Stream roughness. Four case studies from Victoria.

Simon Lang
Research Assistant
Department of Civil Engineering
Monash University, 3080

Tony Ladson
PhD, MSc, BE (Hons)
Department of Civil Engineering
Monash University, 3800

Brett Anderson
BE (Hons), BBus
The Cooperative Research Centre for Catchment Hydrology
School of Anthropology, Geography and Environmental Studies
The University of Melbourne, 3010

Ian Rutherford
PhD, BA (Hons)
The Cooperative Research Centre for Catchment Hydrology
School of Anthropology, Geography and Environmental Studies
The University of Melbourne, 3010

Summary:

In many open channel hydraulic calculations the selection of an appropriate stream roughness coefficient, such as Manning's *n*, is required, but often this is not straightforward. In other countries, particularly New Zealand and the United States, roughness coefficients have been collected for broad classes of streams, different types of vegetation and specific discharge conditions. Pictorial guides provide a firm basis for estimating these roughness coefficients. In Australia at present, there is no recognised guide for selecting stream roughness coefficients. To remedy this situation, the Cooperative Research Centre for Catchment Hydrology (CRCCH), the National Rivers Consortium, and Land and Water Australia, have been working together to collect examples of streams where roughness coefficients have been measured. This paper presents four case studies for use in this Handbook. At four sites in Victoria, the Acheron River at Taggerty, the Merrimans Creek at Stradbroke West, the Mitta Mitta River at Hinomunjie Bridge and the Tambo River at Ramrod Creek, reach-representative Manning's *n* were calculated for various discharges. Values of Darcy-Weisbach's *f* and Chezy's *C* were then calculated from Manning's *n*. Manning's *n* was found to remain almost constant over large ranges of discharge.

Notation

A	area of wetted channel cross-section
ΔA	percentage expansion in area from upstream to downstream cross-section
ARI	average recurrence interval
α	Coriolis coefficient
C	Chezy's roughness coefficient
f	Darcy-Weisbach's friction factor
g	gravitational acceleration
h	water surface elevation (stage)
h_f	head loss due to boundary friction
h_v	velocity head
Δh	upstream water surface elevation minus downstream water surface elevation
Δh_v	upstream velocity head minus downstream velocity head
k	a coefficient for defining energy losses due to diverging or converging flow
L	length of reach
m	number of cross-sections
n	Manning's roughness coefficient
Q	discharge
R	hydraulic radius of channel cross-section
S_f	friction slope

S_w	water surface slope
V	mean velocity
X	a factor equal to $AR^{1/2}$
Z	a factor equal to $AR^{2/3}$
%	percent of time in which discharge from a stream is less than the discharge of interest

1 Introduction

Stream roughness is a critical parameter for open channel calculations and has an important influence on hydrographic and engineering practice. For example, estimating discharge in ungauged catchments is a common requirement when working on stream management problems. Estimates of discharge are required for the design of meander restoration, grade control structures, sediment transport rates, habitat improvement works, and stable channel size and shape.

The standard method for estimating natural stream flows is to use Manning's formula,

$$Q = \frac{1}{n} AR^{2/3} S_f^{\;1/2}, \tag{1}$$

where Q is the discharge (in m^3/s), n is Manning's roughness coefficient, A is the area of the wetted channel cross-section (in m^2), R is the hydraulic radius of the channel cross-section (in m) and S_f is the friction slope (often referred to as the energy gradient). Use of this formula (or something similar) requires estimating the resistance to flow in the form of a stream roughness coefficient such as Manning's n.

Specifying an accurate roughness coefficient for a natural channel is not straightforward. Manning's n is used to express quantitatively the degree of retardation of the flow[1,2] by incorporating the many factors that contribute to the loss of energy in a stream channel. The major factor is channel-surface roughness, which is determined by the size, shape and distribution of the grains of material that line the bed and sides of the channel. Five other main factors are channel-surface irregularity, channel-shape variation, obstructions, type and density of vegetation, and degree of meandering.[1] Five additional factors that affect energy loss in a channel, and hence Manning's n, are flow depth, seasonal changes in vegetation, amount of suspended material, bedload, and changes in channel configuration due to deposition and scouring.[3] Although these factors are identifiable, their individual contributions to the total roughness, and therefore the value of Manning's n are difficult, if not impossible, to quantify.[2]

In New Zealand and the US, to assist those requiring estimation of stream roughness coefficients, Manning's n for wide-ranging classes of streams at different discharges have been collected and published. Hicks and Mason[4] includes estimates of Manning's n for 78 streams in New Zealand, and

Barnes[5] includes estimates of Manning's *n* for over 50 streams in the US. Both these publications include color photos that serve to guide Manning's *n* estimation in streams not included in their studies, but appearing physically similar to those that are. The applicability of these guides to Australian conditions has not been tested and therefore there is large uncertainty involved with using this method to estimate Manning's *n* in Australian streams. At present, there is no recognised guide to selecting Manning's *n* in Australian streams.

Improved estimation of stream roughness coefficients has the potential to provide benefit to those working in the area of hydraulics, including hydrographers, and to reduce costs to society. Inaccurate estimation of roughness coefficients adds substantially to the cost of river management and stream restoration works. For example, overly conservative estimation of tail-water depths for rock chute design can increase costs by between 20% and 100%, typically $1,000 to $20,000 or more, per structure.

Duncan, Weinmann and Wellington[6] wrote that the most promising method for improved estimation of Manning's *n* in natural Australian streams was a comprehensive data bank of Manning's *n* for typical stream reaches, accompanied by descriptive and photographic information.

If at a stream reach, stage at more than one cross-section, and discharge are measured simultaneously, wetted cross-sectional area, hydraulic radius and friction slope can be calculated (and discharge is known), leaving Manning's *n* the only unknown of equation (1). There have been only four sites in Victoria meeting this criterion – the Acheron River at Taggerty, the Merrimans Creek at Stradbroke West, the Mitta Mitta River at Hinnomunjie Bridge and the Tambo River downstream of Ramrod Creek. Field data from these sites have enabled direct measurement of Manning's *n* over a large range of discharges. Values of Darcy-Weisbach's *f* and Chezy's *C* have then been calculated from Manning's *n*. Results are presented in the same format as used by Hicks and Mason.[4]

2 Data Collection

Arnold et al[7] state that the ideal characteristics of a reach to which Manning's formula is applied, are:

- it is straight
- its length is at least five times its width
- it has uniform cross-sections or is converging
- its flow is contained without overflow
- it has straight entrance and exit conditions, with no backwater effects

Site visits to the Acheron River at Taggerty, the Merrimans Creek at Stradbroke West, the Mitta Mitta River at Hinnomunjie Bridge and the Tambo River downstream of Ramrod Creek showed these stream reaches satisfied these characteristics to the best extent hoped for in natural conditions. Indeed, these stream reaches are used as gauging sites within the Victorian stream-monitoring network because they meet these characteristics. Photos of the stream reaches are presented in Section 4.

Raw data used in this paper consisted of the following:

Table 1. Raw data collected for measuring Manning's *n* at the four Victorian sites.

Site	**Dates**	**Number of simultaneous stage and discharge measurements**	**Number of surveyed cross-sections at which stage measurements were taken**
Acheron River	1993, 1994	11	3
Merrimans Creek	1984, 1985	4	3
Mitta Mitta River	1983, 1984, 1985, 1986, 1990	15	5(stream depth measured at 3)
Tambo River	1983, 1984, 1985, 1988	8 (5* unable to be used)	4

* discharge above surveyed channel cross-section.

All the stream reaches are in the vicinity of gauging stations (Figure 1). Stage is measured automatically by the gauging station and discharge determined from the applicable rating table.

Figure 1. The gauging station for the Merrimans Creek at Stradbroke West.

