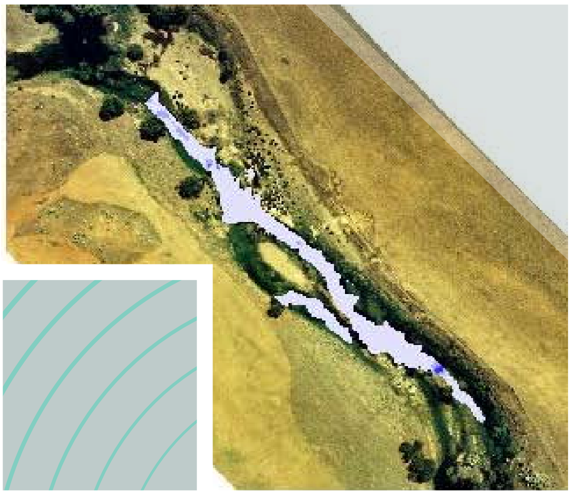
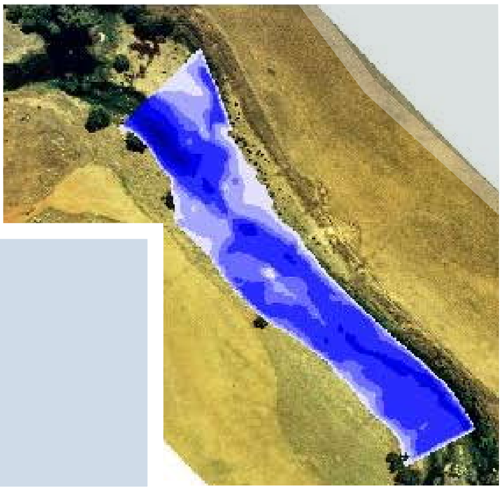
SNOWY RIVER RECOVERY

SNOWY RIVER FLOW RESPONSE MONITORING

HYDRAULIC MODELLING TO ESTIMATE THRESHOLD DISCHARGES FOR SEDIMENT ENTRAINMENT IN THE SNOWY RIVER, AUSTRALIA





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Snowy River Recovery
Snowy River flow response monitoring:
Hydraulic modelling to estimate threshold discharges for sediment entrainment in the Snowy River, Australia

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Abstract

The development of the Snowy Mountains Scheme (SMS) through the 1950-60s had a profound impact on the hydrology, hydraulic characteristics, geomorphology and ecology of the Snowy River and several tributaries. Mean annual flows downstream from Jindabyne Dam (the most downstream dam of the SMS) have been reduced by 96% at Dalgety and 43% at Jarrahmond, with similar reductions also apparent in daily, monthly and annual flow data.

Reinstating environmental flows and investigating flow-sediment interactions in the Snowy River downstream from Jindabyne, formed two key recommendations of an Expert Panel established to assess environmental flow requirements for the river. Although sediment movement was briefly examined in the Expert Panel Report, this report extends that analysis by undertaking one-dimensional hydraulic modelling with HEC-RAS 2.2 at several of the Snowy River Flow Response Monitoring and Modelling sites under a range of pre-regulation, post-regulation and environmental flows. Modelled outputs of shear stress are used in conjunction with grain size data to investigate sediment movement to discharge thresholds.

This report forms stage one of the hydraulic modelling program for the Snowy River Flow Response Monitoring and Modelling Program and utilises the early survey data collected for the program. Stage two of the hydraulic modelling program will utilise additional survey collected post 2000 to refine and update the HEC-RAS hydraulic models and integrate the modelling results with high resolution aerial photography and geographic information systems. The hydraulic modelling outputs for median and mean daily snowmelt discharges provide an indication of hydraulic conditions in the Snowy River under the following conditions:

- the maximum average daily flows that occurred prior to regulation;
- the current flow regime; and
- flows estimated to occur under a 15% environmental flow regime.

Average flows for all months outside of the spring snowmelt, particularly the environmental flow regime (EFR), will be considerably lower than the minimum discharge (1,000 ML/day) modelled in the current study. At flow rates of 1,000 ML/day (the maximum median daily snowmelt discharge expected to occur in September under a 15% environmental flow regime), the average shear stress in deep pools at the Snowy River sites downstream of the Mowamba River and at Rockwell was found to range from 0.58 – 0.91 N/m^2. Flows of 1,000 ML/day are thus capable of initiating movement in unconsolidated and hydraulically exposed coarse sands up to about 1.9 mm in diameter.

Average velocities in pools at downstream Mowamba and Rockwell sites at flow rates of 1,000 ML/day ranged from 0.21 – 0.29 ms^{-1}. Velocities of about 0.15 ms^{-1} are known to initiate transport of unconsolidated fine-grained sediment such as the flocculated fine grained sediment laminae that have been described as smothering parts of the Snowy River bed. Flows of 1,000 ML/day are therefore sufficient to initiate flushing of these deposits in pools of the Jindabyne Gorge and Dalgety Uplands reaches of the Snowy River.

The hydraulic modelling outputs from the study indicate that at flow rates of 1,000 – 3,000 ML/day, shear stress velocities across riffles are substantially greater than in pools and that this difference decreases with increasing discharge. One of the more notable results from the hydraulic modelling is the development of a velocity reversal effect at the Snowy River site downstream of the Mowamba River under the pre-regulation 50% annual exceedance probability flood of 28,646 ML/day. Velocity reversal produces higher velocities and shear stress in pools than across riffles, which is important for scouring pools and maintaining pool-riffle sequences. Modelling suggests that at the McKillops Bridge site, a strong velocity reversal effect also occurs at flow rates between the pre-regulation 90% and 50% annual exceedance floods. The occurrence of velocity reversals in two of the three sites modelled suggests that velocity reversal in confined sections of the Snowy River under high flows between the pre-regulation 90% and 50% annual exceedance probability floods may have been a common process.

Analysis of discharge data indicates that under a 15% environmental flow regime, November is the month of greatest divergence between pre-regulation and 15% EFR flows. Ratios of mean to median daily snowmelt discharges for pre-regulation and 15% EFR flow regimes indicate that reconstructed snowmelt flows will be more variable than the steady high discharges experienced prior to regulation. A 28% EFR flow regime should effectively redress these issues. Similarly, a 28% EFR flow regime may enable occasional release of peak discharges of up to about 20,000 ML/day to initiate velocity reversals in pools of the Jindabyne Gorge reach of the Snowy River.

The Snowy River has been previously described as “a cot-size river in a king size bed” meaning that there is insufficient water in the river compared to the size of the original (pre-regulation) riverbed. The Snowy River needs to contract under the influence of native vegetation and the environmental flow regime to form a smaller river within the larger former channel bed. Environmental flows of sufficient magnitude to erode, transport and redistribute sediment provide the only means to holistically enable a river to attain this condition and to reconstruct a new suite of alluvial landforms and a channel morphology adjusted to the reduced flow regime. Although smaller than the pre-regulation river channel, the EFR rejuvenated channel should provide an improved habitat conditions over the current situation.

It is suggested that the second stage of the program should include more detailed topographic survey data and integrate the hydraulic models with high resolution aerial photography, LIDAR and geographic information systems.

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Introduction

The development of the Snowy Mountains Scheme (SMS) through the 1950-60s had a profound impact on the hydrology, hydraulic characteristics, geomorphology and ecology of the Snowy River and several tributaries (Erskine *et al*., 1996, 1999). Mean annual flows downstream from Jindabyne Dam (the most downstream dam of the SMS) have been reduced by about 96% at Dalgety to 43% at Jarrahmond, with similar reductions also apparent in daily, monthly and annual flow data (Erskine *et al.,* 1999).

Reinstating environmental flows and investigating flow-sediment interactions in the Snowy River downstream from Jindabyne formed two key recommendations of an Expert Panel established to assess environmental flow requirements (Erskine *et al*., 1996). Although sediment movement to discharge thresholds were briefly examined in the Expert Panel Report (Erskine *et al*., 1996), this report extends that analysis by undertaking one-dimensional hydraulic modelling with HEC-RAS 2.2 at several of the Snowy River Flow Response Monitoring and Modelling sites under a range of pre-regulation, post-regulation and environmental flows. HEC-RAS 2.2 modelled outputs of shear stress are used in conjunction with grain size data collected by Dr Wayne Erskine and colleagues to investigate sediment movement to discharge thresholds using established methodologies (eg. Elliott and Hammack, 2000) at selected Snowy River Flow Response Monitoring and Modelling sites.

The aims of this report are to:

i. determine significant geomorphologic flows under pre-regulation, post-regulation and environmental flow release (EFR) conditions;

ii. model these discharges in HEC-RAS 2.2 through selected Snowy River monitoring sites; and

iii. use HEC-RAS 2.2 modelled outputs of shear stress and mean velocity to investigate thresholds of sediment movement.

This report forms stage one of the hydraulic modelling program for the Snowy River Flow Response Monitoring and Modelling Program, and accesses the available early survey data collected.

THE SNOWY RIVER CATCHMENT

The Snowy River rises in the Australian Alps and has a catchment area of approximately 24,900 km^2. The Snowy River has two major dam in the upper catchment (ie. Jindabyne and Eucumbene), and downstream of Jindabyne Dam the river flows for 352 kilometres until it reaches the Tasman Sea near Orbost (Figure 1).

Jennings and Mabbutt (1986) mapped four geomorphic classes in the Snowy River basin; the Australian Alps, the Monaro Tableland, the East Victorian Uplands and the Gippsland Plain. Erksine *et al.* (1999) briefly describes this classification. Sampling sites are contained within these geomorphic units (Figure 2).

The general distribution of rainfall over the Snowy River catchment is controlled to a large extent by the orographic effects. There is a strong rainfall gradient across the catchment. Average annual rainfall range from 1,800 mm over areas above 1,500 m in the north western corner of the catchment to below 500 mm along the rain shadow effected north eastern parts of the catchment around Dalgety (Morton *et. al*. in prep).

HYDROLOGY

Pre-regulation hydrology

The Snowy River has an extensive catchment above the winter snowline. Prior to construction of the SMS, the river exhibited a strong snow-melt signal in its flow regime that was apparent at all gauging stations between Jindabyne and Jarrahmond (Erskine *et al*., 1999). The flash flood magnitude index for the Snowy River prior to regulation, determined as the standard deviation of the $\log_{10}$ of the annual maximum series, was around 0.20 at Dalgety (Erskine *et al*., 1999), indicating that the river had a low variability between the largest and smallest floods that occur on an annual basis. The low flood variability and low flash flood magnitude index occurs primarily because the smallest annual floods in the Snowy River were relatively large due to the influence of snowmelt on spring flood magnitudes (Erskine *et al*., 1999).

The strong pre-regulation snow-melt signal in the Snowy River can be seen in Figure 3 for the Jindabyne and Jarrahmond gauges as the ‘white peaks’ just above the X-axes indicating an extended period of high minimum daily discharges occurring on an annual basis (Figure 3). This seasonal trend clearly apparent in the daily flow data could be enhanced by presenting a shorter period of data than illustrated in Figure 3, or by using wavelet transforms to characterise streamflow patterns (eg. Smith et al., 1998).

Assessment of downstream trends in river flow characteristics under pre-regulation conditions is possible by comparing a short period of overlapping data from 1941-45 available for the Jindabyne, McKillops Bridge and Jarrahmond gauges (Figure 3; Table 1), and a second overlapping period from 1949-54 available for Jindabyne and Dalgety (Figure 3; Table 1;). In the context of the full record length at Jindabyne, the 1941-45 period was characterised by about 10% lower than average mean and median daily snowmelt discharges, whereas the 1949-54 period was characterised by about 25% above average mean and median daily snowmelt discharges (Table 1). The 1949-54 overlap is available for only two stations (Jindabyne and Dalgety –Figure 3) and is therefore of limited use for further analysis except to proportionate unregulated discharges at Dalgety to reflect flows from 1941-45 and to extend the Dalgety flow record by regression analysis with Jindabyne (eg. Erskine *et al*., 1999).

Pre-regulation daily mean and median snowmelt discharges between Jindabyne and Jarrahmond were dominated by flows from the Eucumbene, Snowy, Thredbo and Mowamba Rivers, with limited contributions from the McLaughlin, Bombala-Delegate and Buchan River catchments (Figure 1). Average mean and median mean daily snowmelt discharges at Jindabyne with a catchment area of 710 km^2 account for 77% and 86%, respectively, of these flows at McKillops Bridge with a catchment area of 10,800 km^2, and 68% and 63%, respectively, of the same flows at Jarrahmond with a catchment area of 13,421 km^2 (Table 1). The unregulated mean and median daily discharges at Jindabyne for October had exceedence probabilities greater than 99% on the annual instantaneous maximum series.

Figure 1. The Snowy River Catchment showing the location of geomorphic sites (blue) and hydrometric stations (red).

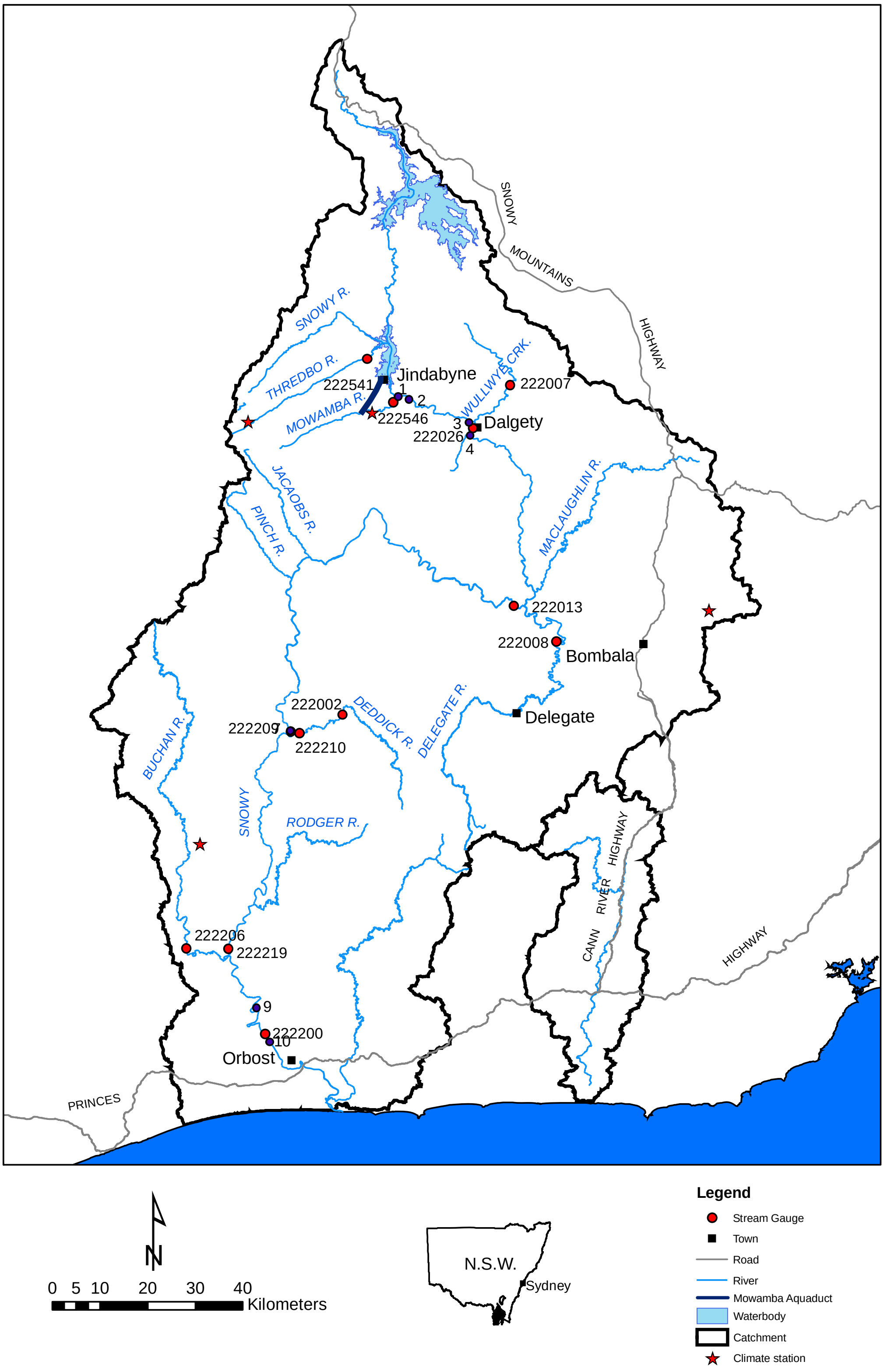

Figure 2. **Snowy River Flow Response Monitoring and Modelling sampling sites.**

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No.	Site Name
1	Snowy River d/s Mowamba River
2	Snowy River u/s Sugarloaf Creek
3	Snowy River at Rockwell
4	Snowy River d/s Blackburn Creek
7	Snowy River at McKillops Bridge
9	Snowy River at Long Point
10	Snowy River at Bete Bolong

Post regulation and environmental flow release (EFR) hydrology

The change to mean and median daily snowmelt discharges in the Snowy River since regulation is one of the most acute hydrological effects of regulation. Mean and median daily snowmelt discharges at Dalgety from 1976-96 are reduced to about 2% and 0.7%, respectively, of pre-regulation flows at Jindabyne (Table 1). At McKillops Bridge, mean and median mean daily snowmelt flows have been reduced to about 31% and 27%, respectively, of pre-regulation flows, and at Jarrahmond to about 43% and 33%, respectively (Table 1). Median daily snowmelt flows at Dalgety now account for only about 2% of this discharge at both McKillops Bridge and Jarrahmond, in contrast to the 86% and 63% under pre-regulation conditions (Table 1).

