into account the vegetation characteristics

For the low flow regime clearly the vegetated boundary significantly influences the hydraulics. The determination of the 'real' cross sectional area and the wetted perimeter is not defined and would vary with flow characteristics. In this study, as is common in the industry, it is assumed the intermediate to high flow hydraulic analysis, and parameter determination, can be used for the low flow regimes.

For the low flow regime this assumption will result in a larger flow area than that which occurs in the 'real' drain and requires a Correction Factor (CF) to be applied to be able to accurately estimate the average 'real' flow velocity characteristics. The CF is expected to depend on the flow regime that is being modeled, being low flow (non-submergence), intermediate flow and high flow (full submergence). It is expected the CF will asymptote to 1.0 for the full submergence regime. In this study the limited field data reported by Larcombe (2003) has been used to calibrate the CF. For the range of flow conditions reported by Larcombe (2003) the CF varies from approximately 2.7 at low flow depth (40mm for the tested swale drain) to 1.6 at high flow depth (69mm for the tested swale drain). However it is considered more reliable low flow velocity data is required to raise confidence with this CF and further research is recommended. The Prototype flow velocity = Model flow velocity x CF.

The water quality procedures for SD and FS design requires reliable average flow velocity data to be assessed so the treatment length can be accurately determined. It is considered necessary the flow velocity data correlate with the prototype SD or FS flow velocity as this allows in-situ testing (using a dye trace test or similar) of the constructed SD or FS and confirmation the flow characteristics meet those expected by design.

The author considers the above hydraulic analysis methodology will add robustness and hence confidence in the SD and FS water quality design.

In undertaking this study it is observed there is a significant increase in flow velocity for only a small incremental change in flow depth above submergence, refer to Figure 3. As it is expected high local velocities will result in early re-suspension of settled sediments and contaminants suggests a change in the water quality design process to maximize treatment performance is justified. For design purposes it is suggested a Peaking Factor (PF) be used to account for this effect. It is considered the PF will depend on the flow regime. There will need to be agreement in the industry on the flow depth and flow velocity increment to be adopted before the PF can be determined. The peak flow velocity for the re-suspension check = Prototype flow velocity x PF. From inspection of Figure 3 the PF could be of the order 2 or 3 depending on the flow regime and actual flow velocity profiles. Further research is hence suggested to better define the PF.

The author currently considers that the industry is trying to use the Manning's equation to predict both discharge and flow velocity in one calculation and using a 'single Manning's n value' is considered likely to result in neither predicted values being real. Only once these aspects are better understood and defined will there be confidence in using Manning's equation for hydraulic modeling of SD and FS.

5   DISCHARGE CALIBRATION

In this study detailed calibration analysis has been undertaken comparing the proposed 'single curve' n-VR relationship generated discharge with the Larcombe (2003) recommended discharge for a typical trapezoidal drain cross section with a 2m invert width and 3:1 side slopes for the typical flow depth range. The drain longitudinal grade