In addition to the gauging station, each site has at least three surveyed cross-sections at different locations along the stream reach (Figure 2). Wetted cross-sectional area and wetted perimeter (and therefore hydraulic radius) are determined at each location using the surveyed cross-sections and the stage measured manually from gauge boards.

Figure 2. The gauge boards at surveyed cross-sections 2 and 3 on the Merrimans Creek at Stradbroke West.

Water surface slope is determined from measurements of stage to the same datum at the upstream and downstream cross-sections (Figure 3). The change in elevation of the water surface and the length of the stream reach are required to calculate friction slope.

3 Calculating Manning's n

Manning's *n* is intended for use in equation (1).

The friction slope is defined as

$$S_f = \frac{h_f}{L} = \frac{\Delta h + \Delta h_v - k(\Delta h_v)}{L}, \tag{2}$$

where (as shown in Figure 3) h_f is the head loss due to boundary friction along the reach, L is length of reach, Δh is the change in elevation of the water surface between the upstream and downstream cross-sections, Δh_v is the change in velocity head between the upstream and downstream cross-sections and $k(\Delta h_v)$ approximates the energy loss due to acceleration or deceleration in a contracting or expanding reach. Following the work of Chow[3] and Barnes,[5] k is assumed equal to zero for contracting reaches and 0.5 for expanding reaches.

The velocity head, h_v, at a cross-section is

$$h_v = \alpha \frac{V^2}{2g}, \tag{3}$$

where α is the Coriolis coefficient, which indicates the uniformity of velocity across the channel, V is the mean velocity and g is the acceleration due to gravity. Typically α has a value greater than 1.0 for most natural channel conditions,[4] however following the work of Chow,[3] Barnes[5] and Jarrett[8] α is assumed to be 1.0.

For this project, following the procedures documented in Barnes,[5] Jarrett[8] and Hicks and Mason,[4] a representative Manning's *n* for multi-section reaches is obtained by equating the head loss due to friction calculated from the friction slope in equation (1) with the head loss due to friction given by equation (2). That is, from (1),

$$h_f = h_{f\,1.2} + h_{f\,2.3} + \ldots\, h_{f\,(m-1).m};$$
$$h_f = n^2 Q^2 \left(\frac{L_{1.2}}{Z_1 Z_2} + \frac{L_{2.3}}{Z_2 Z_3} + \ldots\, \frac{L_{(m-1).m}}{Z_{(m-1)} Z_m} \right), \tag{4}$$

where *m* is the number of cross-sections (with the *m*th cross-section being furthest upstream) and $Z = AR^{2/3}$, and from equation (2),

$$h_f = (h_m - h_1) + (h_{V\,m} - h_{V\,1}) - (k_{1.2}\Delta h_{V\,1.2} + k_{2.3}\Delta h_{V\,2.3} + \ldots\, k_{(m-1).m}\Delta h_{V\,(m-1).m}). \tag{5}$$

where *h* is the stage.

Therefore, from equation (4) and equation (5),

$$n = \frac{1}{Q}\left(\frac{(h_m - h_1) + (h_{v\,m} - h_{v1}) - (k_{1.2}\Delta h_{v1.2} + \ldots\, k_{(m-1).m}\Delta h_{v\,(m-1).m})}{\frac{L_{1.2}}{Z_1 Z_2} + \frac{L_{2.3}}{Z_2 Z_3} + \ldots\, \frac{L_{(m-1).m}}{Z_{m-1} Z_m}} \right)^{1/2}. \tag{6}$$

Reach-representative values of other hydraulic parameters presented were determined as follows:

Water surface slope, $$S_w = \frac{(h_m - h_1)}{L}. \tag{7}$$

Hydraulic radius, $$R = \frac{(R_1 + R_2 + \ldots\, R_m)}{m}. \tag{8}$$

Wetted channel cross-sectional area, $$A = \left(\frac{A_1 + A_2 + \ldots\, A_m}{m} \right). \tag{9}$$

Mean velocity, $$V = \left(\frac{Q}{A_1} + \frac{Q}{A_2} + \ldots\, \frac{Q}{A_m} \right) \frac{1}{m}. \tag{10}$$

Percentage expansion, $$\Delta A = 100 \frac{(A_1 - A_m)}{A_m}. \tag{11}$$

ΔA shows the extent to which the reach is either expanding (positive value) or contracting (negative value) between its upper and lower cross-sections.

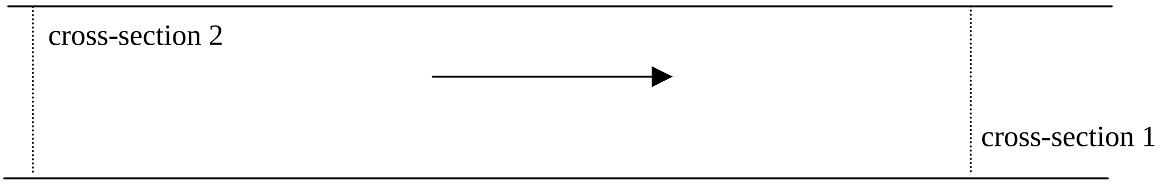
Chezy's C, $$C = \frac{R^{1/6}}{n}. \tag{12}$$

Darcy-Weisbach's friction factor, $$f = 8g \left(\frac{n}{R^{1/6}} \right)^2. \tag{13}$$

The average recurrence interval (ARI) of each discharge was determined using the partial flood series derived from the maximum instantaneous flow data from each site. The method used is outlined in Australian Rainfall and Runoff, Book IV, Section 2.[9] 28 years of data was available from the Acheron River at Taggerty, 10 years of data from the Merrimans Creek at Stradbroke West, 47 years of data from the Mitta Mitta River at Hinnomunjie Bridge and 28 years of data from the Tambo River downstream of Ramrod Creek.

Lack of daily flow data from the Merrimans Creek at Stradbroke West meant a log-normal line of best fit to the annual flood series was the best estimate of ARI's for discharges from this site, and hence confidence in the presented values is low.

The percent of time in which discharge from the stream is less than the discharge of interest was also calculated.



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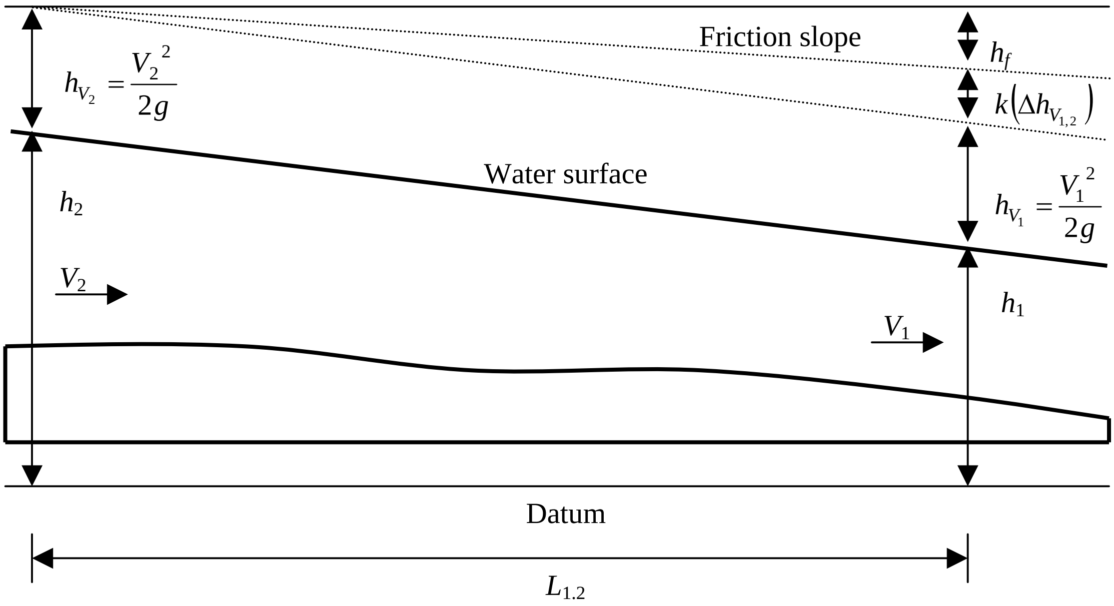


PROFILE

Figure 3. A definition sketch for a two cross-section reach.[4] Friction slope is required to calculate Manning's *n*. The friction slope is defined as $S_f = \frac{h_f}{L} = \frac{\Delta h + \Delta h_v - k(\Delta h_v)}{L}$ where h_f is the head loss due to boundary friction along the reach, L is length of reach, Δh is the change in elevation of the water surface between the upstream and downstream cross-sections, Δh_v is the change in velocity head between the upstream and downstream cross-sections and $k(\Delta h_v)$ approximates the energy loss due to acceleration or deceleration in a contracting or expanding reach.