Mean and median daily flows summarised into monthly averages provide further insight as to the effects of regulation on river flows and flow increases provided by Environmental Flow Releases (EFR's). Pre-regulation flow data presented in Figure 4 and Figure 5 for the Dalgety gauge (222206) have been proportionally reduced according to the percentage difference between the mean and median daily flows for each month between 1949-54 and 1941-45 at Jindabyne (222501) to account for the above average flows in 1949-54. All data presented for pre-regulation conditions, including those from Dalgety, are from or reflect the period 1941-45, a time of below average flows. All data for post-regulation conditions are from 1976-96, and data for EFR conditions are for a 15% flow regime as modelled by the existing Snowy River hydrological model for a 20 year period from 1974-95.

The 1941-45 period was characterised by below average flows; the magnitude of differences between pre-regulation and subsequent (post-regulation and EFR) discharges illustrated in Figures 3 and 4 can therefore be regarded as conservative. It is interesting that from analyses of Murray River at Biggarah flow records from 1948-57 and 1967-88, Erskine *et al.* (1999) noted that the magnitude of flow changes in the Snowy River were not as large as previously reported by James (1989) and Brizga and Finlayson (1992, 1994). However, discharge data from Jindabyne indicate that the period 1949 to 1954, which comprises the bulk of the pre-regulation flow record at Biggarah used by Erskine *et al*. (1999), was characterised by mean and median daily flows 21% and 30%, respectively, higher than mean and median daily flows for the longest unregulated Snowy River record available (222501 Jindabyne from 1902 to 1954). The 36% natural flow decrease at Biggarah reported by Erskine *et al*. (1999) thus appears to be at least partly a function of above average flows during 1948-57.

Modelled environmental flows (EFR's) at Dalgety for the mean daily discharge in October reach about 20.9% of pre-regulation flows but this figure decreases to about 9.5% for the median daily discharge (Figure 4 and Figure 5). Ratios of mean to median daily discharges for October under pre-regulation, post-regulation and EFR conditions are 1.23, 4.84 and 2.70, respectively. These ratios provide a relative measure of flow variability and indicate that although the EFRs provide a flow regime closer to that under pre-regulation conditions, they do not achieve the steady high snowmelt discharge of the pre-regulation Snowy River. Both mean and median daily flows indicate that under EFR conditions, the Snowy River at Dalgety in November will experience the greatest water deficit relative to the unregulated flow regime (Figure 4 and Figure 5). Finally, the EFR flow regime produces a consistent shift in the month of maximum median daily snowmelt discharge from October to September at all gauging stations (Figure 5).

Figure 3. **Daily flows for Jindabyne, Dalgety, McKillops Bridge and Jarrahmond. Pre-regulation, post-regulation and construction periods are indicated. Note that a short period of overlapping data exists for Jindabyne, McKillops bridge and Jarrahnond gauges from 1941-45 for the pre-regulation period. The presence of regular white peaks close to the X-axis for all gauges in the pre-regulation data which disappears in the post-regulation period. These white peaks represent consistently high daily discharges driven by snowmelt over spring, particularly in October.**

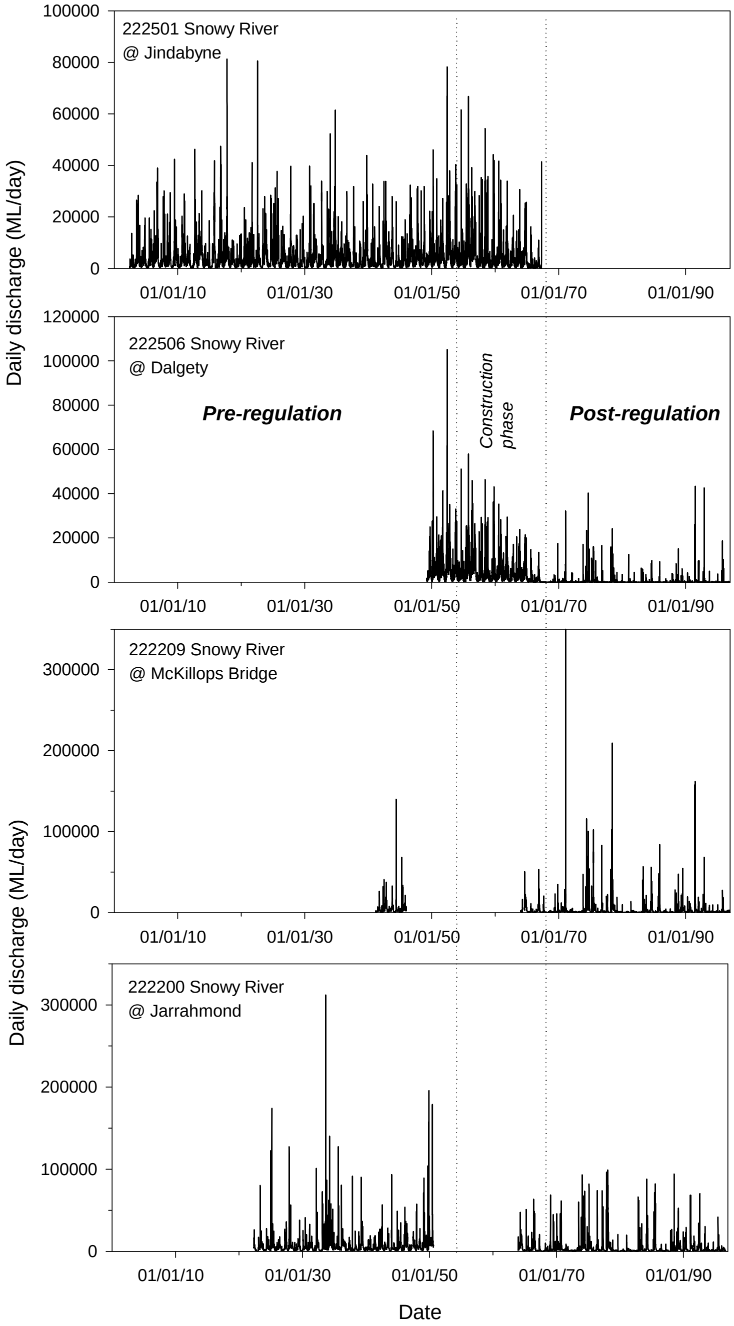


Figure 4. **Mean daily flows for Snowy River at Dalgety, McKillops Bridge and Jarrahmond under pre-regulation, post regulation and environmental flow (EFR) conditions. Dalgety record proportionate to 1941-45 flows at Jindabyne. All other pre-regulation flows from actual 1941-45 records; post-regulation discharges at all sites from actual 1976-96 records; EFR modelled flows. Note the decreasing effect of regulation on flows downstream and that the greatest divergence between pre-regulation and EFR flows is modelled to occur in November at Dalgety.**

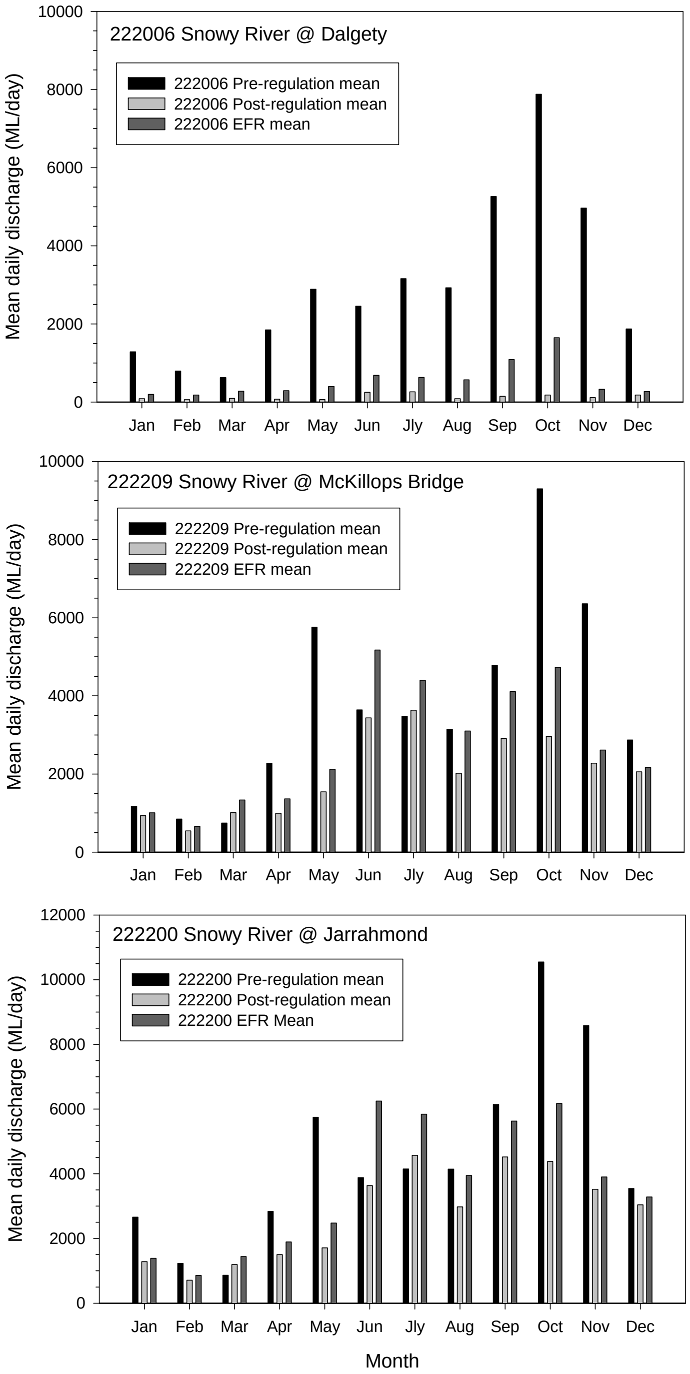


Figure 5. Median daily flows for Snowy River at Dalgety, McKillops Bridge and Jarrahmond under pre-regulation, post regulation and environmental flow (EFR) conditions. Dalgety record proportionate to 1941-45 flows at Jindabyne. All other pre-regulation flows from actual 1941-45 records; post-regulation discharges at all sites from actual 1976-96 records; EFR modelled flows. Note that the greatest divergence between pre-regulation and EFR flows is modelled to occur in October and November at Dalgety and that the month of maximum median daily snowmelt discharge at all stations is predicted to change from October under pre-regulation flows to September under EFR flows.

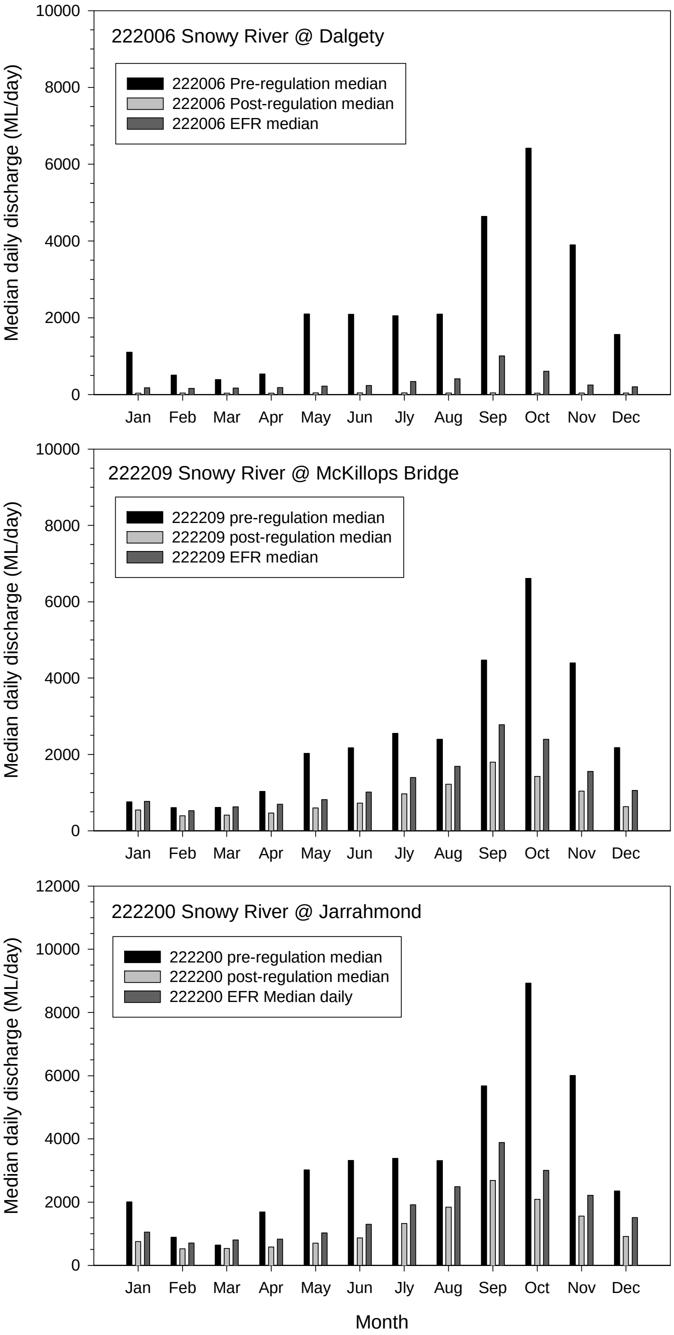


Table 1. Mean daily, median daily, maximum mean daily and minimum mean daily snowmelt discharges (ML/day) for spring month of maximum discharge under pre-regulation and post-regulation conditions. Mean and median daily snowmelt discharges under a 15% EFR modelled flow regime. The maximum recorded daily discharges for the full period of record under pre-regulation and post regulation conditions are also provided.

Gauging station	**Analysis period**	**Catchment area**	**Pre-regulation snowmelt discharge (ML/day)**				**Post-regulation snowmelt discharge (ML/day)**				**Environmental flow release (EFR) discharges (ML/day)**		**Maximum recorded daily (ML/day)**
			Mean daily	Median daily	Maximum mean daily	Minimum mean daily	Mean daily	Median daily	Maximum mean daily	Minimum mean daily	Mean daily	Median daily	
222501 Jindabyne	1/5/1902 – 31/12/1954	1830 km^2	7851	6372	26034	942	-	-	-	-	-	-	81227 (Oct. 1917)
222501 Jindabyne	1/1/1941 – 31/12/1945	“	7183	5665	10968	1645	-	-	-	-	-	-	“
222501 Jindabyne	1/1/1949 – 31/12/1954	“	8481	7527	10969	2467	-	-	-	-	-	-	“
222006 Dalgety	1/1/1949 – 31/12/1954	1190 km^2	9300	8213	11999	3317	-	-	-	-	1595	998	105086 (Jun. 1952)
222006 Dalgety	1/1/1969 – 31/12/1996	“	-	-	-	-	313	42	3686	20	-	-	“
222006 Dalgety	1/1/1976 – 31/12/1996	“	-	-	-	-	179	42	1200	20	-	-	“
222013 Burnt Hut	1/1/1976 – 31/12/1996	7081 km^2	-	-	-	-	1645	650	8204	79	2431	1826	310799 (Jun. 1978)
222209 McKillops Br	1/1/1941 – 31/12/1945	10800 km^2	9300	6608	17216	2136	-	-	-	-	4733	2799	404238 (Feb. 1971)
222209 McKillops Br	1/1/1965 – 31/12/1996	“	-	-	-	-	2916	1792	12221	148	-	-	“
222209 McKillops Br	1/1/1976 – 31/12/1996	“	-	-	-	-	2911	1797	11733	148	-	-	“
222200 Jarrahmond	1/1/1922 – 1/1/1954	13421 km^2	10514	8242	29990	2545	-	-	-	-	6174	3887	311938 (Jan. 1934)
222200 Jarrahmond	1/1/1941 – 31/12/1945	“	10545	8929	19542	2545	-	-	-	-	-	-	“
222200 Jarrahmond	1/1/1976 – 31/12/1996	“	-	-	-	-	4523	2690	14952	219	-	-	“

Geomorphologically significant flows

Channel forming, effective and dominant discharges

The concepts of channel forming, effective and dominant discharges encompass the range of flows that govern the shape and size of river channels (Gordon *et al.,* 1992). All three discharges commonly include definitions involving sediment entrainment, such as the most effective discharge being the flow that transports the greatest sediment load on an annual basis.