Figure 4:   Discharge versus Flow Depth
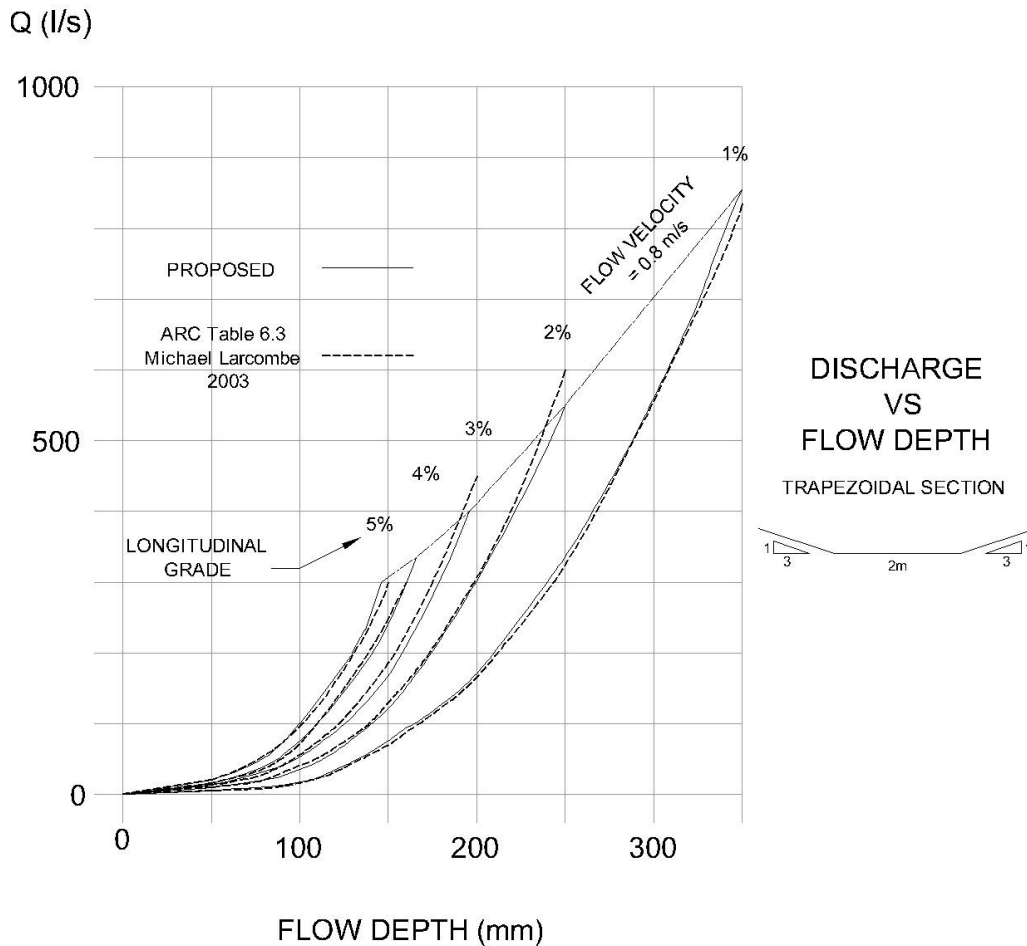
used for the calibration is in the practical 1% to 5% range. The Larcombe (2003) 150mm grass length data has been used as that best correlates to the expected roadside vegetation length of 100 to 200mm. The calibration data is presented in Figure 4.

In general it is observed there is good agreement between the Larcombe (2003) and proposed empirical Manning's equation based hydraulic model for discharge estimation. Close examination of the respective curves shows there is a trend in the small differences, with these varying with flow depth and longitudinal grade.

The author determined it was necessary to investigate this effect further and this is discussed below.

6   VELOCITY CALIBRATION

The velocity calibration has been undertaken using the same swale drain cross section, boundary roughness conditions and longitudinal grade range as for the discharge calibration. Due to limitations with the reported Larcombe (2003) data the analysis has