4 Results

4.1 Acheron River at Taggerty

Table 2. Physical properties of reach – Acheron River at Taggerty.

Gauge No.	405209
Drainage area	619 km^2
Map Reference	Warbuton SJ55-6 Edition 1 Latitude 37.317° Longitude 145.717°
Average daily flow	800 ML/day
Flow data	www.vicwaterdata.net
Period of record for slope gauges	11.05.93 – 02.08.94
Manning's n range	0.034 – 0.047
Cross-Section 3	Gauging Station
Cross-Section 2	191.5 metres downstream of Cross-Section 3
Cross-Section 1	283.0 metres downstream of Cross-Section 3

Figure 4. The Acheron River at Taggerty (1st August 2002, discharge 5.16 m^3/s).

Figure 5. View downstream from top of reach (1st August 2002, discharge 5.16 m^3/s) – Acheron River at Taggerty

Figure 6. View downstream from middle of reach (1st August 2002, discharge 5.16 m^3/s) – Acheron River at Taggerty.

Table 3. Hydraulic properties of reach – Acheron River at Taggerty.

Discharge (m^3/s)	**ARI** (yr)	**Flow Percentile**	**Water Surface Slope**	**Friction Slope**	**Area** (m^2)	**Expansion** (%)	**Hydraulic Radius** (m)	**Mean Velocity** (m/s)	**Manning *n***	**Chezy *C***	**Darcy and Wiesbach *f***
3.17	0.1	26.8%	0.00002	0.00003	28.21	51%	1.23	0.12	0.047	22.0	0.162
15.74	0.2	80.5%	0.00011	0.00012	38.68	39%	1.56	0.41	0.034	32.1	0.076
17.04	0.2	82.7%	0.00013	0.00015	39.60	38%	1.59	0.44	0.036	30.0	0.087
19.10	0.2	85.1%	0.00021	0.00023	40.56	36%	1.62	0.48	0.042	26.1	0.115
21.06	0.2	87.1%	0.00025	0.00026	42.16	34%	1.67	0.51	0.043	25.2	0.124
21.64	0.2	87.8%	0.00025	0.00026	42.65	34%	1.63	0.52	0.043	25.5	0.121
22.82	0.2	88.9%	0.00030	0.00032	43.53	33%	1.61	0.53	0.045	23.9	0.138
26.50	0.3	91.5%	0.00030	0.00032	46.70	34%	1.66	0.58	0.043	25.1	0.124
34.55	0.4	95.2%	0.00042	0.00045	52.66	33%	1.75	0.67	0.046	23.7	0.140
42.55	0.5	97.2%	0.00046	0.00049	59.84	37%	1.84	0.72	0.046	23.9	0.137
72.94	1.7	99.7%	0.00085	0.00090	81.94	43%	1.45	0.91	0.043	24.9	0.126

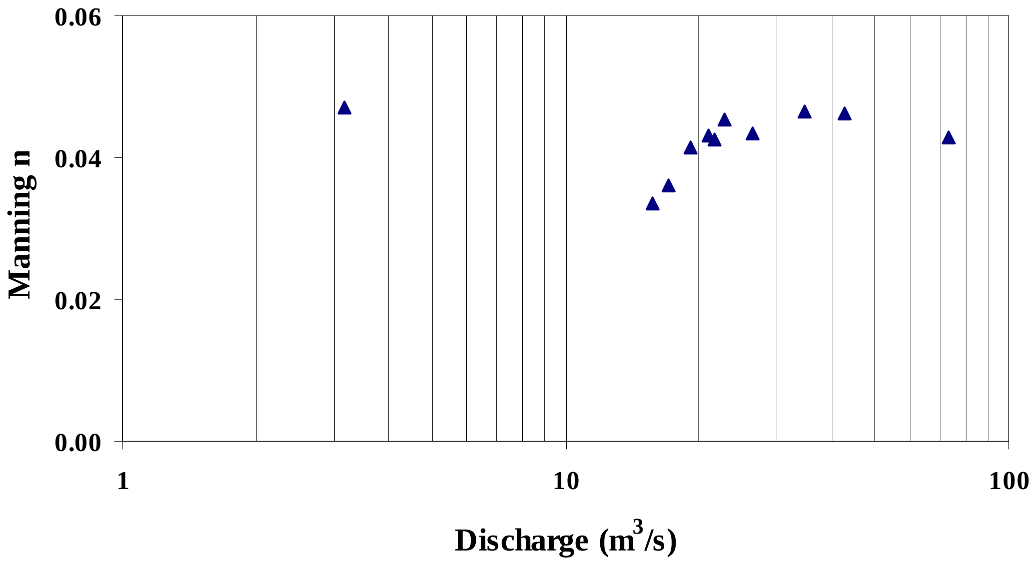


Figure 7. Manning’s *n* against discharge – Acheron River at Taggerty.

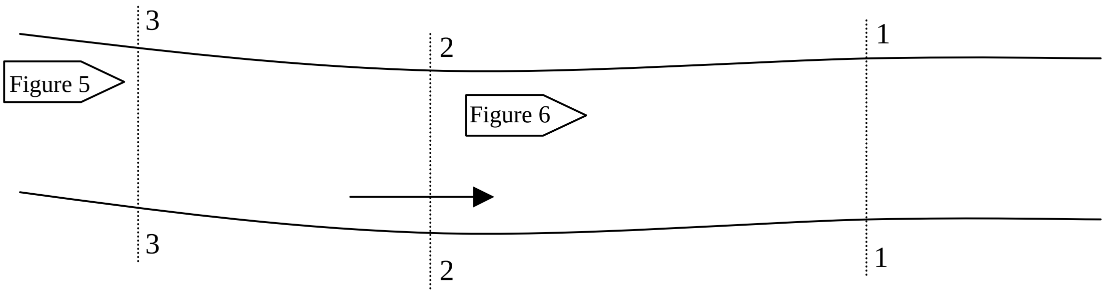


Figure 8. Plan view (not to scale) – Acheron River at Taggerty.