A range of discharges control channel form. The gross dimensions of rivers are commonly the product of infrequent high magnitude flows that maintain the dimensions of the ‘trench’ in which a lower flow channel sits. Medium scale features such as benches inset within the large ‘trench’ are destroyed by exceptional floods and re-constructed by moderate events (Erskine and Livingstone, 1999). Smaller scale features forming and defining the ‘active channel bed’, such as readily mobilised sediment bars, bedforms and the lower limit of perennial vegetation, are generally controlled by frequent, smaller discharges around bankfull (Gordon *et al*., 1992). A commonly accepted dominant discharge for alluvial rivers, therefore, is the bankfull discharge which is the flow that fills the stream to the top of its banks without extensive inundation of floodplains.

In a detailed study of USA rivers, Williams (1978) found that bankfull discharges occurred over a range of recurrence intervals, most commonly from 1-10 years and averaging about 2 years on the annual series. Mosely (1981) reported a similar range of recurrence intervals for New Zealand rivers and a median value of about 1.5 years. The bankfull channel cross-section can often be readily identified in the field within alluvial settings from a variety of indicators and hence provides a useful field-based technique by which a ‘dominant discharge’ can be estimated. Because of the general consistency of recurrence intervals for bankfull flow in equilibrium alluvial rivers, frequency defined discharges such as the mean annual flood or discharges around the 2 to 10 years recurrence interval, are commonly accepted as one of the range of channel forming, effective or dominant discharges.

Significant geomorphic flows in the Snowy River and selection of flows for hydraulic modelling

The Snowy River, prior to regulation, was Australia’s largest snowmelt river characterised by consistently high mean and median daily flows especially over October. These snowmelt flows over long durations are likely to have controlled features such as the lower limit of perennial vegetation and readily mobilised sediment deposits such as lateral bars and point bars. Both the mean and median daily snowmelt discharges under pre-regulation, post-regulation and EFR conditions are available for sufficient gauging stations to enable their reliable estimation at each of the Snowy River monitoring sites. The mean and median daily snowmelt discharges are therefore selected for hydraulic modelling in HEC-RAS 2.2.

Sufficient total daily discharge data are available at the Jindabyne, Dalgety, Burnt Hut, McKillops Bridge and Jarrahmond flow gauges to construct annual maximum log-Pearson III curves from actual data, and in the case of McKillops Bridge, from synthesised data based on regression analyses of overlapping data with the Jarrahmond gauge. Log-Pearson III estimates of the 90% and 50% annual exceedence probability floods (1.1 year and 2.0 floods) are selected as additional higher discharges to model through the monitoring sites.

Modelled daily discharge under EFR conditions were generated by the Department of Water and Energy by extending the hydrological model prepared by Lyall and Macoun Consulting Engineers. (1998). However, these data were not available at the time of the hydraulic modelling. It was therefore not possible to undertake log-Pearson III flood frequency analyses to determine 90% and 50% annual exceedence probability floods under EFR conditions for hydraulic modelling in HEC-RAS 2.2.

The Snowy River Flow Response Monitoring and Modelling hydrological methods manual (DWE, unpublished) identified that EFR releases will provide a number of flushing flows in the range of 1000 ML/day to 3000 ML/day instantaneous maximum flow and one annual flood event of around 12,000 ML/day instantaneous maximum flow. These discharges are hence selected for modelling in HEC-RAS 2.2.

In summary, significant geomorphologic flows selected for HEC-RAS 2.2 modelling through the Snowy River monitoring sites include:

i. daily mean and daily median snowmelt discharges for pre-regulation, post-regulation and 15% EFR flow conditions;

ii. the 50% and 90% annual exceedence probability floods as determined by LPIII analysis of annual maximum daily discharges for pre-regulation and post-regulation flow conditions; and

iii. for monitoring sites upstream of the McLaughlin River, EFR flushing flows of 1000 ML/day and 3000 ML/day and an annual maximum EFR event of 12,000 ML/day.

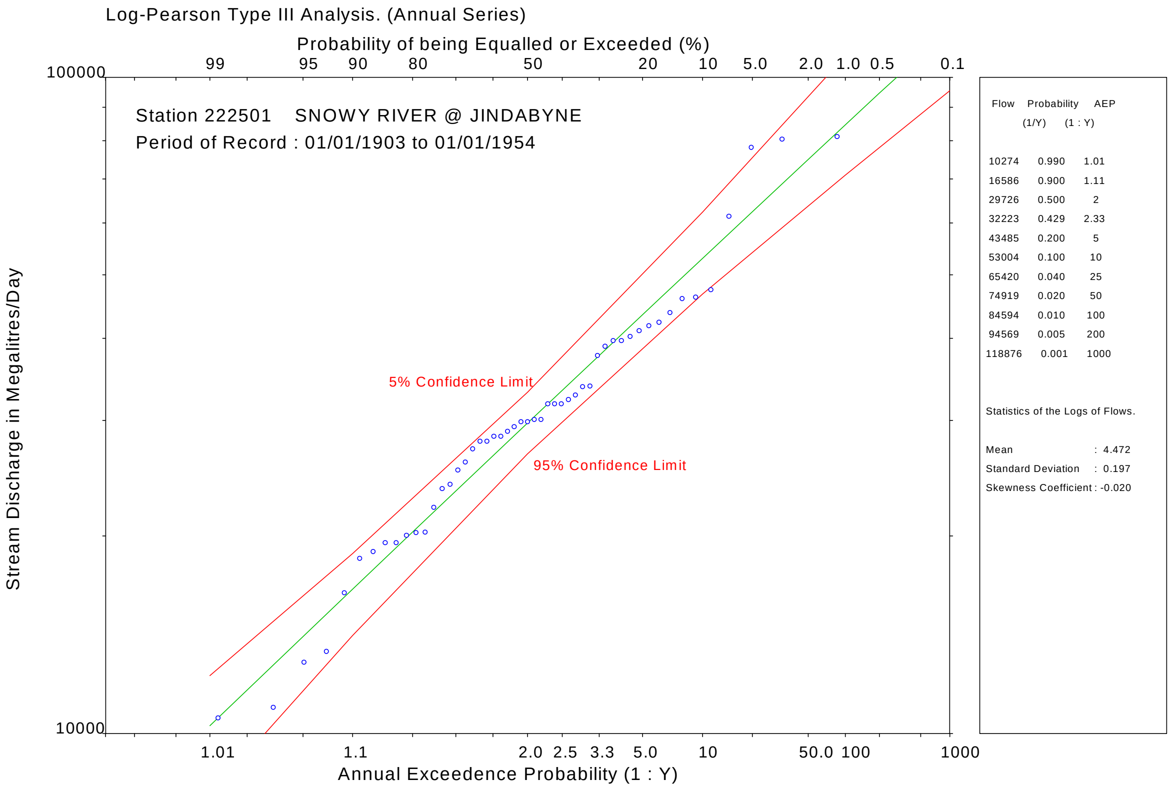
Methods

ESTIMATION OF DISCHARGES AT MONITORING SITES

Three gauging stations, Jindabyne (222501), McKillops Bridge (222209) and Jarrahmond (222200), are used to provide representative pre-regulation discharges at three monitoring sites; downstream Mowamba River, Rockwell and McKillops Bridge. Post-regulation flow conditions for monitoring sites can be similarly established from four gauging stations, namely Dalgety (222006), Burnt Hut Crossing (222013), McKillops Bridge (222209) and Jarrahmond (222200). In the current study, discharges at the downstream Mowamba River and Rockwell sites are unadjusted for variations in catchment area between the monitoring sites and representative gauging stations (Jindabyne and Dalgety). Analysis of pre-regulation median daily snowmelt flows over the overlapping 1941-45 period between the Jindabyne and McKillops Bridge gauging stations indicates that the median daily snowmelt discharge increases linearly by only 0.0634 ML/day for every 1 km^2 increase in catchment area between the Jindabyne gauge (1830 km^2 catchment area) and McKillops Bridge (10,400 km^2 catchment area) (Reinfelds, unpublished data). Differences in snowmelt flows between the Jindabyne gauge (1830 km^2 catchment area), the downstream Mowamba River site (2200km^2 catchment area) and the Rockwell site (2500 km^2 catchment area) are a maximum of 0.7% and can be regarded as insignificant. Representative mean and median daily snowmelt discharges for pre-regulation, post-regulation and EFR conditions for a range of monitoring sites are summarised in Table 2. These discharges form the first of a suite of hydraulic modelling runs in HEC-RAS 2.2.

The 90% and 50% annual exceedence probability floods as determined from LPIII analyses (Figure 6) of annual maximum daily mean flows for pre-regulation and post-regulation conditions forms a second suite of discharges for hydraulic modelling. Although daily instantaneous maximum discharges are usually used for this type of analysis, instantaneous maximum flows for the pre-regulation period are unavailable for all gauges except Jindabyne (222501). However, comparison of log-Pearson III plots of annual daily instantaneous maximum flows with annual daily mean flows for the pre-regulation period indicates that the difference between daily instantaneous maximum and daily mean flows was only about 5% for recurrence intervals less than 5 years. 90% and 50% annual exceedence probability floods based on daily mean data are given in Table 3. The annual maximum series for pre-regulation conditions at McKillops bridge was synthesised from a regression relationship derived from five years of overlapping daily data with the Jarrahmond gauge ($r^2 = 0.74$).

Figure 6. **Log-Pearson III plot of annual instantaneous maximum flows for the Snowy River at Jindabyne from 1903 to 1954 (pre-SMS). Source Hydsys database.**



Flow	Probability (1/Y)	AEP (1 : Y)
10274	0.990	1.01
16586	0.900	1.11
29726	0.500	2
32223	0.429	2.33
43485	0.200	5
53004	0.100	10
65420	0.040	25
74919	0.020	50
84594	0.010	100
94569	0.005	200
118876	0.001	1000

Statistics of the Logs of Flows.

Mean : 4.472
Standard Deviation : 0.197
Skewness Coefficient : -0.020

Table 2. **Mean daily and median daily snowmelt discharges in ML/day for pre-regulation, post-regulation and EFR conditions for each monitoring site. Note Dalgety gauge (222006) pre-regulation data proportionally adjusted to 1941-45 values based on overlapping data with Jindabyne (222501) gauge. All pre-regulation data are from or reflect 1941-45, a period of slightly below average flows, and all post-regulation data are from 1976-96. To convert ML/day to SI units of m3s^{-1}, multiply ML/day by 0.01157.**

Site Name	Site No.	Mean daily snowmelt discharge			Median daily snowmelt discharge		
		Pre-regulation	Post-regulation	EFR	Pre-regulation	Post-regulation	EFR
Snowy River d/s Mowamba River	1	7877	179	1595	6181	42	998
Snowy River u/s Sugarloaf Creek	2	7877	179	1595	6181	42	998
Snowy River at Rockwell	3	7877	179	1595	6181	42	998
Snowy River d/s Blackburn Creek	4	7877	179	1595	6181	42	998
Snowy River at McKillops Bridge	7	9300	2911	4733	6608	1797	2799
Snowy River at Long Point	9	10545	4523	6174	8242	2690	3887
Snowy River at Bete Bolong	10	10545	4523	6174	8242	2690	3887

Table 3. **The 90% and 50% annual exceedence probability flood discharges for pre-regulation and post-regulation conditions to be modelled in HEC-RAS 2.2. Note that the pre-regulation mean annual flood for Jindabyne is used as a 'representative' discharge for sites downstream of the Mowamba River because of the short pre-regulation record length for the Dalgety (222006) gauge.**

Site name	Site No.	90% flood (annual series of daily mean flow in ML/day)		50% flood (annual series of daily mean flow in ML/day)	
		Pre-regulation	Post-regulation	Pre-regulation	Post-regulation
Snowy River d/s Mowamba River	1	16388	509	28646	2835
Snowy River u/s Sugarloaf Creek	2	16388	509	28646	2835
Snowy River at Rockwell	3	16388	509	28646	2835
Snowy River d/s Blackburn Creek	4	16388	509	28646	2835
Snowy River at McKillops Bridge	7	17724	4996	54614	27458
Snowy River at Long Point	9	20717	7833	56282	39769
Snowy River at Bete Bolong	10	20717	7833	56282	39769

HYDRAULIC MODELLING

HEC-RAS 2.2 is a one dimensional hydraulic modelling package produced by the US Army Corps of Engineers Hydrologic Engineering Centre. Hydraulic capabilities include calculation of steady flow water surface profiles and output of associated parameters (eg. shear stress and stream velocity) from solving the one-dimensional energy equation (HEC-RAS 2.2 hydraulics manual, 1998). Under steady flow conditions, energy losses are evaluated from Manning's equation and contraction/expansion coefficients. The momentum equation is used in situations where the water surface varies rapidly over short distances, for example in steep gradient channels, as a result of hydraulic jumps. Input data needed for modelling includes channel cross-sections, identified channel and overbank zones, specified discharges, a schematic diagram of channel planform and estimates of channel and floodplain roughness (Manning's 'n').

Channel cross-sections, longitudinal profiles and planform schematics were surveyed by the Department over 1998-2000 and provided the base geometric information required to set up the HEC-RAS 2.2 models at each monitoring site. Manning's 'n' was estimated as 0.04 for the current active channel bed and 0.06 for overbank areas. These values are typical roughness coefficients for natural streams (HEC-RAS 2.2 hydraulics manual, 1998). Discharges modelled through the monitoring sites are those specified in Table 2 and Table 3. Channel bank stations were set at the top of the low banks defining the current active channel bed and were not varied between pre-regulation, post-regulation and EFR flow conditions.

The hydraulic modelling is uncalibrated as there are insufficient data to enable adjustment of model parameters and fitting of modelled water surface profiles to observed water surface profiles. A mixed flow regime option was selected to enable calculation sub-critical and critical water surface profiles. Normal depth channel slope was specified as the downstream boundary condition with slopes determined from either regression analysis of thalweg elevations or from values presented by DLWC (1998).

Questionable outputs from the HEC-RAS 2.2 models may occur at the most-upstream and most-downstream cross-sections at each site because channel characteristics and boundary conditions upstream and downstream are unknown (HEC-RAS 2.2 hydraulics manual, 1998). Further issues that may introduce imprecision in modelled water surface profiles and estimates of shear stress, stream power and mean velocity include:

I. the non-varying active channel width specified under pre-regulation, post-regulation and EFR flow conditions;

II. the non-varying estimates of Manning's 'n' under pre-regulation, post-regulation and EFR flow conditions; and

III. significant differences between energy gradients and channel bed slopes as determined from thalweg elevation regressions or as obtained from DLWC (1998).

Despite any imprecision introduced under the above uncertainties, it is believed that the modelled HEC-RAS 2.2 outputs provide a reasonable indication of water surface profiles and hydraulic conditions across pools and riffles under various flows at the monitoring sites.

ESTIMATION OF THRESHOLD CONDITIONS FOR SEDIMENT ENTRAINMENT

Entrainment of bedload sediment in alluvial channels is partly a function of shear stress acting on the bed of the stream where:

$\tau = pgRS$

and τ is shear stress (N/m^2), p is the density of water (1000 kg/m^3), R is hydraulic radius (m) and S is the energy gradient (m/m) (Gordon *et al*., 1992). The Shields (1936) equation enables estimation of the critical shear stress (τ_c) at which movement of the median bed particles fraction (d50 in mm) begins to move where:

$\tau_c = \tau_c^*(\gamma_s - \gamma)d_{50}$

and τ_c is the critical shear stress (N/m^2), τ_c^* is the dimensionless critical shear stress (also known as Shields parameter), γ is the specific weight of water (9810 N/m^3), γ_s is the specific weight of sediment (commonly assumed to be 2.65 times the specific weight of water) and d50 is the median bed particle size (Gordon *et al*., 1992; Elliott and Hammack, 2000).