Figure 5:   Swale Length versus Swale Slope
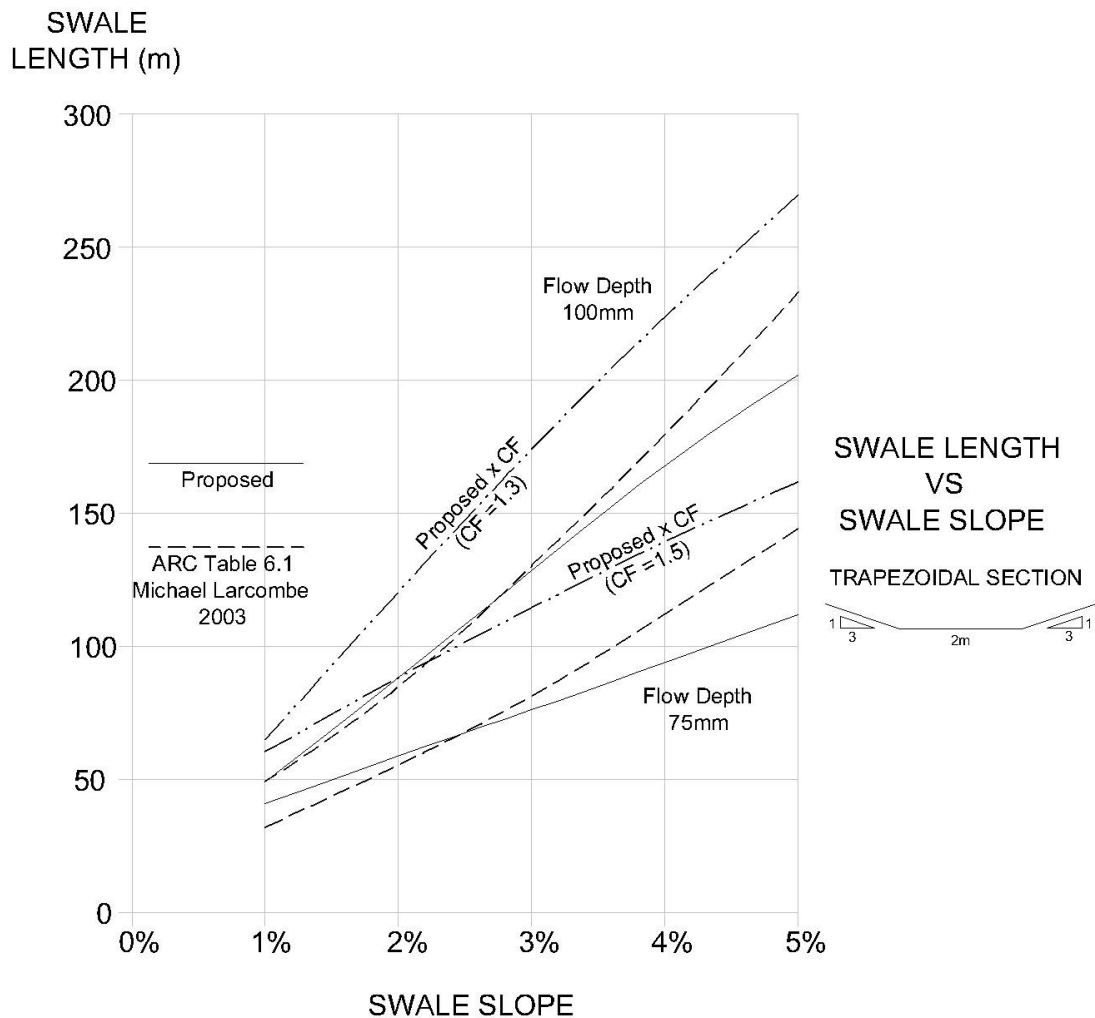
been limited to two flow depths, 75mm and 100mm. Rather than plotting velocity the swale length has been used as this is more relevant for swale treatment performance (where swale length = average flow velocity (m/s) x 540 seconds). As noted above this study recognises the need for differentiating model and prototype flow velocity and suggests the use of a CF to account for this. The 'velocity' calibration data is presented in Figure 5 with the Proposed Model data presented in both its raw and corrected form. For presentation purposes the CF has been assumed to be 1.5 and 1.3 for the 75mm and 100mm flow depth respectively.

Examination of Figure 5 clearly shows the differences in the velocity trends with the Larcombe (2003) flow velocity increasing at an increasing rate as the swale slope increases where as the Proposed Model flow velocity increases at a decreasing rate. This difference relates in principle to the difference in the n-VR relationship differences shown in Figure 1, comparing the Proposed Model (Option 3) and Larcombe (2003) (Option 1) n-VR curves. It was noted above that Larcombe (2003) reported limited field measurements on hydraulic performance. As part of this study the Larcombe (2003) measured prototype flow velocity was plotted against the maximum flow depth recorded for the constant grade swale drain, refer to Figure 6. When the measured data is extrapolated back to the origin (no velocity and no flow depth) the curve shows the flow

velocity increasing at a decreasing rate and hence confirms the Proposed Model is more appropriate. While this was one check on 'hydraulic model calibration' further checks were made as discussed below.