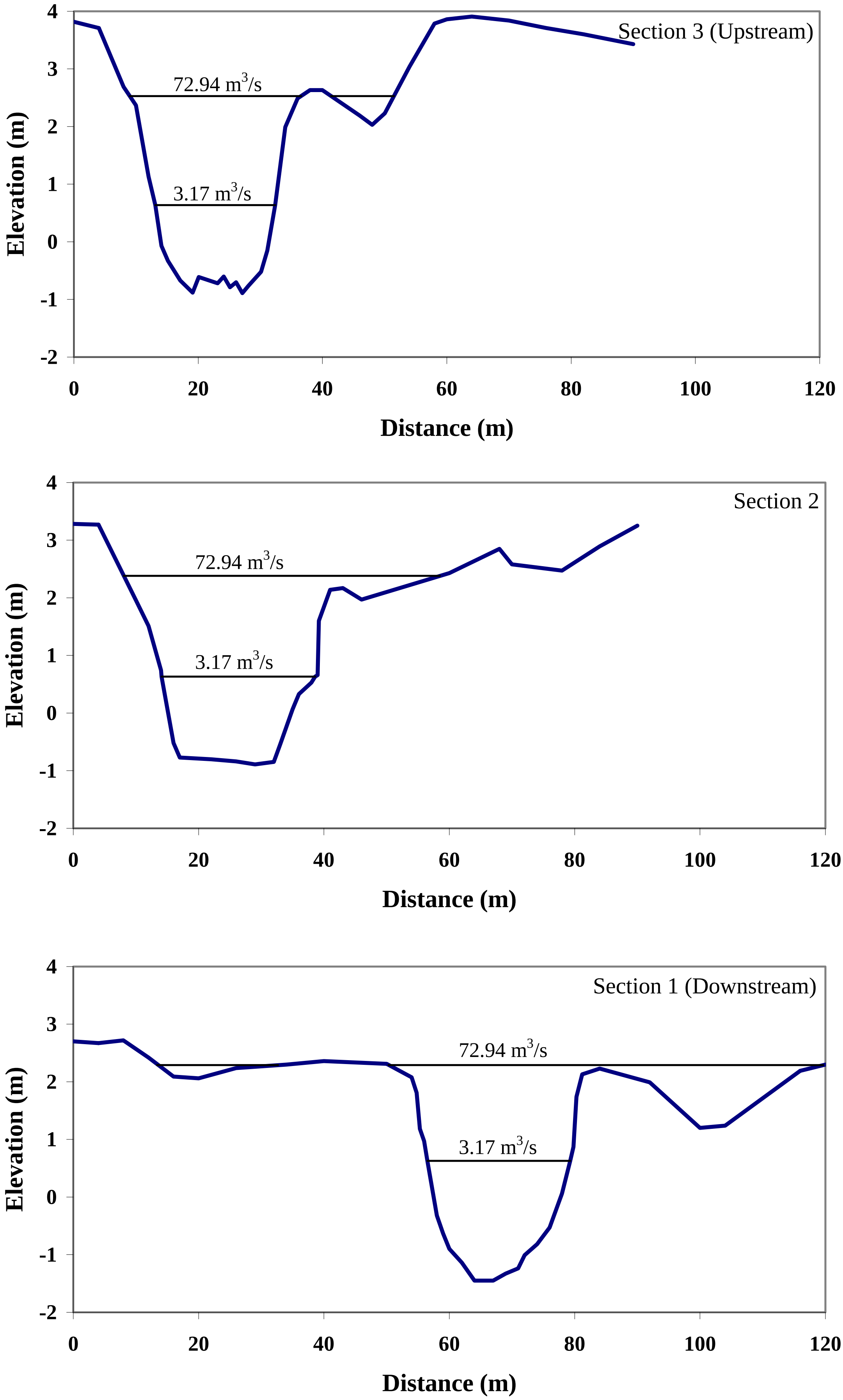


Figure 9. Cross-sections 1, 2 and 3 – Acheron River at Taggerty.

4.2 Merrimans Creek at Stradbroke West

Table 4. Physical properties of reach – Merrimans Creek at Stradbroke West

Gauge No.	227239
Drainage area	256 km^2
Map Reference	Sale SJ55-11 Edition 1 Latitude 38.270° Longitude 146.910°
Average daily flow	255 ML/day
Flow data	www.vicwaterdata.net
Period of record for slope gauges	30.07.84 – ongoing
Manning's n range	0.076 – 0.080
Cross-Section 3	68.4 metres upstream of Cross-Section 2
Cross-Section 2	
Cross-Section 1	59.7 metres downstream of Cross-Section 2

Figure 10. View downstream from top of reach (1st April 2003, discharge (recorded downstream at Seaspray) 0.047 m^3/s) – Merrimans Creek at Stradbroke West.

Figure 11. View upstream from bottom of reach (1st April 2003, discharge (recorded downstream at Seaspray) 0.047 m^3/s) – Merrimans Creek at Stradbroke West.

Figure 12. View downstream from middle of reach (1st April 2003, discharge (recorded downstream at Seaspray) 0.047 m^3/s) – Merrimans Creek at Stradbroke West.

Table 5. Hydraulic properties of reach – Merrimans Creek at Stradbroke West.

Discharge (m^3/s)	ARI (yr)	Water Surface Slope	Friction Slope	Area (m^2)	Expansion (%)	Hydraulic Radius (m)	Mean Velocity (m/s)	Manning *n*	Chezy *C*	Darcy and Weisbach *f*
8.56	1.1	0.00027	0.00027	30.38	3%	1.60	0.28	0.076	14.2	0.387
15.12	1.2	0.00035	0.00035	42.82	9%	1.90	0.35	0.079	14.1	0.395
31.31	1.6	0.00055	0.00056	63.24	13%	2.22	0.50	0.080	14.3	0.385
36.49	1.8	0.00059	0.00060	68.77	13%	2.31	0.53	0.080	14.4	0.378

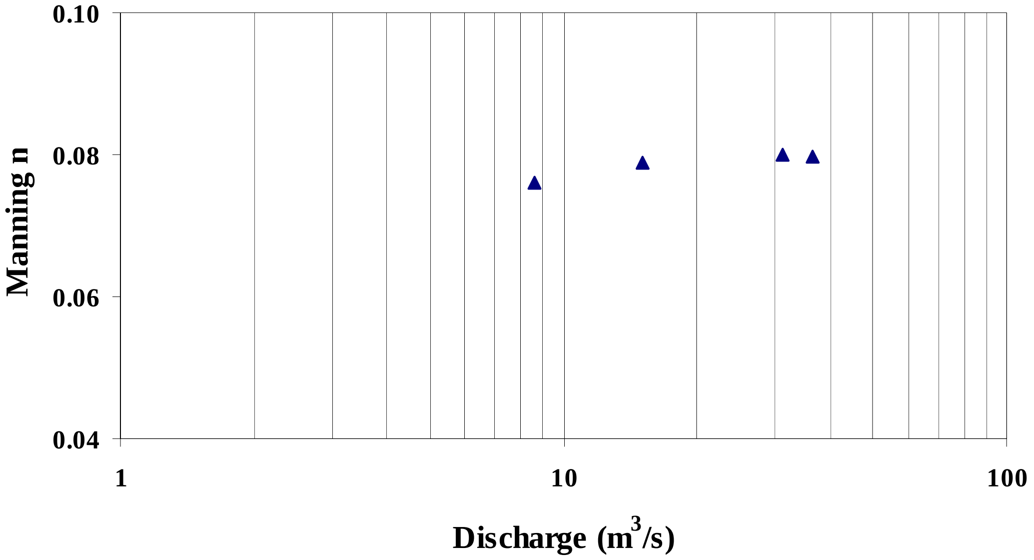


Figure 13. Manning’s *n* against discharge – Merrimans Creek at Stradbroke West.