Dimensionless critical shear stress is the most difficult parameter in Shields equation to estimate and is known to vary from about 0.01 to 0.1 depending on the degree of armouring, imbrication and sheltering of channel-bed particles (Gordon *et al*., 1992; Komar, 1987; Elliott and Hammack, 2000). Meyer-Peter and Muller (1948) concluded from flume studies that the onset of bedload transport was associated with a τ_c^* of 0.030. Neill (1968) recommended a τ_c^* of 0.030 for streambeds composed of coarse materials. Powell and Ashworth (1995) found that tightly structured channel beds (those with sheltered particles, interlocked grains or strong imbrication) had a τ_c^* of between 0.055 and 0.067 and loosely structured beds (those with an open particle framework) had a τ_c^* between 0.0096 and 0.011. Erskine (1985) found that the Neill (1968) criterion successfully defined thresholds of sediment movement in gravel-bed reaches of the Hunter River. Erskine *et al*. (1996) therefore recommended that the Neill (1968) dimensionless shear stress criterion be used to investigate thresholds of critical shear stress required to initiate sediment movement in the Snowy River.

Results and discussion

Output data for each of the HEC-RAS 2.2 modelling runs for the Snowy River sites- downstream of Mowamba (Site 1), at Rockwell (Site 3) and McKillops Bridge (Site 7) are provided in Appendices A to C. Two to three sets of flows are modelled for each site:

- median and mean daily snowmelt discharges under pre-regulation, post-regulation and EFR conditions at all three sites;
- EFR flushing flows of 1000 ML/day, 3000 ML/day and 12,000 ML/day at the downstream Mowamba River and Rockwell sites; and
- the 90% and 50% annual exceedence probability floods under pre-regulation conditions at all sites, and under post-regulation conditions at McKillops Bridge.

The following sections provide a discussion of the modelled outputs for each site. Graphical presentations of flow depths at each cross-section, water surface profiles through the monitoring site, shear stress profiles over the current active channel bed together with estimates of the critical shear stress required to entrain the graphic mean bed particle size at each cross-section and mean flow velocity profiles are provided in Appendices A to C. HEC-RAS 2.2 tabulated outputs for all modelled flows are included in the appendices from which the graphical representations are derived.

SNOWY RIVER DOWNSTREAM MOWAMBA RIVER (SITE 1)

The Snowy River site downstream of Mowamba River is located within the Jindabyne Gorge reach (Figure 1). DLWC (1998 p. 52) described the geomorphic characteristics of the site which includes, in downstream sequence: a markedly contracted gravel-bed riffle; a deep remnant pool floored by bedrock and large boulders and with bedrock banks; a contracted riffle at a tributary mouth bar; and a long remnant pool that terminates at a shallow *Phragmites* choke. Riffles at cross-sections 1 and 5 are characterised by the coarsest bedload sediments sampled at the site with graphic mean particle sizes of 163 mm and 45 mm, respectively. Bedload samples from pools had graphic mean particle sizes ranging from medium to very coarse sand (0.25 – 2.0 mm).

Median and mean daily snowmelt flows under pre-regulation conditions generally inundated the low to medium height benches, bar platforms and associated chute channels that are apparent on the cross-sections presented in Appendix A and were described by DLWC (1998 Table 20 p. 62). The 50% annual exceedence probability flood under pre-regulation conditions inundated these low-medium level features by up to 4 metres and rose well above the maximum surveyed height on four cross-sections (see cross-sections Appendix A). The 90% annual exceedence flood filled the high level chute channel on the right bank at cross-section 2 (see cross-sections Appendix A). Current post-regulation mean and median daily snowmelt discharges are sufficient to only spread onto a single low level bar surface on the right bank of cross-section 5 (see cross-section Appendix A) which DLWC (1998 Table 20 p. 62) described as a portion of the inner channel.

Median daily snowmelt flows under EFR conditions generally fill the active channel and provide minor inundation of the lowest level sedimentological surfaces (see cross-sections in Appendix A). Mean daily snowmelt flows likewise fill the active channel but provide more extensive inundation of low level surfaces (see cross-sections in Appendix A). EFR flushing flows of 1000 ML/day are essentially the same as the median daily snowmelt discharge (Table 3) and fill the active channel with very little inundation of low lying surfaces. EFR flushing flows of 3000 ML/day overtop low level surfaces and generally rise to just below or lap onto mid-level surfaces. EFR flushing flows of 12,000 ML/day inundate all mid-level features apparent on cross-sections surveyed at the downstream Mowamba River site (see cross-sections in Appendix A).

Water surface profiles for flows below 12,000 ML/day indicate that the steepest water surface occurs at cross-section 4 (river station 5 in HEC-RAS outputs) (see water surface profiles in Appendix A), producing the highest channel shear stress and mean velocity in the monitoring reach (see shear stress and velocity profiles in Appendix A). For higher discharges at about the pre-regulation 50% exceedence probability flood, hydraulic modelling outputs indicate a velocity reversal effect occurring at cross-section 8 (river station 2) whereby higher the channel velocities and shear stress occur in pools instead of riffles (see shear stress and velocity profiles for in Appendix A) (Keller, 1971; Lisle, 1979; Keller and Florsheim, 1993). The velocity reversal effect was noted by Erskine *et al.* (1996) as possibly being an important process leading to scour and rejuvenation of deep pools in the Jindabyne Gorge reach by snowmelt floods; these results confirm that insight. It is noteworthy, however, that the maximum EFR flushing flow of 12,000 ML/day as noted in the Draft Methods for Hydrology document (DLWC, unpublished), as well as the pre-regulation 90% exceedence probability annual flood of 16,388 ML/day, were insufficient to induce this effect at the Snowy River downstream of the Mowamba River (Site 1).

Channel shear stress in pools under the median daily snowmelt discharge, mean daily snowmelt discharge and EFR flushing flows of 1000 ML/day to 3000 ML/day range from about 0.25 N/m^2 to 5 N/m^2, and reach up to 120 N/m^2 across riffles. Threshold conditions for entrainment of the graphic mean grain size at each cross-section are indicated by asterisks on the shear stress profiles (see Appendix A). Shear stress across riffles under median daily snowmelt flows, mean daily snowmelt flows and EFR flushing flows of 1000 to 3000 ML/day are sufficient to entrain the d50 particle size by a comfortable margin under the Neill (1968) dimensionless shear stress threshold of 0.03 but would be at about the entrainment threshold under a dimensionless shear value of 0.06.

Entrainment of pool sediments by flows of about the median daily snowmelt discharge (998 ML/day) and EFR flushing flows of 1000 ML/day becomes questionable as shear stress in pools remains low, ranging from 0.24 N/m^2 to 1.58 N/m^2, averaging 0.91 N/m^2 (n=4). Under the Neill (1968) criterion, the average shear stress under these flows is sufficient to initiate movement in d50 sediments up to about 1.9 mm. However, where pool bedload sediments include a significant component of cohesive fine grained sediments and/or aquatic macrophyte beds, shear stress in pools under the median daily snowmelt discharge and EFR flushing flow of 1000 ML/day are likely to be insufficient for significant bedload transport. EFR flushing flows of 3000 ML/day generate average shear stress in pools of 3.7 N/m^2 (n=4) which are capable of transporting particles up to 8 mm in size. EFR flows of 12,000 ML/day produce average shear stress in pools of 20.6 N/m^2 (n=4) and are capable of initiating movement in gravels up to about 42 mm in size. By way of comparison, the velocity reversal effect produced by the 50% annual exceedence flood of 28,646 ML/day raises the average pool shear stress to 97.0 N/m^2 (n=4), capable of initiating movement in cobbles up to 200 mm in size.

SNOWY RIVER AT ROCKWELL (SITE 3)

The Rockwell site is located within the Dalgety Uplands reach of the Snowy River (Figure 1). DLWC (1998 p. 66, 68) described the geomorphic characteristics of the site which includes, in downstream sequence: a contracted sand and gravel riffle; a partially infilled remnant pool with extensive bedrock outcrop in the right bank and mud, algae and submerged macrophytes in a backwater downstream of the bedrock outcrop; a bedrock riffle contracted by invading willows; a remnant pool accumulating mud; and a bedrock riffle vegetated by *Carex* and blackberries. Riffles at cross-sections 1 and 5 are characterised by the coarsest bedload sediments at the site with graphic mean particle sizes of 26 mm and 74 mm, respectively. Bedload samples from pools had graphic mean particle sizes ranging from silt to pebbles (0.025 – 14.0 mm).

Median and mean snowmelt flows under pre-regulation conditions generally inundated the low to medium height benches, bar platforms and associated chute channels on these lower levels that are apparent on the cross-sections presented in Appendix B and were also described by DLWC (1998 his Table 30 on p. 77). The 50% annual exceedence probability flood under pre-regulation conditions inundated these low-medium level features by up to 4 metres and rose above the maximum surveyed height on at least two cross-sections (see cross-sections Appendix B). The 90% annual exceedence flood generally inundated these features and benches identified by DLWC (1998 Table 30 p. 77) by 1-2 metres (see cross-sections Appendix B). Current post-regulation mean and median daily snowmelt discharges are sufficient to only spread onto a single low-level bar surface on the right bank of cross-section 7 (see cross-section Appendix B). Bankfull levels suggested by DLWC (1998 Table 30 p. 77) all plot between modelled water surface elevations for the 90% and 50% annual exceedence probability floods (compare water surface tabulations in Appendix B and bankfull levels of DLWC unpublished Table 30 p. 77).

Median daily snowmelt flows under EFR conditions generally do not fill the active channel and inundate only the lowest level sedimentological surface at cross-section 6 (see cross-sections in Appendix B). Mean daily EFR snowmelt flows generally fill the active channel and inundate low level surfaces at cross-sections 1, 6 and 7 but are insufficient to inundate chute channels on cross-sections 3, 4 and 5 (see cross-sections in Appendix B). EFR flushing flows of 3000 ML/day are also insufficient to inundate the chute channels on cross-sections 3, 4 and 5, however, EFR flushing flows of 12,000 ML/day inundate these features (see cross-sections in Appendix B).

Water surface profiles for flows below 3,000 ML/day indicate that the steepest water surface occurs at cross-section 4 (river station 5 in HEC-RAS outputs) (see water surface profiles in Appendix B), producing the highest channel shear stress and mean velocity in the monitoring reach (see shear stress and velocity profiles in Appendix B). The riffle at cross-section 4 also has the coarsest graphic mean grain size in the monitoring reach of about 74 mm. At higher discharges between the EFR flushing flow of 12,000 ML/day and the 50% flood of 28,646 ML/day, local steep gradients at riffles are downed out and shear stress and velocity profiles through the reach become less variable (see shear stress and velocity profiles in Appendix B), in keeping with established hydraulic principles (Knighton, 1996 p. 119). Unlike the downstream Mowamba River site, no velocity reversal effect is apparent in flows up to the 50% annual exceedence flood (see shear stress and velocity profiles Appendix B).

Channel shear stress in pools at cross-sections 2, 3 and 7 (river stations 7, 6 and 2 in HEC-RAS outputs) ranges from about 0.30 N/m2 to 3.0 N/m2, whereas the pool cross-section 6 (river station 3) has channel shear stress ranging from 7.4 N/m^2 to 8.6 N/m^2 for flows up to 3000 ML/day (Appendix B). Riffles at cross-sections 4 and 5 have shear stresses ranging from about 15 N/m^2 to 80 N/m^2 for flows up to 3000 ML/day (Appendix B).

Threshold conditions for entrainment of the graphic mean grain size at each cross-section are indicated by asterisks on the shear stress profiles (see Appendix B). EFR flushing flows of 1000 to 3000 ML/day are sufficient to entrain the d50 particle size at riffles (cross-sections 4 and 5; HEC-RAS river stations 5 and 4) by a comfortable margin under the Neill (1968) dimensionless shear stress threshold of 0.03. It is interesting that shear stress declines substantially across the riffle at cross-section 4 under increasing discharge (Appendix B) suggesting that this location will be primarily modified by falling flood stages rather than peak flows.

Entrainment of pool sediments by flows of about the median daily snowmelt discharge (998 ML/day) and EFR flushing flows of 1000 ML/day is questionable as shear stress in pools at cross-sections 2, 3 and 7 remains low, ranging from 0.30 N/m^2 to 0.74 N/m^2, averaging 0.58 N/m^2 (n=3). Under the Neill (1968) criterion, the average shear stress under these flows is sufficient to initiate movement in d50 sediments up to about 1.2 mm. However, where pool bedload sediments include a significant component of cohesive fine grained sediments and/or aquatic macrophyte beds, shear stress in pools under the median daily snowmelt discharge and EFR flushing flow of 1000 ML/day may be insufficient for bedload transport. EFR flushing flows of 3000 ML/day generate average shear stress at these pool cross-sections of 2.2 N/m^2 (n=3) which are capable of transporting particles up to 4.6 mm in size, whereas EFR flows of 12,000 ML/day produce average shear stress of 9.1 N/ms (n=3) and are capable of initiating movement in gravels up to about 19 mm in size. The bedrock bounded pool at cross-section 6 (HEC-RAS river station 3) exhibits greater shear stresses than cross-sections 2, 3 and 7 which are sufficient to transport gravel 15-18 mm in size by 1000-3000 ML/day flows, and gravel to 36 mm by 12,000 ML day flows.

SNOWY RIVER AT MCKILLOPS BRIDGE (SITE 7)

The McKillops Bridge site is located within the Willis Sand reach of the Snowy River (Figure 1). DLWC (1998 p. 66, 68) described the geomorphic characteristics of the site which includes, in downstream sequence: a gravel riffle; a run sandwiched between two riffles with bedrock exposed at the base of the left bank; a gravel and bedrock riffle with sand deposits in hydraulically sheltered locations; a sand-bed pool formed in a bedrock slot; a boulder run; a pool formed in a bedrock slot with sand deposits in the tail; and a steep boulder riffle. Riffles at cross-sections 4 and 8 returned the coarsest bedload sediments sampled with graphic mean particle sizes of 103 mm and 152 mm, respectively. Bedload samples from pools had graphic mean particle sizes of very coarse sand, ranging from 1.04 to 1.43 mm.

Median and mean snowmelt flows under pre-regulation (and therefore also EFR) conditions are in most cases (except for cross-sections 1 and 3) too low to inundate the bench levels identified by DLWC (1998 Table 76 p. 135) and also apparent on the cross-section (Appendix C). The inner channel level identified by DLWC (1998) was generally filled by the 90% exceedence flood and the 50% exceedence flood generally inundated upper level benches (compare reduced levels in Table 76 of DLWC unpublished and water surface elevations in Appendix C). All bankfull levels identified by DLWC (1998) were not inundated by the pre-regulation 50% exceedence probability flood (compare reduced levels in Table 76 of DLWC (1998) and water surface elevations in Appendix C).

Water surface profiles for flows below the pre-regulation mean daily snowmelt discharge indicate that the steepest water surface occurs at cross-section 2 (river station 7 in HEC-RAS outputs) (see water surface profiles in Appendix C), producing the highest channel shear stress and mean velocity at low flows in the monitoring reach (see shear stress and velocity profiles in Appendix C). At higher discharges at about the pre-regulation 90% exceedence flood and the post-regulation 50% exceedence flood, but especially at about the pre-regulation 50% exceedence flood, hydraulic modelling outputs indicate a strong velocity reversal effect occurring at cross-sections 8 and 6 (river stations 2 and 4), similar to that found at the Snowy River downstream of the Mowamba River (Site 1).

Channel shear stress in pools under the median and mean daily EFR snowmelt discharge range from about 14.1 N/m^2 to 35.6 N/m^2, and reach up to 80 N/m^2 across riffles. Threshold conditions for entrainment of the graphic mean grain size at each cross-section are indicated by asterisks on the shear stress profiles (see Appendix A). Shear stress across riffles under median and mean daily snowmelt flows are sufficient to entrain the d50 particle size under the Neill (1968) dimensionless shear stress threshold of 0.03. However, if cobbles in the riffle at cross-section 4 are imbricated, thereby necessitating use of a dimensionless shear stress coefficient of around 0.06, EFR median and mean daily snowmelt discharges may be insufficient to entrain riffle d50 grain sizes. Shear stress in pools under EFR median and mean snowmelt flows are sufficient to entrain d50 gravel from 29-73 mm in size and substantially exceed the threshold required to entrain pool d50 bed material sizes.

Table 4. Summary of average shear stress (SS) in pools and riffles and maximum entrainable particle sizes (d50) for EFR flushing flows, EFR mean snowmelt discharge and pre-regulation 90% and 50% annual exceedence probability floods. Note: Neill (1968) dimensionless shear stress criterion of 0.03 used to estimate entrainable d50 particle sizes in pools, dimensionless shear stress of 0.06 used for riffles.