The other issue to be noted from this calibration is determining the Swale Length that is required for treatment purposes. Clearly there are differences and these depend on the model used and whether the CF is applied or not. It is noted that without the CF being applied there is reasonable agreement between the raw Proposed Model data and Larcombe (2003) data in the low Swale Slope range. This observation is important because the Larcombe (2003) study was undertaken with a Swale Slope of 1.6% and if the treatment performance that he has reported can be critically examined then some direction should be given on whether the Swale Length should be based on the model flow velocity or the prototype flow velocity. This matter has not been resolved in this study.

Figure 6:   Flow Velocity versus Maximum Flow Depth (Larcombe (2003))
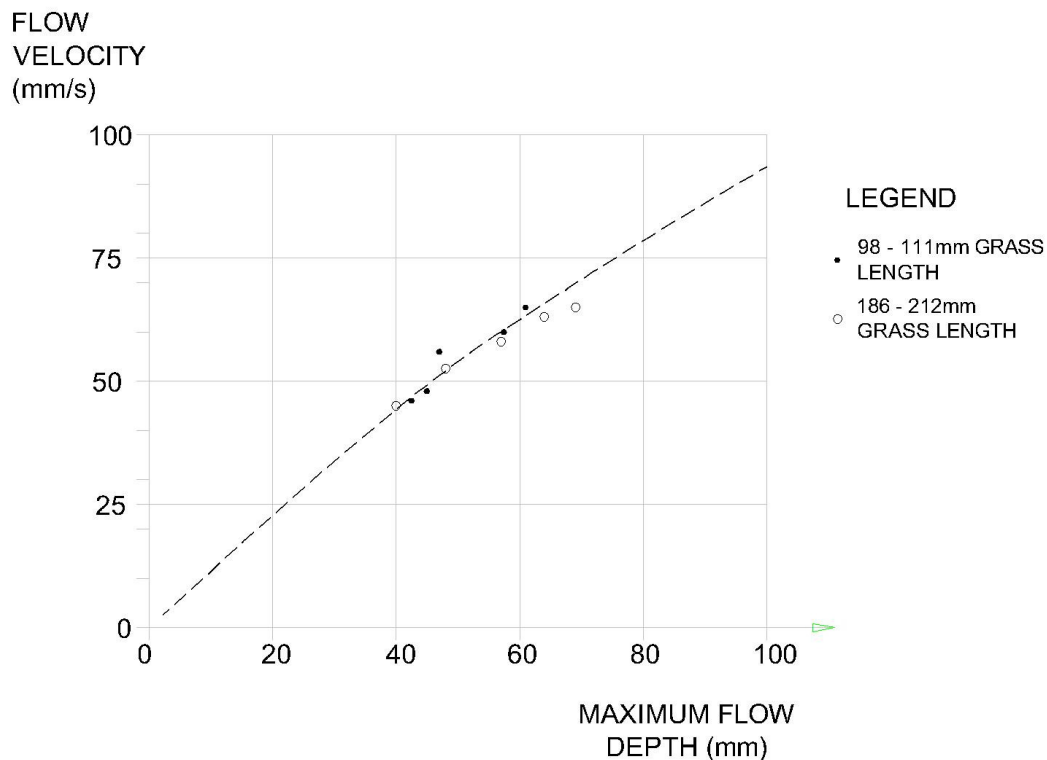
7   ROUGHNESS CALIBRATION

Calibration of discharge and flow velocity has highlighted the difference in roughness relationship and the need for determining which is more appropriate. From the velocity calibration the Proposed Model appears most appropriate. In this study no field testing has been undertaken but an 'indirect' comparative study has been made with the Wu et al (1999) reported test results. A simple 'first check' was made by taking 'constant flow

depth' and flow velocity data for the range of longitudinal slopes tested off the reported information. When this was plotted in a similar format to Figure 5 it was confirmed the flow velocity was increasing with increasing flow depth and longitudinal grade and this occurred at a decreasing rate, again giving support for the Proposed Model.