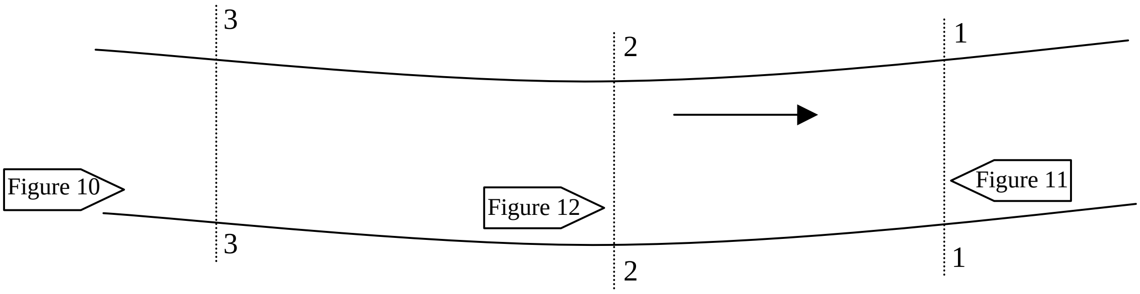


Figure 14. Plan view (not to scale) – Merrimans Creek at Stradbroke West.

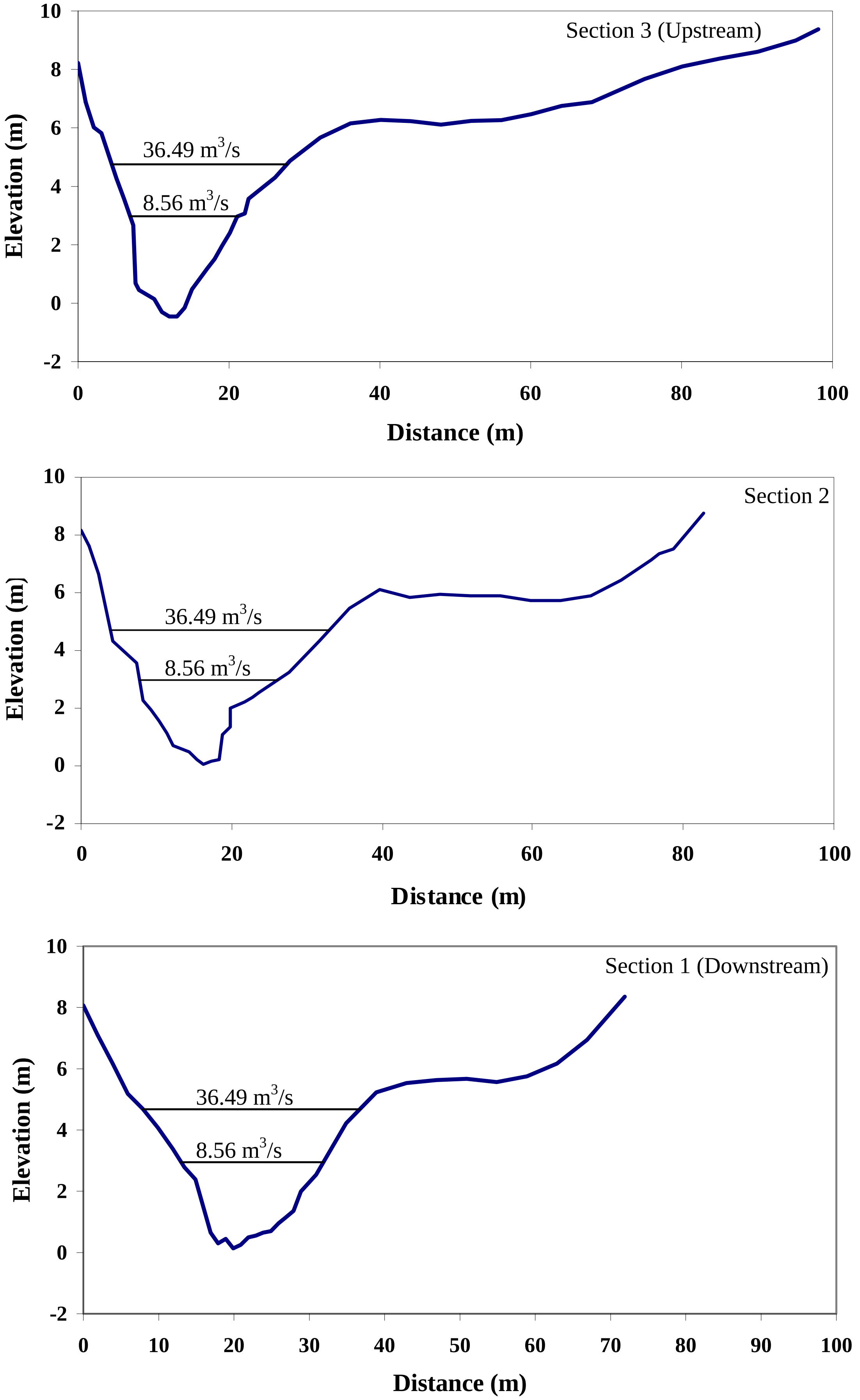


Figure 15. Cross-sections 1, 2 and 3 – Merrimans Creek at Stradbroke West.

4.3 Mitta Mitta River at Hinnomunjie Bridge

Table 6. Physical properties of reach – Mitta Mitta River at Hinnomunjie Bridge.

Gauge No.	401203
Drainage area	1533 km^2
Map Reference	Tallangatta SJ55-3 Edition 1 Latitude 36.950° Longitude 147.600°
Average daily flow	1236 ML/day
Flow data	www.vicwaterdata.net
Period of record for slope gauges	11.04.83 – ongoing
Manning's n range	0.039 – 0.049
Cross-Section 3	223.1 metres upstream of Cross-Section 2
Cross-Section 2	Immediately upstream of endless wire
Cross-Section 1	179.6 metres downstream of Cross-Section 2

Figure 16. View upstream from middle of reach (1st April 2003, discharge 1.68 m^3/s) – Mitta Mitta River at Hinnomunjie Bridge.

Figure 17. View upstream from bottom of reach (1st April 2003, discharge, 1.68 m^3/s) – Mitta Mitta River at Hinnomunjie Bridge.

Figure 18. View upstream to endless wire (1st April 2003, discharge 1.68 m^3/s) - Mitta Mitta River at Hinnomunjie Bridge.

Table 7. Hydraulic properties of reach – Mitta Mitta River at Hinnomunjie Bridge.

Discharge (m^3/s)	**ARI** (yr)	**Flow Percentile**	**Water Surface Slope**	**Friction Slope**	**Area** (m^2)	**Expansion** (%)	**Hydraulic Radius** (m)	**Mean Velocity** (m/s)	**Manning** ***n***	**Chezy** ***C***	**Darcy and Weisbach** ***f***
28.51	0.2	85.0%	0.00074	0.00077	40.10	38%	1.27	0.72	0.043	24.0	0.136
36.88	0.2	90.1%	0.00073	0.00076	44.65	32%	1.39	0.84	0.039	26.9	0.109
41.09	0.2	91.8%	0.00089	0.00091	47.49	24%	1.46	0.87	0.044	24.5	0.131
61.94	0.3	96.4%	0.00094	0.00096	58.42	16%	1.73	1.06	0.041	26.6	0.111
89.53	0.4	98.3%	0.00107	0.00108	69.81	10%	2.00	1.28	0.041	27.7	0.102
95.50	0.5	98.5%	0.00109	0.00111	72.75	8%	2.07	1.31	0.041	27.5	0.103
102.73	0.5	98.8%	0.00124	0.00125	78.00	4%	2.19	1.32	0.045	25.4	0.122
115.79	0.6	99.1%	0.00121	0.00122	82.61	4%	2.28	1.40	0.043	26.5	0.112
127.29	0.7	99.2%	0.00134	0.00134	84.61	2%	2.32	1.50	0.043	26.9	0.108
144.73	0.9	99.5%	0.00139	0.00138	96.14	0%	2.56	1.51	0.046	25.2	0.124
149.94	1.0	99.5%	0.00144	0.00143	97.95	-1%	2.59	1.53	0.047	25.0	0.125
157.94	1.1	99.6%	0.00139	0.00138	100.23	0%	2.63	1.58	0.045	26.0	0.116
174.63	1.4	99.7%	0.00158	0.00156	108.84	-4%	2.78	1.61	0.049	24.2	0.134
178.95	1.5	99.7%	0.00161	0.00158	104.35	-4%	2.71	1.72	0.046	25.9	0.117
242.63	3.5	99.9%	0.00202	0.00194	127.97	-8%	2.71	1.90	0.045	26.1	0.115