Habitat / Site	**1000 ML/day** **SS (N/m^2)** ***d50 (mm)***	**1595 ML/day** **SS (N/m^2)** ***d50 (mm)***	**3000 ML/day** **SS (N/m^2)** ***d50 (mm)***	**12,000 ML/day** **SS (N/m^2)** ***d50 (mm)***	**16,388 ML/day** **SS (N/m^2)** ***d50 (mm)***	**28,646 ML/day** **SS (N/m^2)** ***d50 (mm)***
Pools						
DS of Mowamba (n=4)	0.9 N/m^2 *1.9 mm*	1.7 N/m^2 *3.5 mm*	3.7 N/m^2 *7.6 mm*	20.6 N/m^2 *42.5 mm*	36.9 N/m^2 *76.1 mm*	97.0 N/m^2 *199.9 mm*
Rockwell (n=3)	0.6 N/m^2 *1.2 mm*	1.0 N/m^2 *2.1 mm*	2.2 N/m^2 *4.5 mm*	9.1 N/m^2 *18.8 mm*	12.2 N/m^2 *25.2 mm*	19.1 N/m^2 *39.4 mm*
Riffles						
DS Mowamba (n=1)	106.0 N/m^2 *109.3 mm*	96.8 N/m^2 *99.8 mm*	106.2 N/m^2 *109.5 mm*	97.8 N/m^2 *100.8 mm*	103.3 N/m^2 *106.5 mm*	127.4 N/m^2 *131.3 mm*
Rockwell (n=1)	67.5 N/m^2 *69.6 mm*	95.2 N/m^2 *98.1 mm*	80.9 N/m^2 *83.4 mm*	32.8 N/m^2 *33.8 mm*	30.2 N/m^2 *31.1 mm*	33.5 N/m^2 *34.5 mm*

Discussion

Hydraulic modelling outputs for median and mean daily snowmelt discharges provide an indication of hydraulic conditions in the Snowy River under the maximum average daily flows that occurred prior to regulation, are currently occurring and are estimated to occur under a 15% environmental flow regime. Average flows for all months outside of the spring snowmelt, particularly under an environmental flow regime (EFR), will be considerably lower than the minimum discharge (1000 ML/day) modelled in the current study. Under a 1000 ML/day flow, which represents the maximum median daily snowmelt discharge that is expected to occur in September under a 15% environmental flow regime, the average shear stress in deep pools at the Snowy River sites downstream of the Mowamba River (Site 1) and at Rockwell (Site 3) ranges from 0.58 – 0.91 N/m^2. Under the Neill (1968) dimensionless shear stress criterion of 0.03, flows of 1000 ML/day are capable of initiating movement in *unconsolidated and hydraulically exposed* coarse sands up to about 1.9 mm in diameter.

Average velocities in pools under 1000 ML/day flows at downstream Mowamba and Rockwell sites range from 0.21 – 0.29 ms^{-1}. The Hjulstrom curve, as modified by Sundborg (1956) and discussed in detail by Novak (1973), indicates that velocities of about 0.15 ms^{-1} are required to initiate transport of *unconsolidated* fine-grained sediment such as the flocculated fine grained sediment laminae described by Erskine et al. (1996, 1999) and DLWC (unpublished). Flows of 1000 ML/day are therefore sufficient to initiate flushing of these deposits in pools of the Jindabyne Gorge and Dalgety Uplands reaches of the Snowy River. The threshold discharge under which the average velocity in deep pools will fall to below 0.15 ms^{-1} remains to be determined. Once these threshold discharges are determined, however, it would be a relatively simple matter to investigate the frequency with which EFR daily flows achieve the ‘silt flushing’ threshold from 20 years of EFR modelled data output.

Channel shear stress and the maximum particle sizes that are entrained in pools and riffles under the range of flows modelled at the downstream Mowamba River and Rockwell sites are summarised in Table 4. The hydraulic modelling outputs indicate that under flows of 1000 – 3000 ML/day, shear stress velocities across riffles are substantially greater than in pools and that this difference decreases with increasing discharge (Table 4), in keeping with established hydraulic principles (Knighton, 1996 p. 119). The most notable result from the hydraulic modelling is the development of a velocity reversal effect at the Snowy River site downstream of the Mowamba River under the pre-regulation 50% annual exceedence probability flood of 28,646 ML/day. Velocity reversal produces higher velocities and shear stress in pools than across riffles and is important for scouring pools and maintaining pool-riffle sequences (Keller, 1971; Lisle, 1979; Keller and Florsheim, 1993). At the McKillops Bridge site, a strong velocity reversal effect was modelled to occur at flows between the pre-regulation 90% and 50% annual exceedence floods. The occurrence of velocity reversals in two of the three sites modelled to date suggests that velocity reversal in confined sections of the Snowy River under high flows between the pre-regulation 90% and 50% annual exceedence probability floods may have been a reasonably common process (cf. Erskine *et al*., 1996).

Analysis of discharge data indicates that under a 15% EFR flow regime, November is the month of greatest divergence between pre-regulation and 15% EFR flows. Ratios of mean to median daily snowmelt discharges for pre-regulation and 15% EFR flow regimes indicate that reconstructed snowmelt flows will be more variable than the steady high discharges experienced prior to regulation. Under a 28% EFR flow regime, it may be possible to more effectively redress these issues. Similarly, a 28% EFR flow regime might possibly enable occasional release of peak discharges of up to about 28,000 ML/day to initiate velocity reversals in pools of the Jindabyne Gorge reach of the Snowy River.

Seddon (1999) used a metaphor to describe the current Snowy River as “a cot-size river in a king size bed”. Under an environmental flow regime it is still impossible to escape this situation regardless of whether a 15% or 28% regime is reinstated. Upstream monitoring Snowy River sites, such as downstream Mowamba River (Site 1) and Rockwell (Site 3), exhibit a suite of ‘out-of-channel’ sedimentological features that are inundated and formed by the pre-regulation median and mean daily snowmelt discharges. These steady, high and long duration snowmelt discharges cannot be reinstated without de-commissioning Jindabyne Dam. Further downstream at the McKillops Bridge site, sedimentological features exhibit a better relationship to higher discharges between the 90% and 50% annual exceedence probability floods. This may be due to more peaked flood hydrographs at McKillops Bridge than further upstream as a result of rainfall driven floods and a greater disparity between daily instantaneous maximum flows and the daily mean flows that were used to derive the annual maximum flood series. The Snowy River needs to contract under the influence of native vegetation to form an underfit river within a larger, former channel bed. Environmental flows of sufficient magnitude to erode, transport and redistribute sediment provide the only means to holistically enable a river to attain this condition and to reconstruct a new suite of sedimentary landforms adjusted to a reduced flow regime.

Recommendations

The following activities for the hydraulic modelling component of the Snowy River Flow Response Monitoring and Modelling program are recommended.

FIELD STUDIES

- Undertake detailed topographic and bathymetric survey of the sites in the upper reaches of the Snowy River, as this will provide greater spatial representation of the river reach and improve the quality of the hydraulic models (see Reinfelds and Williams 2007).
- Undertake detailed orthorectified aerial photography of the upper reaches and integrate with field survey data.
- Survey-in observed water surface profiles for events of interest to modelled water surface profiles in order to calibrate models.
- Tag rocks of various size grades at several sites to undertake field validation of sediment mobility thresholds.
- Link modelled hydraulic outputs, such as area inundated with other field data and air photographs.

FURTHER MODELLING

- Extend the hydraulic modelling to further investigate sediment mobility discharge thresholds to include all sites:
    - Stage 2 in the upper reaches, including the Cobbin Creek, Sugarloaf, Blackburn Creek and Burnt Hut Crossing sites as the higher priority as these reaches are likely to influenced greatest by dam releases.
    - Stage 3 the lower reaches of Snowy River should be considered once sufficient water savings are available in order to investigate sediment mobility to discharge thresholds.
- Model flows lower than 1000 ML/day to investigate threshold discharges below which the average velocity in deep pools decreases to less than 0.15 ms^{-1}; a situation conducive to deposition of fine grained sediment.
- Once threshold discharges relating to mean pool velocities of 0.15 ms^{-1} for the Jindabyne Gorge and Dalgety Uplands reaches are known, it would be desirable to investigate the pre-regulation, post-regulation and EFR durations under which flows are insufficient to prevent silt deposition.
- Investigate whether velocity reversals in pools can be generated under lower flows than modelled in this study by increasing floodplain roughness coefficients (undertaking a modelling run with Manning’s ‘n’ of 0.06 – 0.15).

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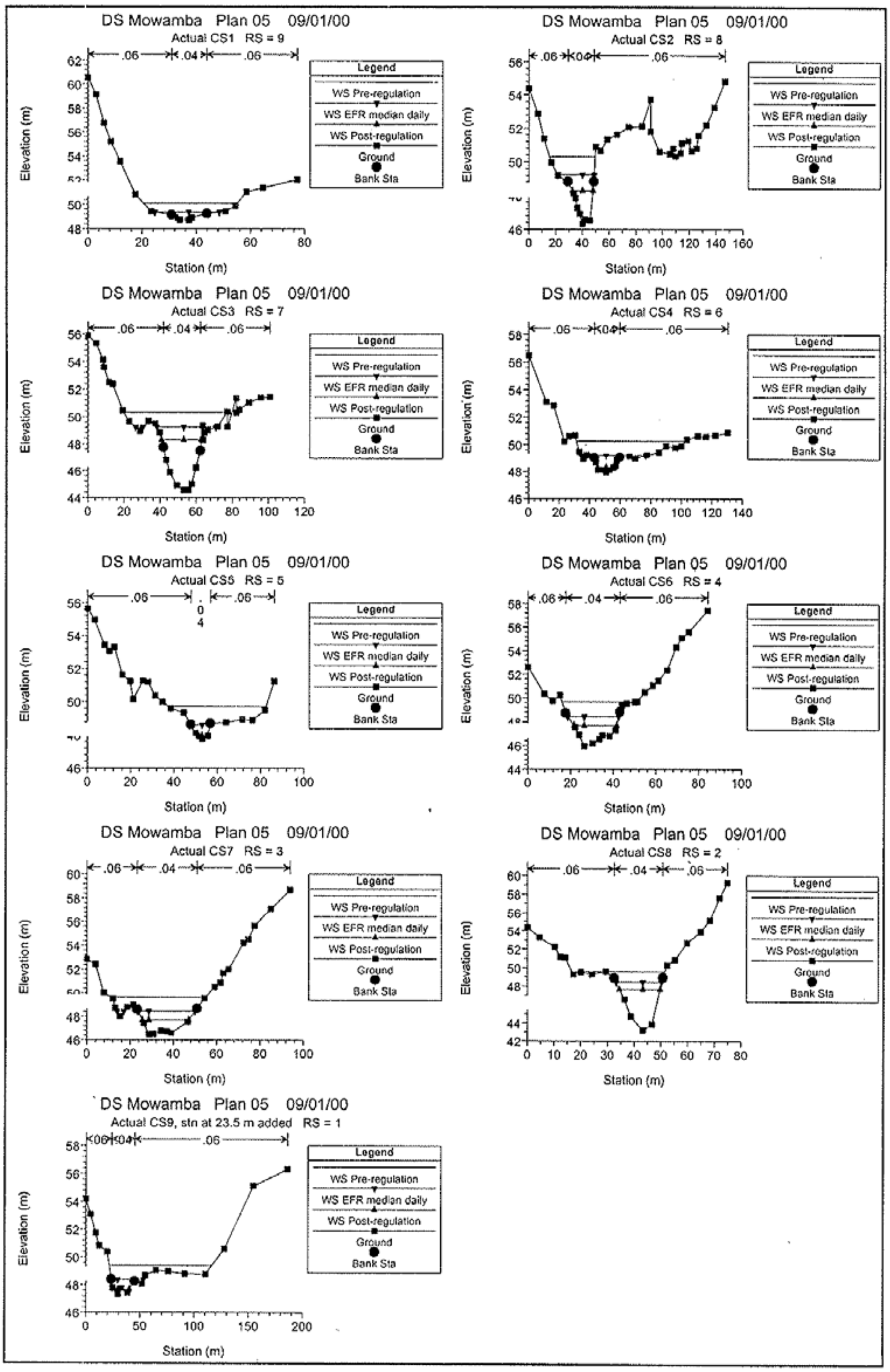
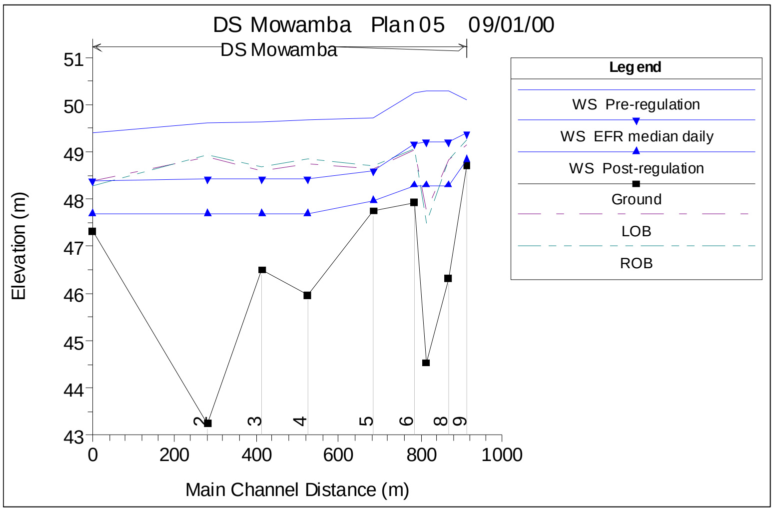
Appendix 1: Snowy River downstream of Mowamba River (site 1)

Snowy River downstream of Mowamba River (site 1) - Median daily snow melt discharges



Snowy River downstream of Mowamba River Junction (A) surface profiles, (B) channel Shear stress, and (C) velocity for median daily snowmelt discharge.

A



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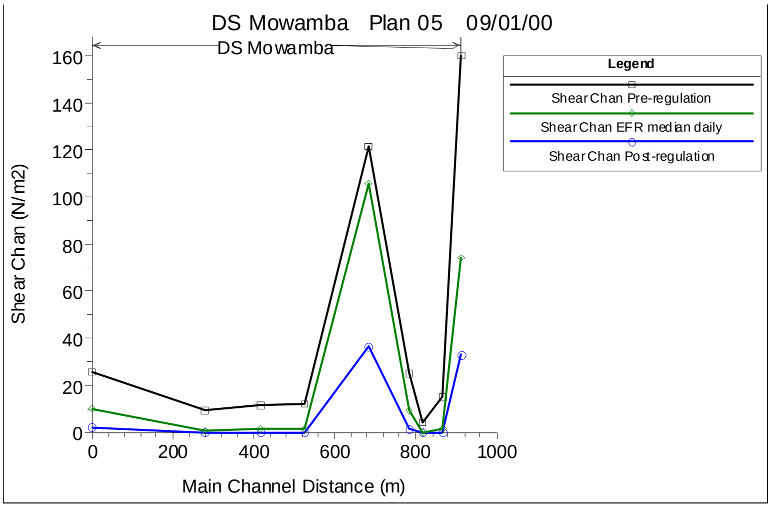