Since Option 2 and the Proposed Model Option 3 n-VR curves, refer to Figure 1, were based on the Wu et al (1999) data this agreement may not be considered relevant. It was hence decided to undertake a more rigorous 'second check'.

In this 'second check' the typical trapezoidal cross section with 2m base width and 3:1 side slopes was used to generate the full range of hydraulic data using the Proposed Option 3 n-VR relationship. The calculated data is presented in Figure 7. For comparison purposes the Wu et al (1999) research data generated for the rectangular smooth sided flume, with the horse hair invert boundary roughness has been included in this paper as Figure 8.

Figure 7: Manning's n and Flow Velocity versus Flow Depth determined using the proposed n-VR relationship
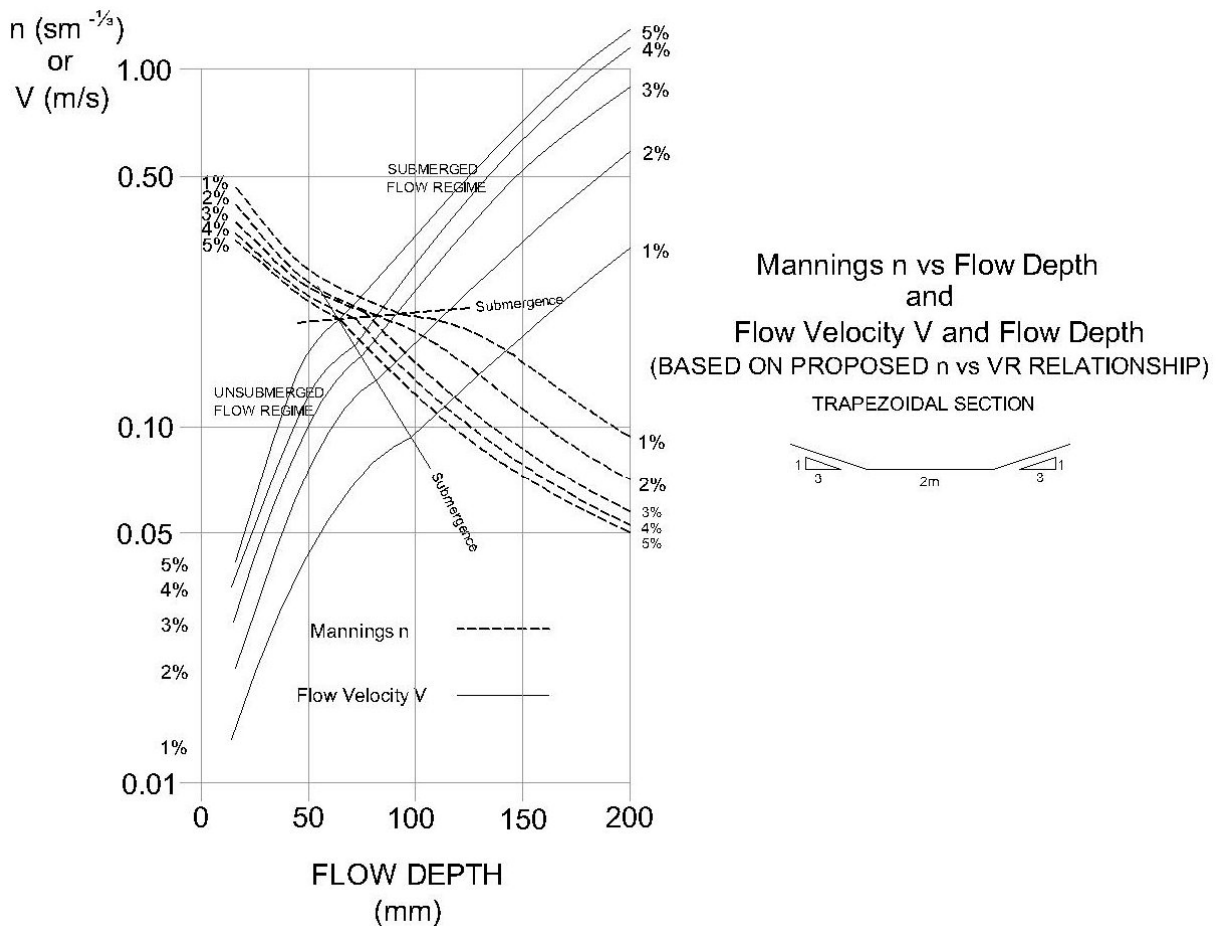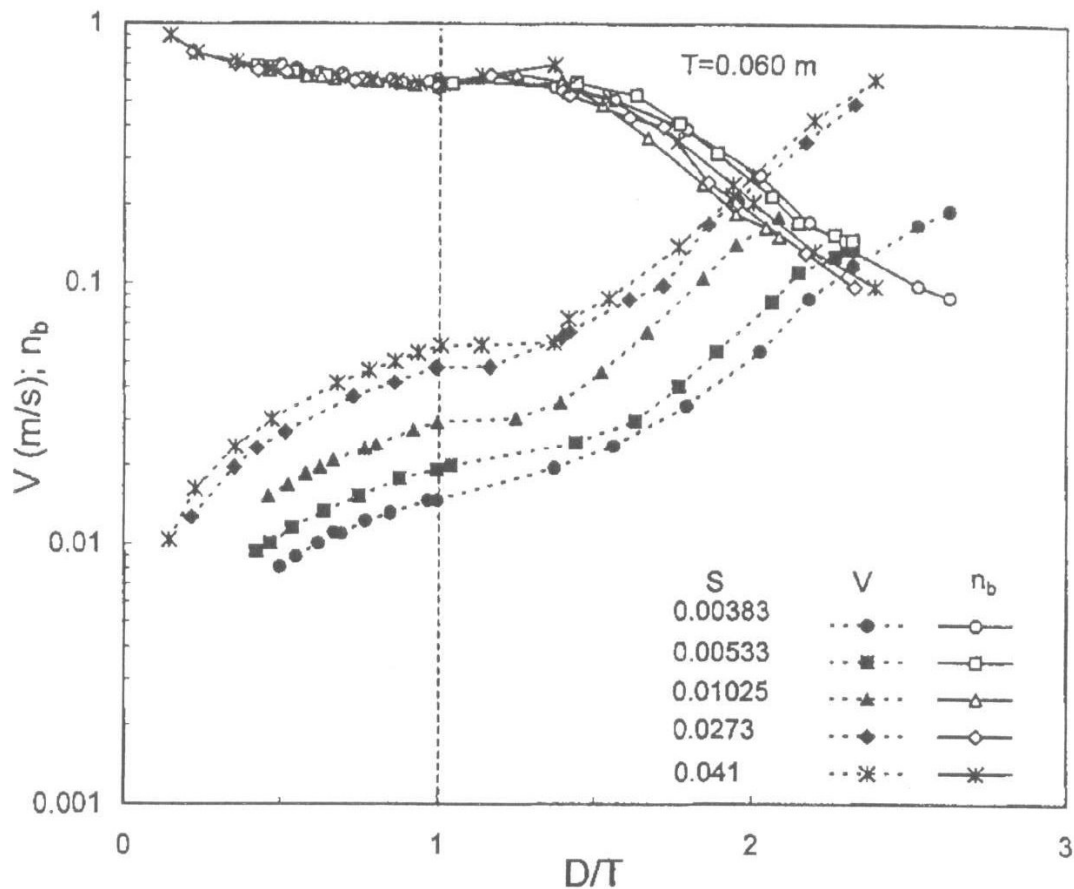
Figure 8:   Manning's n and Flow Velocity versus Normalised Flow depth for various Bed Slopes – Wu et al (1999)

Comparing Figures 7 and 8 we observe the following:

- The cross over of the Manning's n suite of curves and the flow velocity suite of curves is different because of the different drain cross section and the different boundary roughness