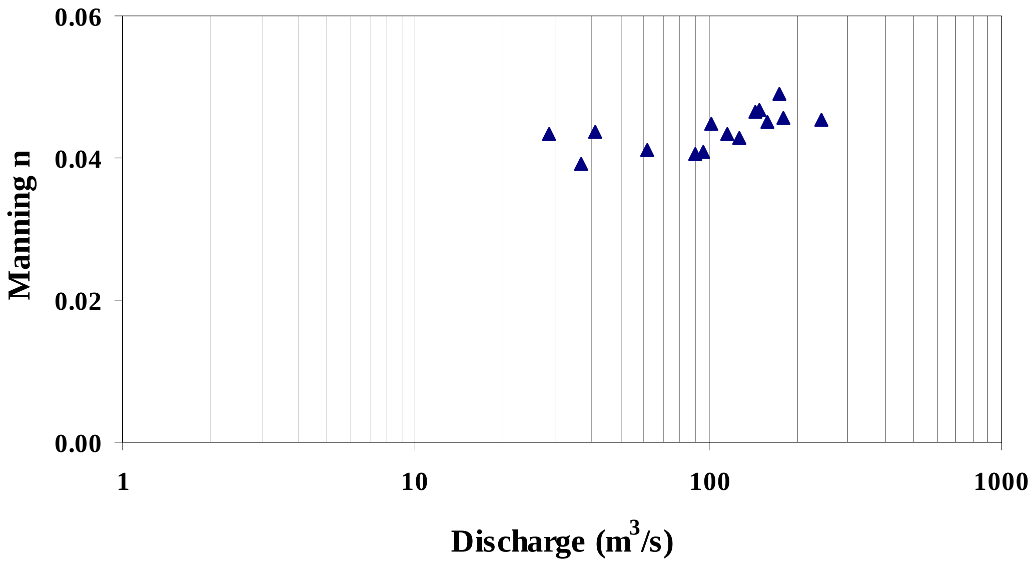


Figure 19. Manning’s *n* against discharge – Mitta Mitta River at Hinnomunjie Bridge.

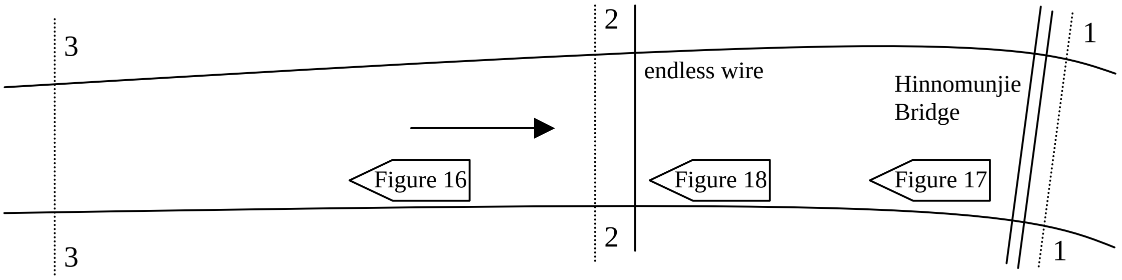
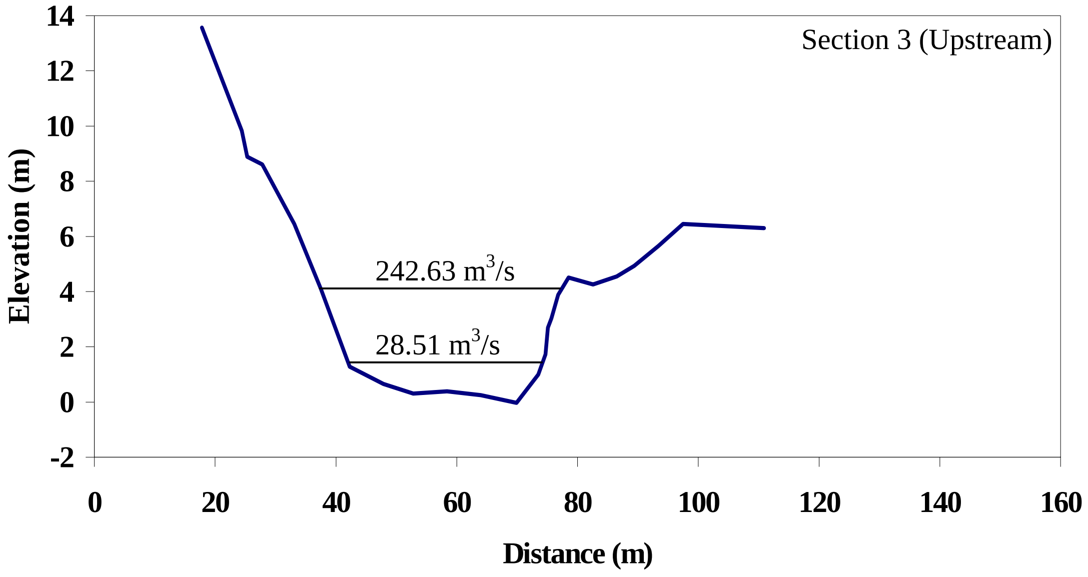
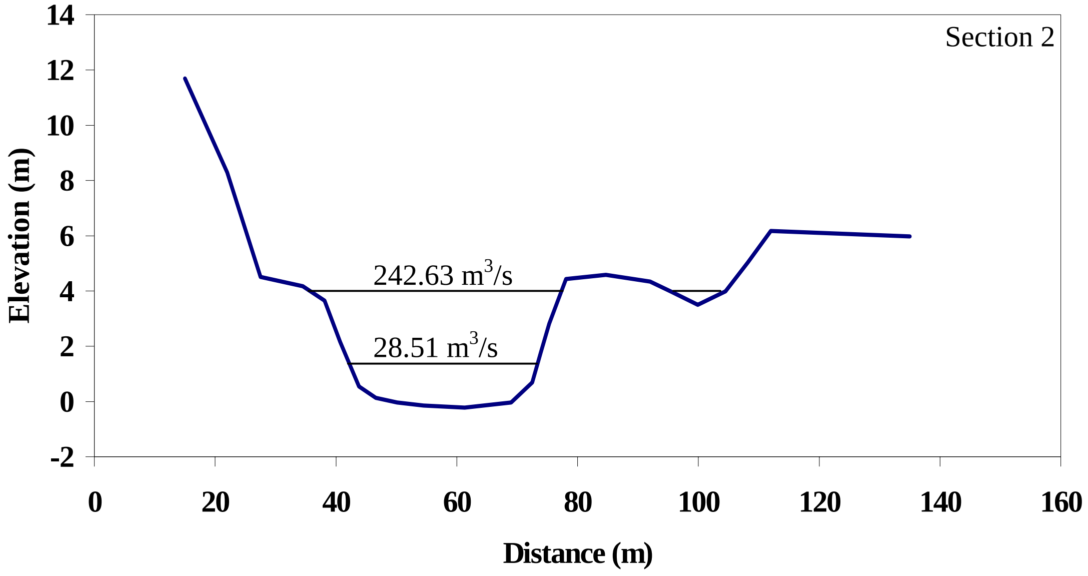


Figure 20. Plan view (not to scale) – Mitta Mitta River at Hinnomunjie Bridge.