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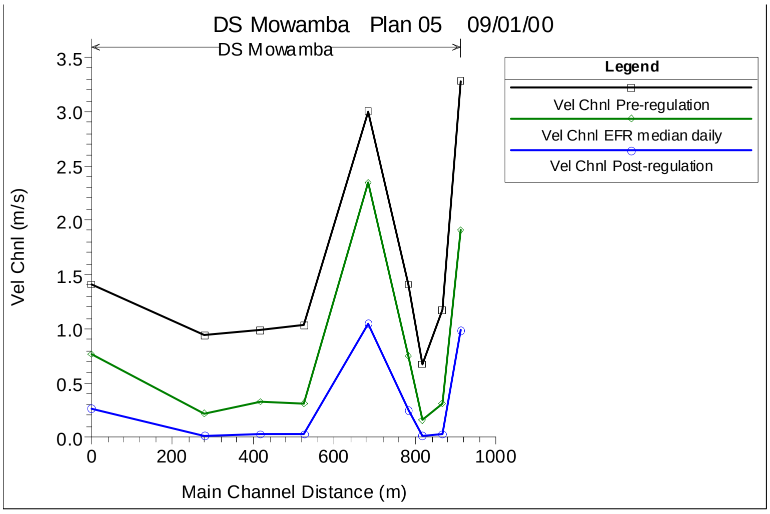
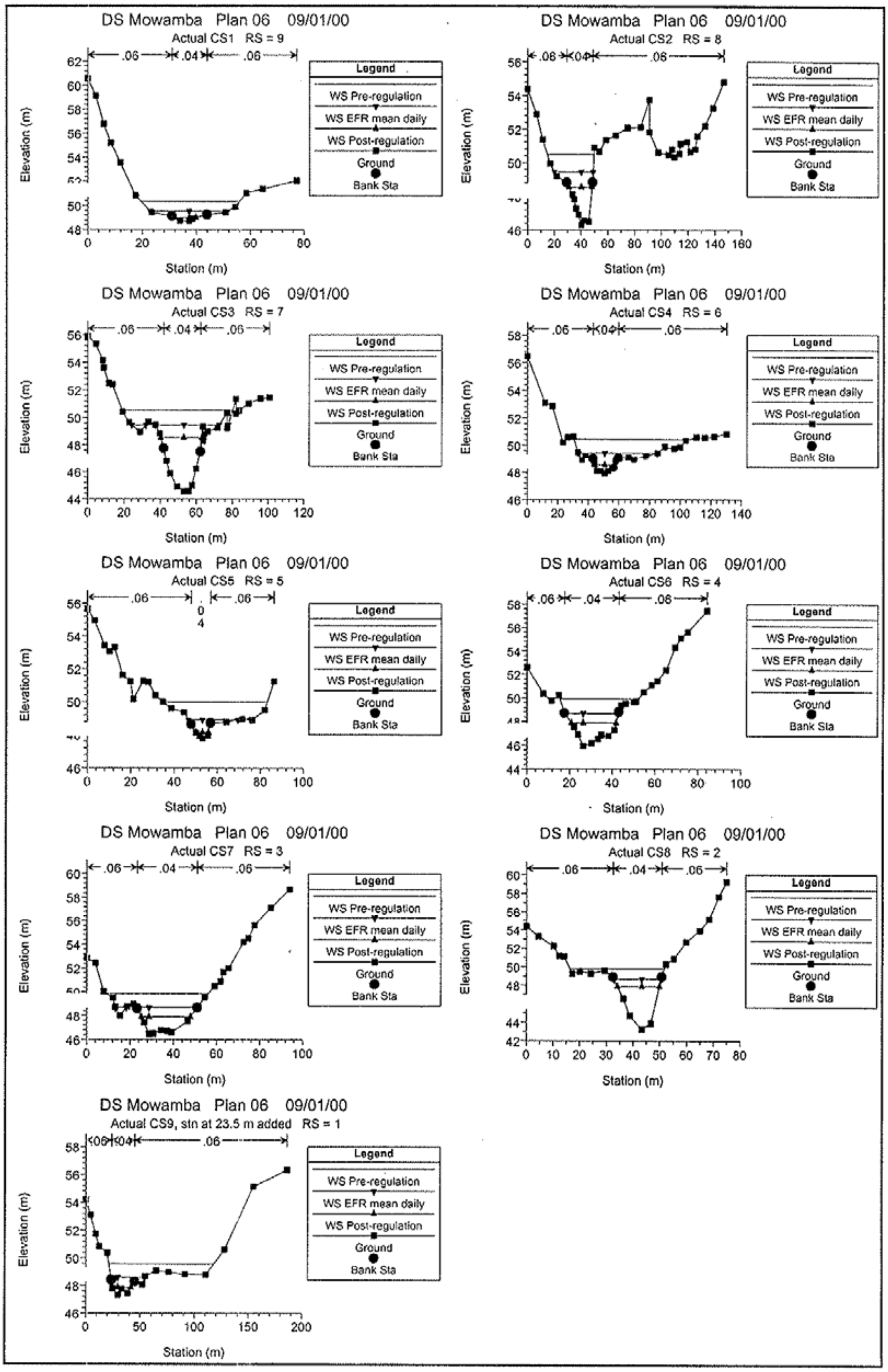
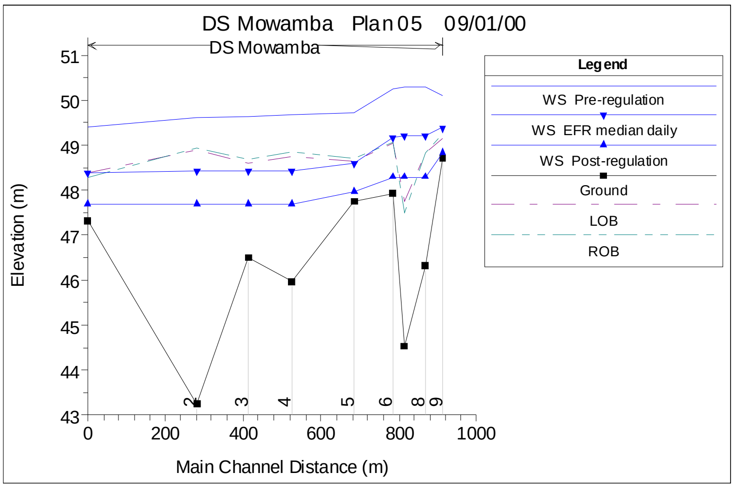


Snowy River downstream of Mowamba River (site 1) - Mean daily snow melt discharges



Snowy River downstream of Mowamba River Junction (A) surface profiles, (B) channel Shear stress, and (C) velocity for mean daily snowmelt discharge.

A



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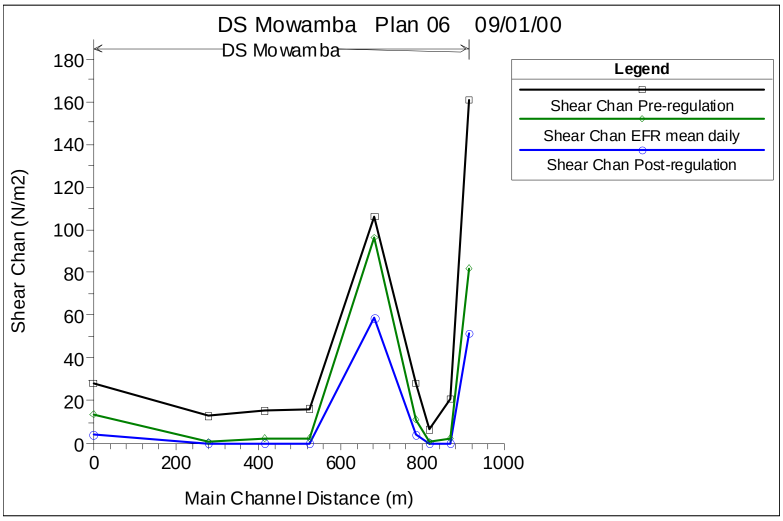

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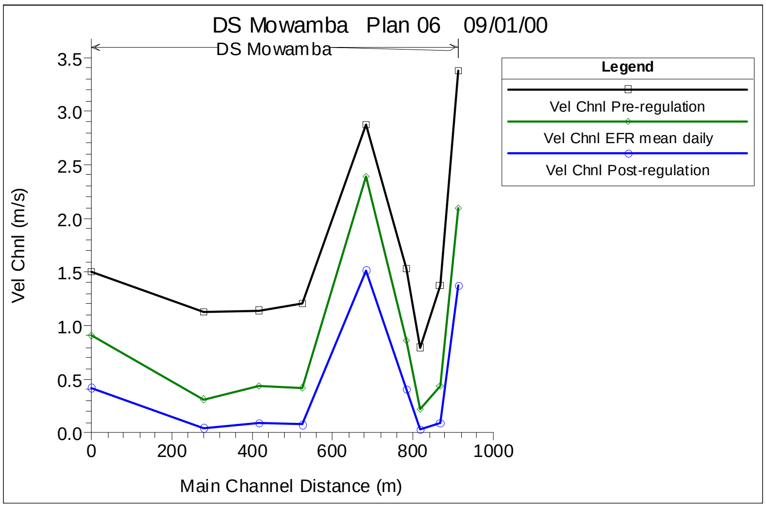
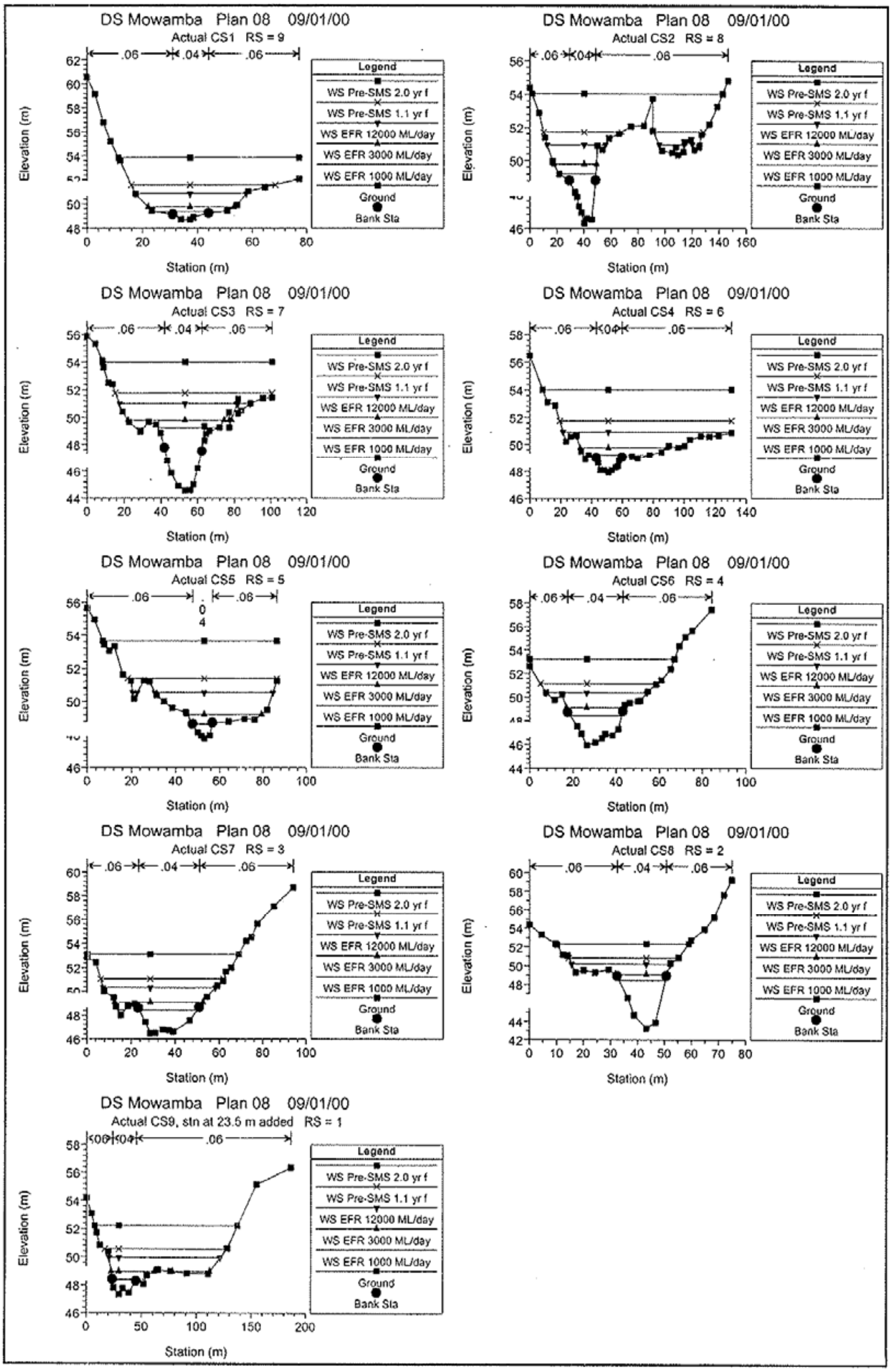


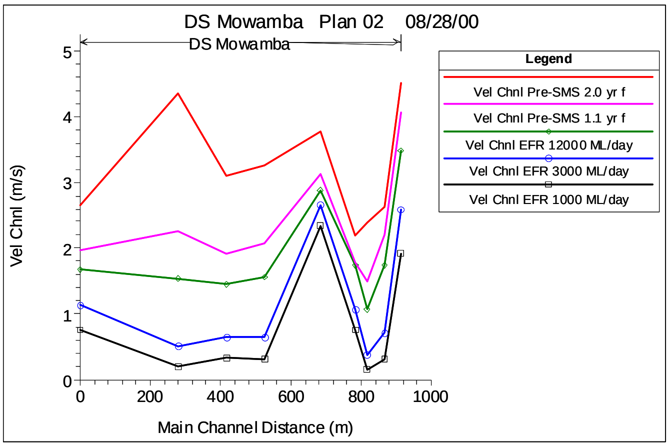
Snowy River downstream of Mowamba River (site 1) – 90% and 50% annual exceedence probabiliy floods



Snowy River downstream of Mowamba River (site 1) –under EFR and Pre-regulation 90% and 50% annual exceedence floods (A) SURFACE PROFILES, (b) Shear Stress and (C) Mean channel velocity.

A

Downstream Mowamba mean channel velocity under EFR and pre-regulation 90% and 50% annual exceedence floods



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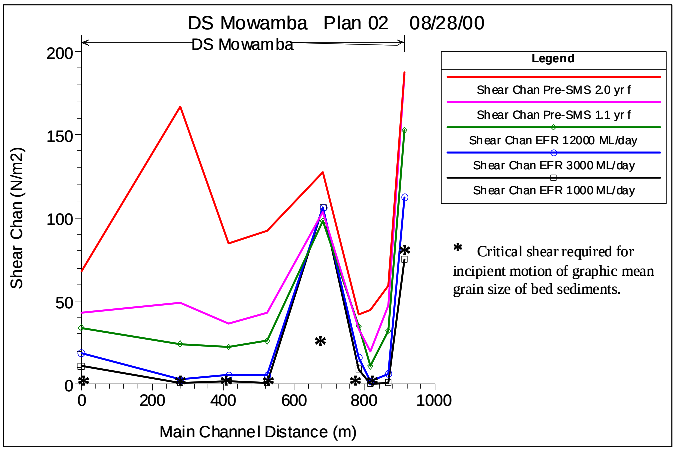
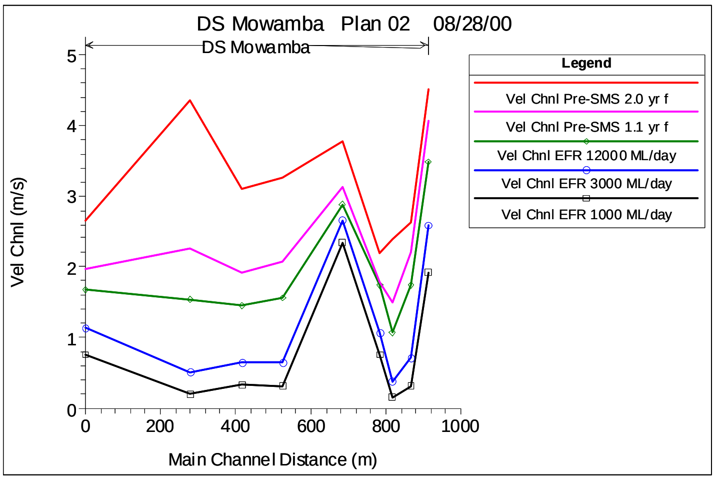


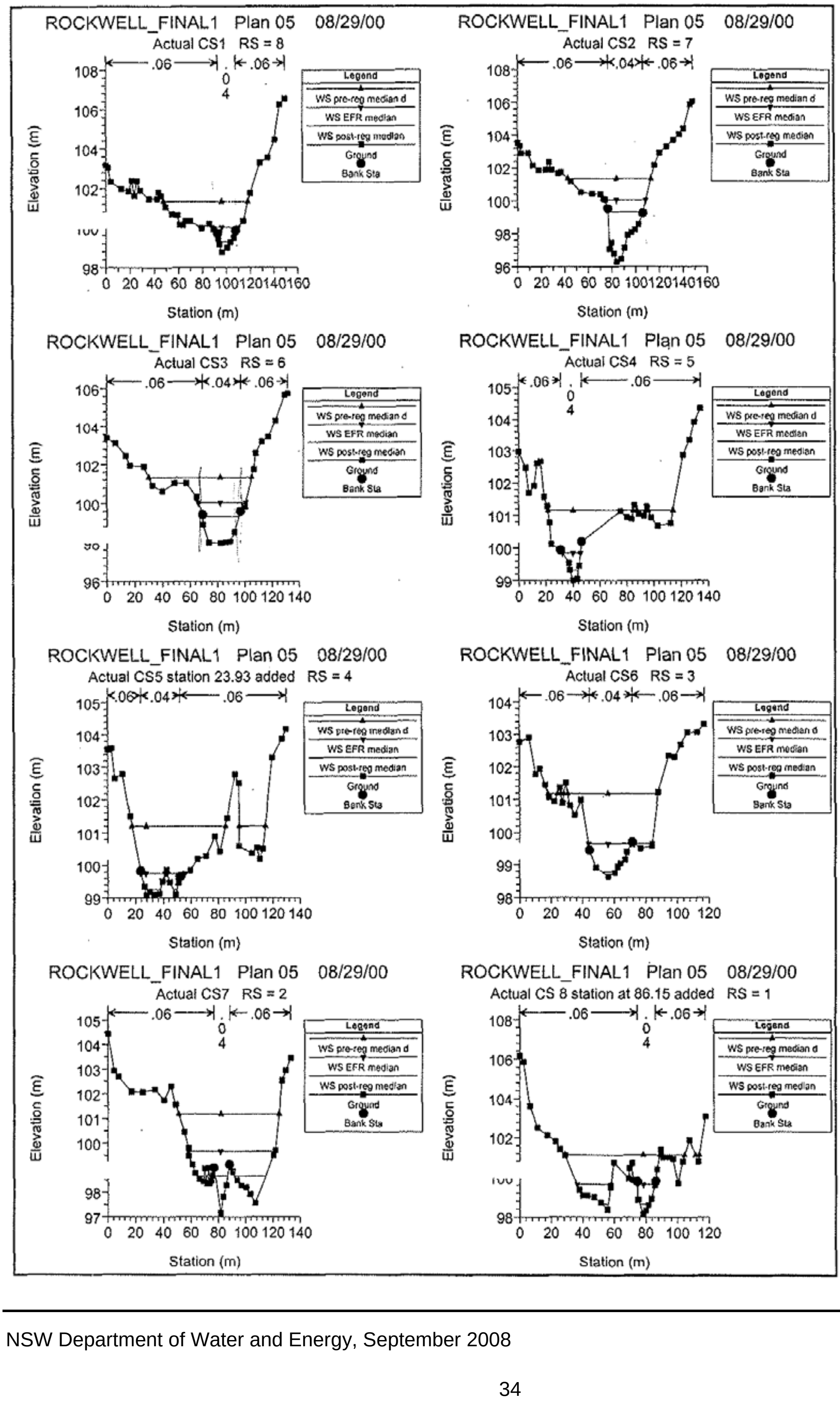
* Critical shear required for incipient motion of graphic mean grain size of bed sediments.