- The Manning's n data does follow similar trends with 'pinching' of the suite of curves below submergence and 'expansion' of the suite of curves above submergence. The suite of curves below submergence shows an increasing rate of increase with reducing flow depth for both sets of data. The suite of curves above submergence shows an asymptotic trend toward a value which can be predicted to be 0.03, the typical Manning's n for deep vegetated side drains, for both sets of data

- The flow velocity suite of curves follow similar trends with plateauing of the curves at submergence, the general slopes of the curves above and below submergence and the spread of the curves with longitudinal slope correlate well for both sets of data

- It is clear from Figure 7 that the depth of submergence varies with the swale longitudinal slope. From Figure 7 it can be inferred that a high slope with high velocity results in a lower submergence depth whereas a low slope with low flow velocity results in a higher submergence depth. This trend is not strongly obvious in Figure 8 because the Normalised Flow Depth has been used rather than the actual depth. It should be noted that T = Height

of the vegetation, which for the Wu et al (1999) research was relatively stiff horse hair and hence is not expected to give a pronounced variation in submergence depth. The author considers the 'plateau' shape of the suite of flow velocity curves does give a 'hint' of variation in submergence depth

- The effect of 'truncating' the n-VR relationship undertaken in this study does not give any observable anomalous impact on the Manning's n and flow velocity trends for the range of flow depths reported in Figure 7. It is expected that for flow depths less than 10mm the effect of 'truncating' the n-VR relationship could become pronounced

It needs to be remembered that the full set of data presented above in Figure 7 has been generated from the single curve Option 3 n-VR relationship.

While the above comparison is qualitative the author considers that in conjunction with the flow velocity calibration there is sufficient evidence to confirm the Option 3 single curve n-VR relationship is appropriate to use with the empirical Manning's equation hydraulic model and can be used to predict the hydraulic performance of high treatment performance roadside SD and FS over the full range of hydraulic conditions. The study has found that the Larcombe (2003) Manning's n data for hydraulic modeling has limited correlation to the Proposed Model roughness and hence must be used with care. The study shows that the 'single value' Manning's n design approach is a simplification and should only be used with care as a first approximation to SD or FS design.

8 DISCUSSION

This study was undertaken in recognition that current 'best practice' swale drain and filter strip design does not follow the fundamental principles and practices of Manning's equation use and as shown in this study the hydraulic parameters do not necessarily correlate well with prototype performance, in particular it under estimates the flow velocity. The review undertaken and back calculation of data presented by Larcombe (2003) from research undertaken in New Zealand resulted in the development of a multi-curve n-VR relationship of which only the low longitudinal swale slope (1%) data was presented as Option 1 in Figure 1.

Examination of prior research identified that the work of Wu et al (1999) was most relevant because of the range of flow conditions examined and the method used to reduce the measured data to that related to the roughened boundary. It is recognized the research work was undertaken in a flume with smooth sides and the boundary roughness was a relatively stiff horse hair rather than flexible vegetation. The Wu et al (1999) research data was rationalized into a single curve n-VR relationship and that is presented as Option 2 in Figure 1.

Following consideration of boundary layer theory and the expectation that laminar flow conditions would occur with shallow flow depth it was decided a truncated n-VR relationship would be appropriate for design. With the application of classical laminar flow theory Option 3 single curve n-VR relationship was developed and has been used for calibration purposes.

The primary calibration has been undertaken against the research undertaken by Larcombe (2003) and used by the ARC in the development of its TP 10 design guide. The calibration work shows the Larcombe (2003) data does not conform to a single curve n-VR relationship and the characteristics of the n-VR relationships are significantly different, refer to Figure 1 and compare the Option 1 and Option 3 curves. The calibration work using all the relevant research data shows that the Proposed Model Option 3 n-VR curve gives the best correlation and hence is most appropriate for designing swale drains and filter strips for all flow regimes. The study hence cautions

designers using the ARC TP 10 Manning's n roughness data and those using single value Manning's n data for analysis.