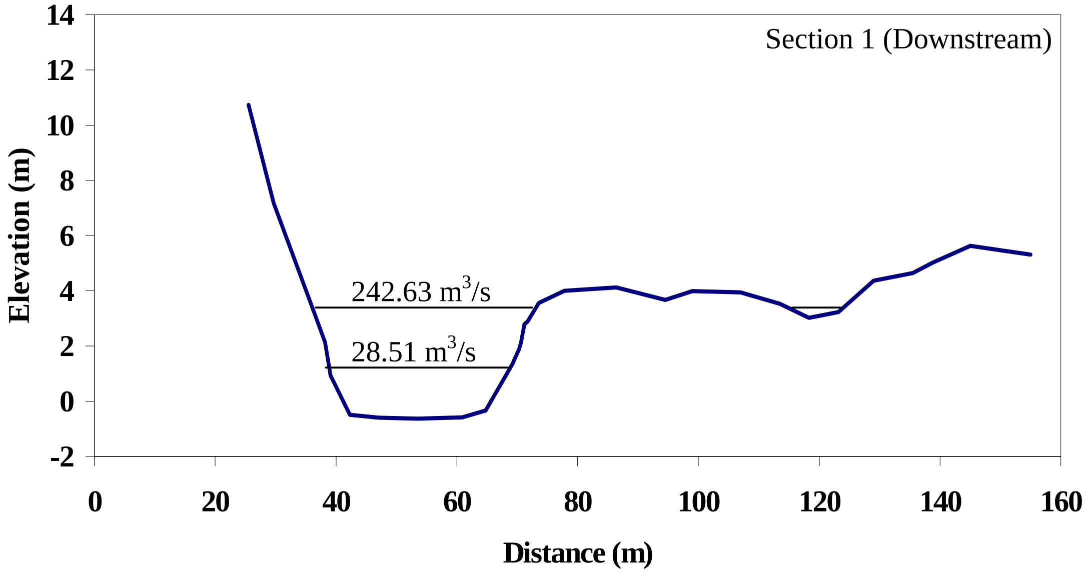


Figure 21. Cross-sections 1, 2 and 3 – Mitta Mitta River at Hinnomunjie Bridge.

4.4 Tambo River downstream of Ramrod Creek

Table 8. Physical properties of reach – Tambo River downstream of Ramrod Creek.

Gauge No.	223205
Drainage area	2681 km^2
Map Reference	Bairnsdale SJ55-7 Edition 1 Latitude 37.670° Longitude 147.870°
Average daily flow	750 ML/day
Flow data	www.vicwaterdata.net
Period of record for slope gauges	17.10.83 – 12.12.85
Manning's n range	0.041 – 0.045
Cross-Section 4	343.65 metres upstream of Cross-Section 3
Cross-Section 3	290.65 metres upstream of Cross-Section 2
Cross-Section 2	315.85 metres upstream of Cross-Section 1
Cross-Section 1	Gauging Station

Figure 22. View downstream from cross-section 2 to cross-section 1 (1st April 2003, discharge (recorded on 30th March 2003) 0.54 m^3/s) – Tambo River downstream of Ramrod Creek.

Figure 23. View downstream from top of reach (1st April 2003, discharge (recorded on 30th March 2003) 0.54 m^3/s) – Tambo River downstream of Ramrod Creek.

Figure 24. View upstream from bottom of reach (1st April 2003, discharge (recorded on 30th March) 0.54 m^3/s) – Tambo River downstream of Ramrod Creek.

Table 9. Hydraulic Properties of Reach – Tambo River downstream of Ramrod Creek.

Discharge	**ARI**	**Water Surface Slope**	**Friction Slope**	**Area**	**Expansion**	**Hydraulic Radius**	**Mean Velocity**	**Manning *n***	**Chezy *C***	**Darcy and Weisbach *f***
(m^3/s)	**(yr)**			**(m^2)**	**(%)**	**(m)**	**(m/s)**			
129.00	0.7	0.00125	0.00121	93.24	-17%	2.15	1.39	0.041	27.3	0.104
428.43	2.8	0.00127	0.00124	218.90	-8%	3.70	1.97	0.042	29.5	0.090
701.66	8.0	0.00134	0.00131	328.99	-5%	4.49	2.15	0.045	28.7	0.095

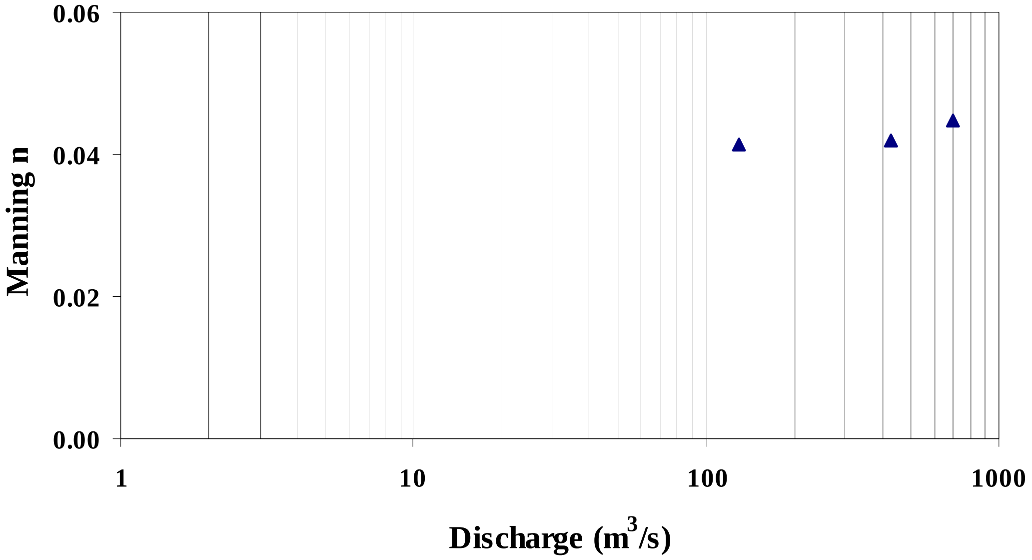


Figure 25. Manning’s *n* against discharge – Tambo River downstream of Ramrod Creek.

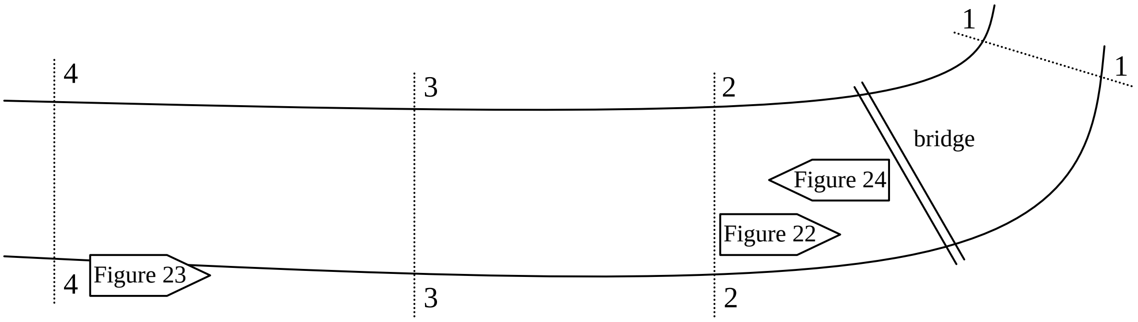


Figure 26. Plan view (not to scale) – Tambo River downstream of Ramrod Creek.