C

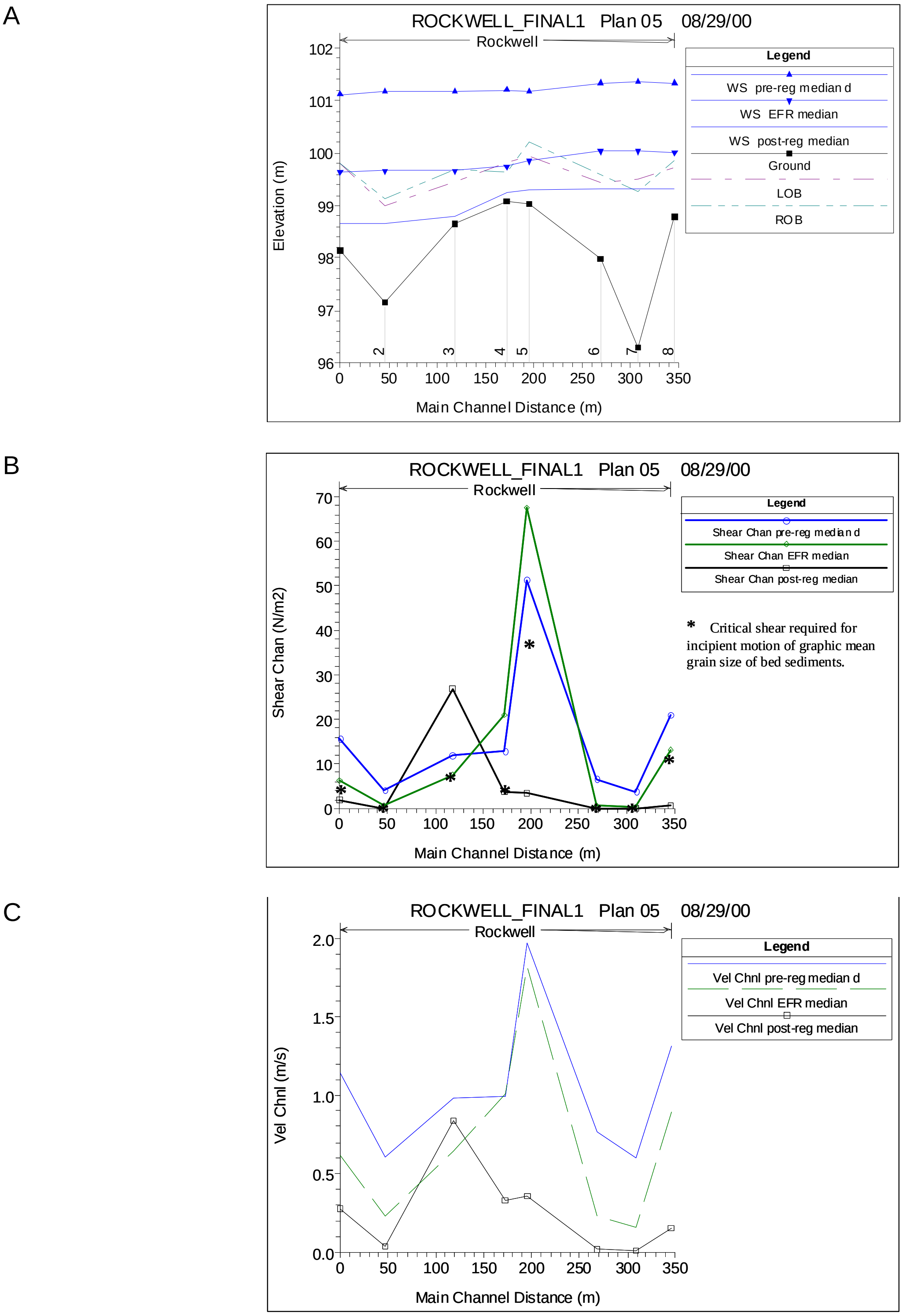


Appendix 2: Snowy River downstream at rockwell (site 3)

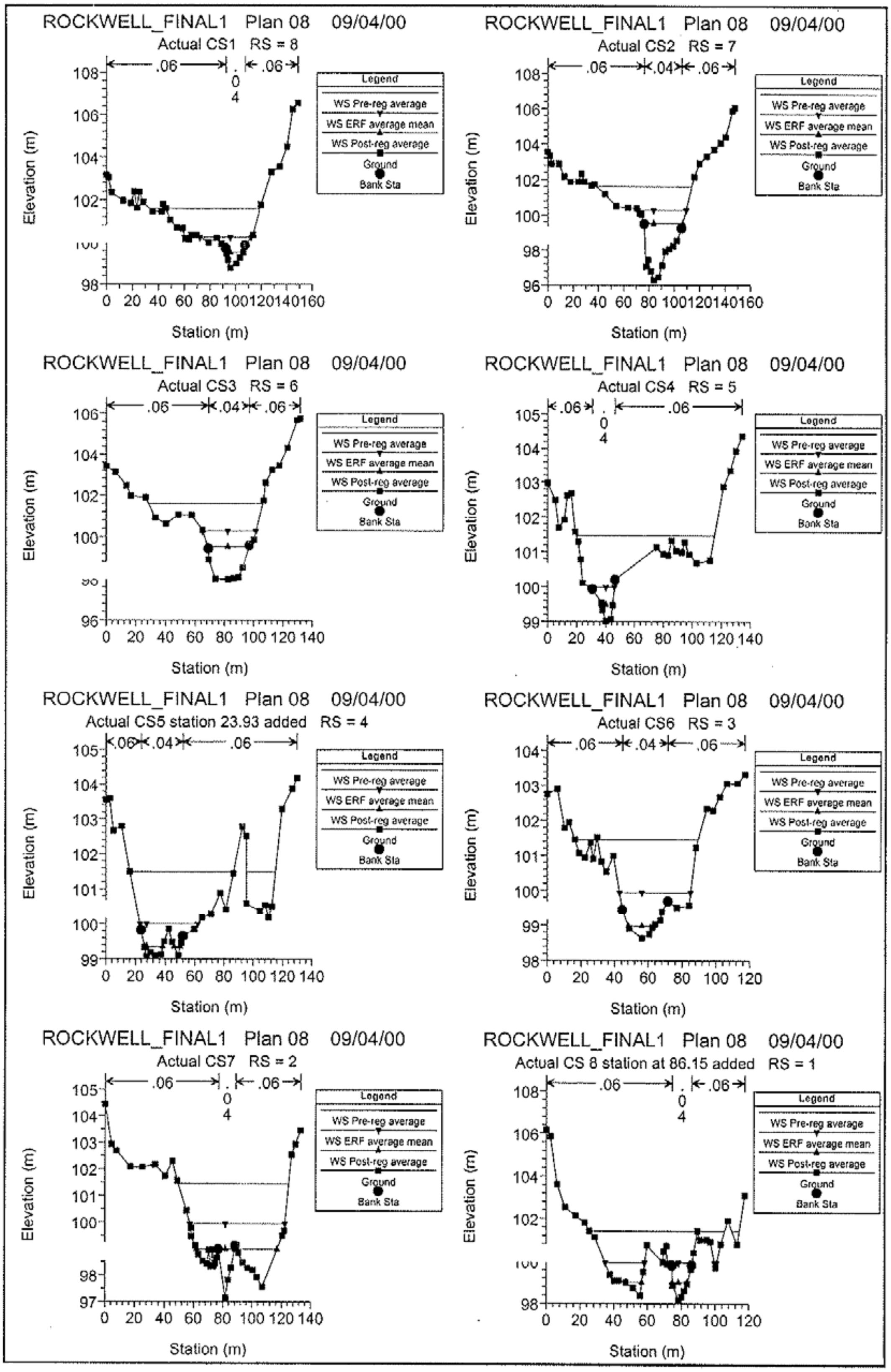
Snowy River downstream at rockwell (site 3) - Median daily snow melt discharges



Snowy River downstream at rockwell (site 3) – Pre-regulation and EFR Median daily snow melt discharges, (A) surface water profiles (B) shear stress and (C) mean velocity.

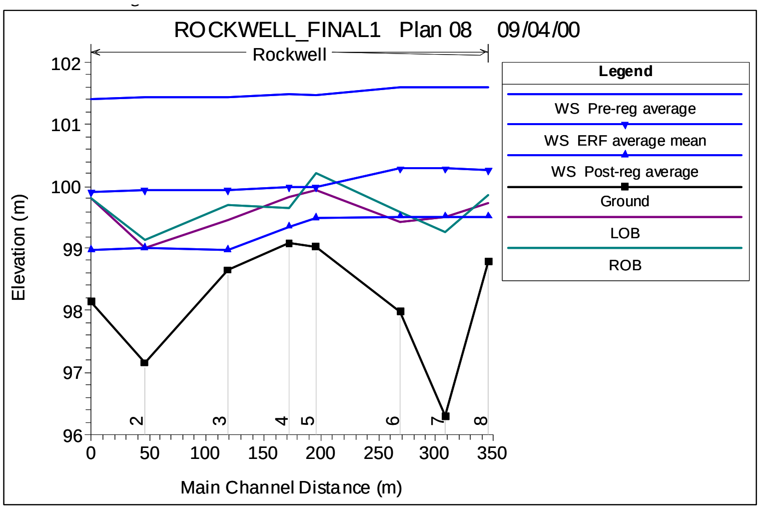


Snowy River downstream at rockwell (site 3) - Mean daily snow melt discharges.

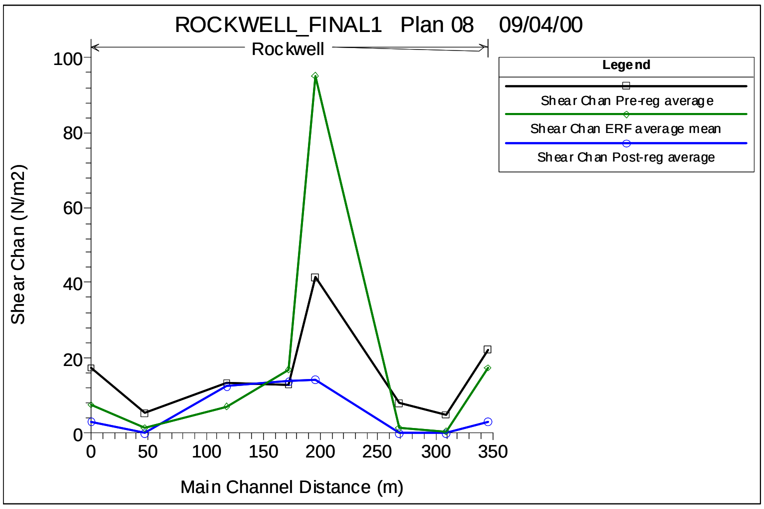


Snowy River downstream at rockwell (site 3) – Pre-regulation and EFR Mean daily snow melt discharges, (A) surface water profiles (B) shear stress and (C) mean velocity.

A



B



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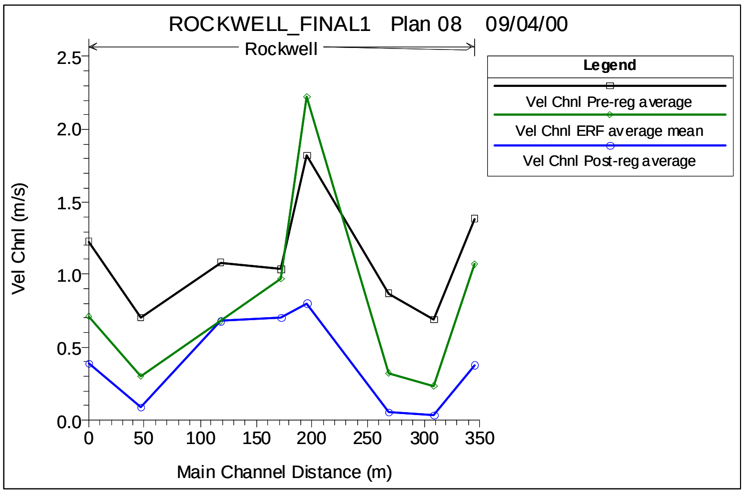
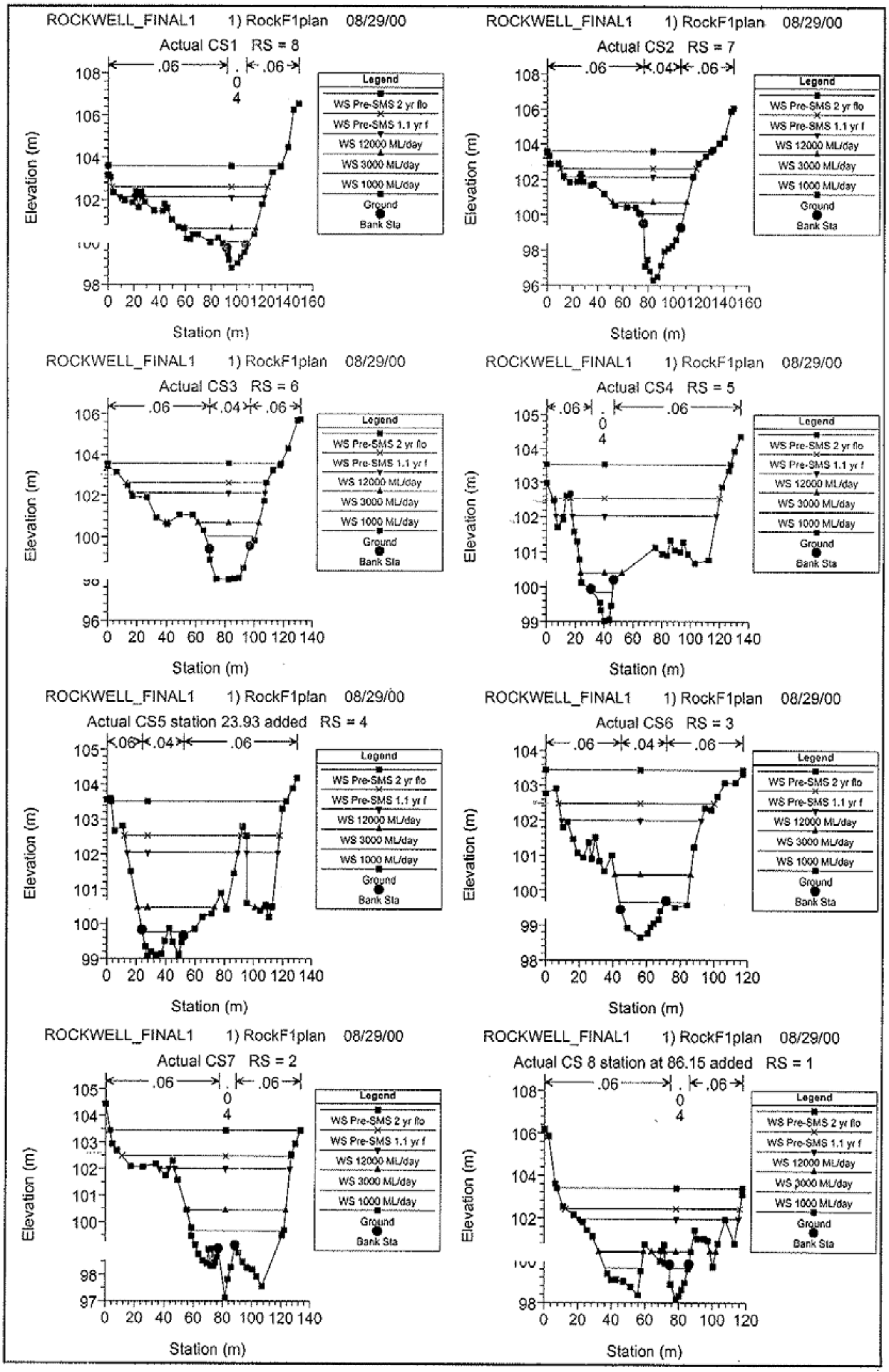
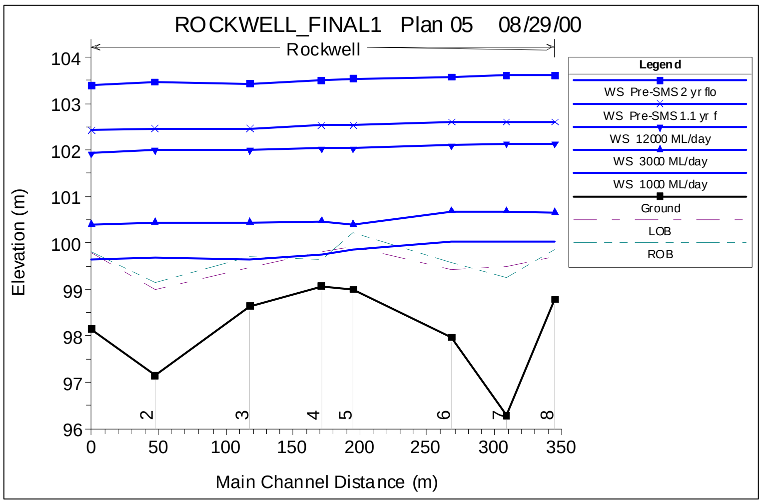


Snowy River downstream at rockwell (site 3) – 90% and 50% annual exceedence probabiliy floods.