The study has shown that when good correlation is achieved using the empirical Manning's equation hydraulic analysis for flow discharge then the prototype flow velocity is under estimated because the model calculations ignore the volume of the grass in the boundary and its effect on waterway area. The study suggests this can be overcome by applying a multiplicative Correction Factor to the model flow velocity. It is recognized the Correction Factor will vary with flow regime.

Since the study has determined that a single curve n-VR relationship is appropriate it implies that once prototype testing has been undertaken to develop the relationship between prototype flow velocity and discharge the hydraulic parameters, irrespective of the flow cross section and longitudinal slope, can be reduced to basic flow area and hydraulic radius parameters then generalized data can be produced. Using this technique negates the need to develop the actual empirical Manning's equation model. While the Larcombe (2003) field measurements provide some data for the low flow regime considerably more data is required to generate hydraulic data for the full range of flow conditions. It is expected this testing would produce the Correction Factor data required.

When reviewing the research undertaken in this topic area it was interesting to note the work of Bateman et al (2005). Through their research a 'new integrated hydro-mechanical' model has been developed and the reporting suggests good agreement to prototype measurements. At this stage it is considered the calibration is in-complete and the testing has been with laboratory flumes and not with prototype swale drains and filter strips. It is considered that if good agreement can be achieved with prototype systems then using this model may negate the need for physical model testing. Should the new integrated hydro-mechanical model become a cost effective 'every day design tool' then of course it would supersede the need to have empirical models. From this study it is considered further work is required to translate theoretical mechanical characteristics of the vegetation to the industry recognized vegetal retardance characteristics. It is considered the development of this new model should be monitored to assess its use in New Zealand. At this time it is considered that for cost effectiveness and simplicity the Manning's equation is still most appropriate for roadside drainage design.

While this study has not specifically addressed water quality issues the importance of the hydraulic data for that design is recognized. This study has identified two aspects of hydraulic design which should be taken into account for Swale Drain and Filter Strip design in New Zealand and recommends a review of the design criteria.

The first is the fact that the prototype flow velocity is higher than the model determined flow velocity. It is considered that having the water quality design criteria based on prototype flow velocity is advantageous since this is a parameter that can be readily measured in the field (e.g. using a dye trace test) to give increased confidence treatment performance requirements will be met. This study has determined that the Larcombe (2003) research should be used as a start point because it has been shown that for the 1.6% longitudinal swale slope the hydraulic model results of Larcombe correlate well with the Proposed Model data for a flow depth range between the low and intermediate flow regimes.

The second hydraulic effect identified and which is considered to significantly affect swale drain and filter strip performance is recognizing the significant increase in flow velocity immediately above submergence depth and the high potential for re-suspension of settled sediment and contaminants. It is considered this effect must be controlled in swale drain design since flow depths are likely to exceed submergence depth and should be checked for filter strip design when large flow depths are considered unlikely. This effect is separate from any check undertaken under high flow depths for drain erosion control purposes. When using an empirical Manning's equation model it is considered this

incremental velocity effect can be determined by using the prototype average flow velocity and using a multiplicative Peaking Factor. It is expected this Peaking Factor will be dependent on the flow regime.

9 CONCLUSIONS

This paper summarises a study into hydraulic modeling of high performance vegetated roadside swale drains and filter strips. The study is focused on increasing the robustness and confidence in applying the empirical Manning's equation and involves developing a generalized Manning's n roughness for all flow regimes. The study has found that a single curve n-VR relationship is appropriate and this extends the industry accepted retardance curve methodology and hence will fit into normal design office practice. It is shown that while good correlation can be achieved with prototype discharge significant variations from prototype flow velocity must be expected. The study has suggested a methodology for accurately estimating prototype flow velocity. More research is required to define prototype flow velocity characteristics for all flow regimes. The study suggests the water quality design criteria be reviewed and updated to ensure best use is made of the more accurate flow velocity data. The study concludes that caution must be used when using the ARC TP 10 Manning's n data or other simplified methods as they have limited applicability.

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