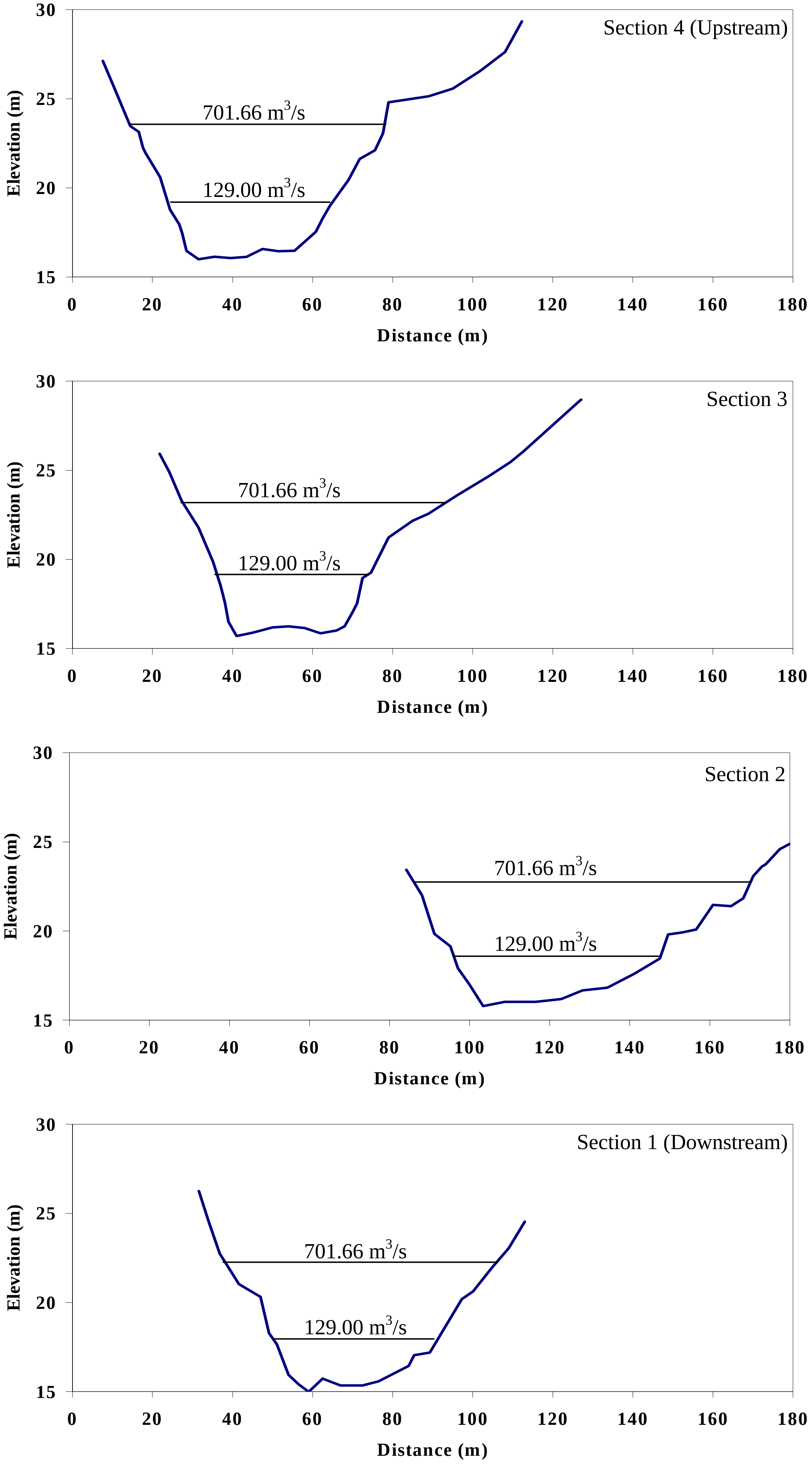


Figure 27. Cross-sections 1, 2, 3 and 4 – Tambo River downstream of Ramrod Creek.

5 Discussion

The calculation of reach-representative stream roughness coefficients, such as Manning's *n*, over varying discharges for the Acheron River at Taggerty, Merrimans Creek at Stradbroke West, Mitta Mitta River at Hinnomunjie Bridge and Tambo River downstream of Ramrod Creek, and the presentation of the information in a Hicks and Mason[4] format is the first time such work has been done in Australia.

The extrapolation of Manning's *n* values from these four Victorian stream reaches to other Australian stream reaches needs to be done with care. As mentioned earlier, Manning's *n* values are dependent on site-specific characteristics such as channel-surface roughness, channel-surface irregularity, channel-shape variation, obstructions, type and density of vegetation, degree of meandering, flow depth, seasonal changes in vegetation, amount of suspended material, bedload, and changes in channel configuration due to deposition and scouring.[1,3] These factors are unique to each stream reach and change in space and time.

At these four Victorian sites, Manning's *n* has remained remarkably constant with changes in discharge. Although this result is surprising, it is supported by other work on stream roughness.

In Hicks and Mason[4] only 11 of 78 stream reaches surveyed could be considered to have an invariant Manning's *n*. Six of these 11 stream reaches however, could be considered to have dense stream bank vegetation comparable to that at the Acheron River at Taggerty, the Merrimans Creek at Stradbroke West, the Mitta Mitta River at Hinnomunjie Bridge and the Tambo River downstream of Ramrod Creek. It appears, from a purely qualitative viewpoint, that dense stream bank vegetation is one factor that may explain a natural stream reach having constant Manning's *n*. That said though, such comparisons need to be treated with care. There are many stream reaches (i.e. in the order of 10's) in Hicks and Mason,[4] that have dense stream bank vegetation comparable to that present at the four Victorian sites, but do not have invariant Manning's *n*. This reinforces the point that the determination of Manning's *n* over varying discharges at stream reaches needs to be done on a case-by-case basis.

Fenton[10] has also shown that although drag on discrete roughness elements such as boulders and vegetation varies with flow depth, this behavior is mimicked quite well by the Manning's formula with constant Manning's *n*. It should be noted though, that Fenton uses the assumption of infinitely wide streams.[10]

In 1963, the American Society of Civil Engineers (ASCE) established a Task Force on Friction Factors in Open Channels. This Task Force recommended the use of the Darcy-Weisbach formula for open-channel hydraulic calculations, with friction factor f, rather than Manning's n.**[11]** The recommendation of ASCE was due in part to f being non-dimensional, unlike Manning's n, which has units of $TL^{-1/3}$. Darcy-Weisbach's f can be related to Manning's n by equation (13).

For roughness of the kind frequently found in natural channels, f is found to be nearly proportional to $1/R^{1/3}$ so that, by equation (13) a nearly constant value of Manning's n is applicable to these channels.**[11]** Hence, Manning's formula with constant n is applicable to fully-rough discharges and is recommended for this application.**[11]** Fully-rough conditions will exist if $n^6(RS_f)^{1/2}$ is greater than 10^{-13} approximately.**[12]** At the four Victorian sites investigated in this paper, $n^6(RS_f)^{1/2}$ has been greater than 10^{-13} at all discharges. This suggests that the Manning's n values discussed in these case studies have been obtained over a relatively narrow range of hydraulic conditions.

6 Conclusion

This paper presents reach-representative stream roughness coefficients for varying discharges from the Acheron River at Taggerty, the Merrimans Creek at Stradbroke West, the Mitta Mitta River at Hinnomunjie Bridge and the Tambo River downstream of Ramrod Creek. At the Acheron River, Mitta Mitta River and Tambo River sites, Manning's n was found to remain approximately constant at 0.043 across discharges ranging from 3.17 m^3/s to 72.94 m^3/s, 28.51 m^3/s to 242.63 m^3/s and 129.00 m^3/s to 701.66 m^3/s respectively. At the Merrimans Creek site, Manning's n was found to remain approximately constant at 0.079 across discharges ranging from 8.56 m^3/s to 36.49 m^3/s.

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