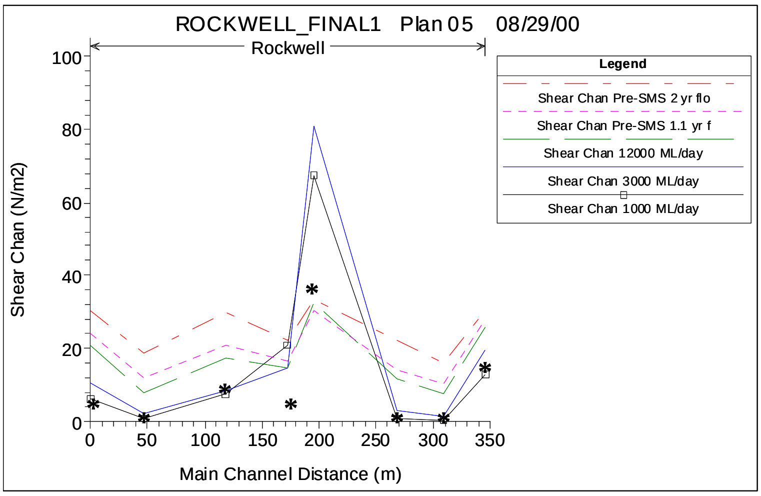


Snowy River at rockwell (site 3) –under EFR and Pre-regulation 90% and 50% annual exceedence floods (A) water Surface profiles (B) Shear Stress and (C) Mean channel velocity.

A



B



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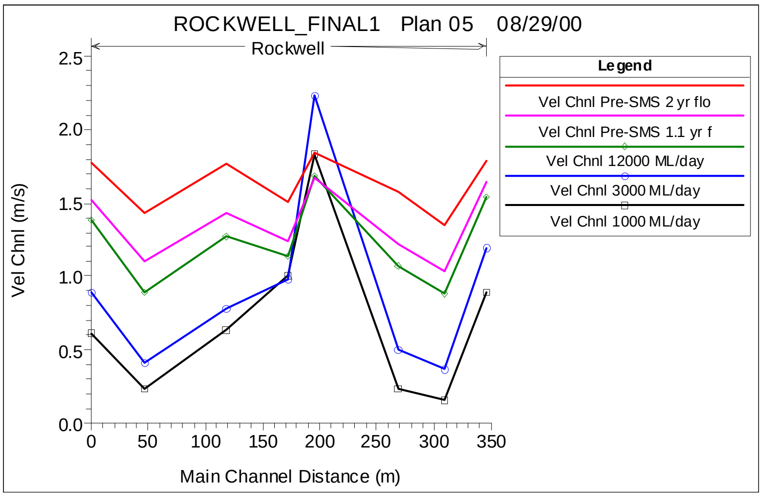
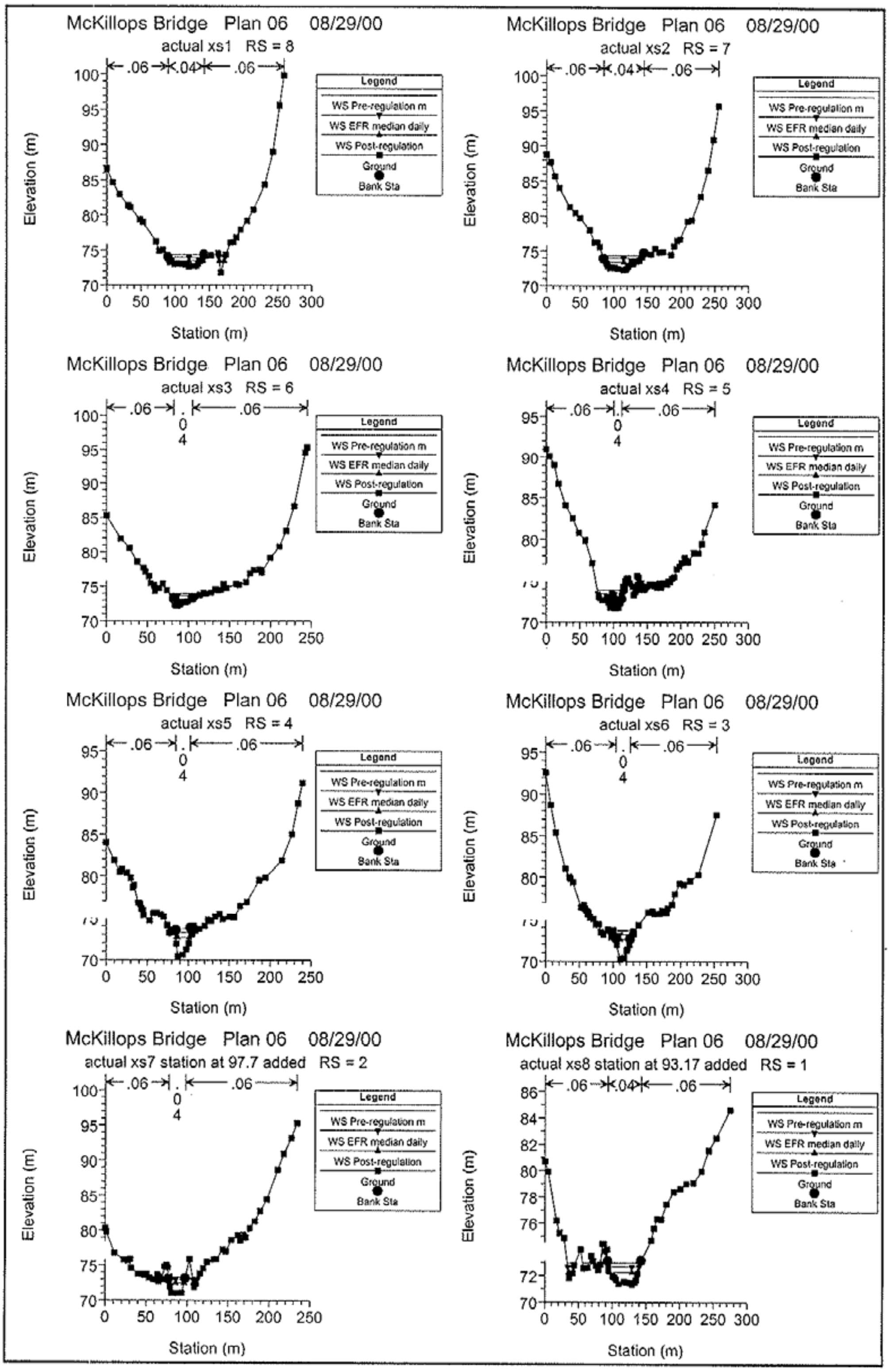


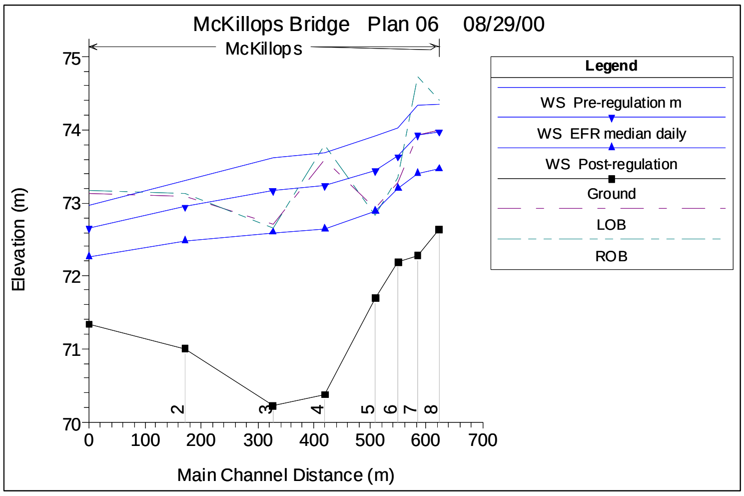
Appendix 3: Snowy River downstream at McKillops Bridge (site 7)

Snowy River downstream at McKillops Bridge (site 7) - Median daily snow melt discharges



Snowy River downstream at Mckillops bridge (site 7) – Pre-regulation and EFR Median daily snow melt discharges, (A) surface water profiles (B) shear stress and (C) mean velocity.

A



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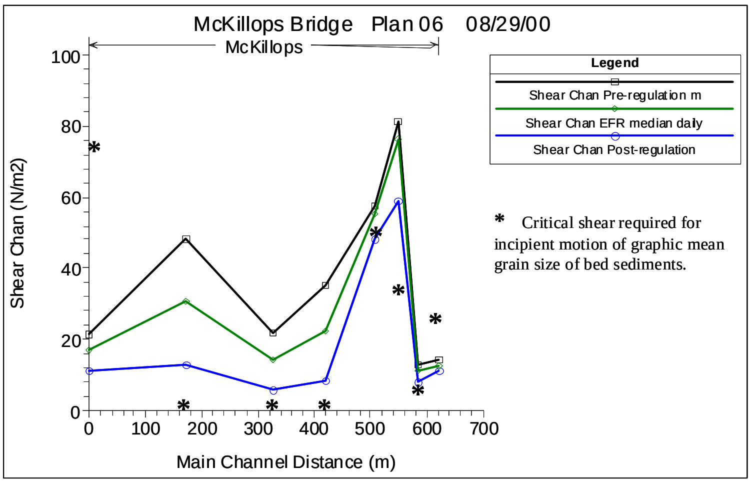

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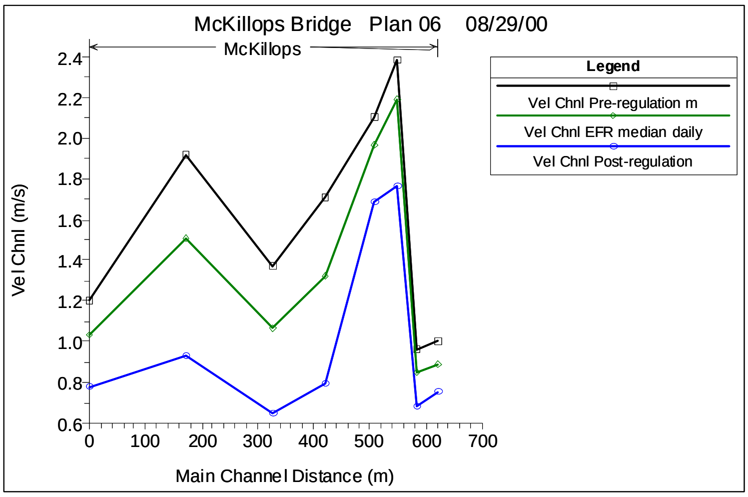
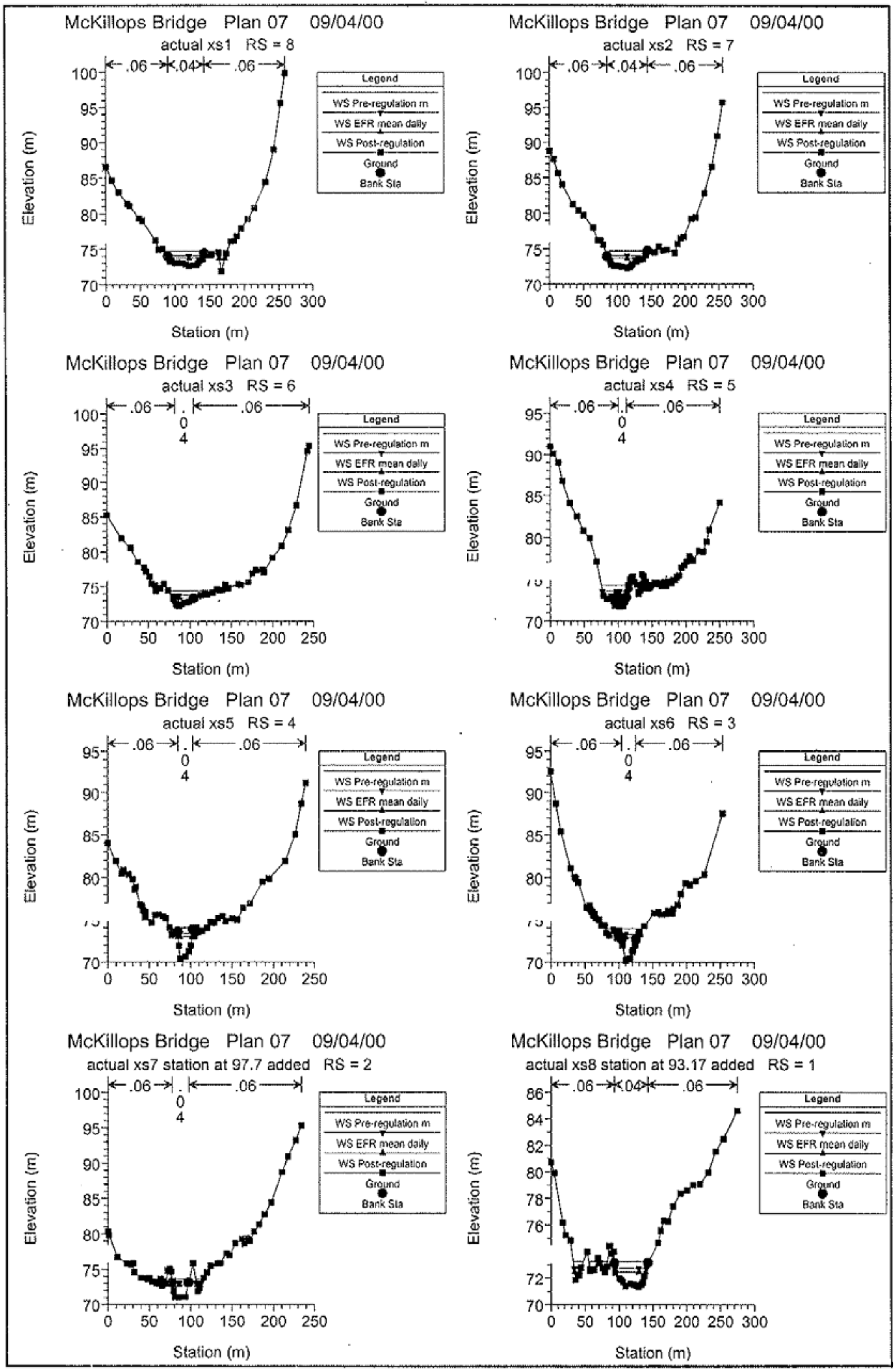
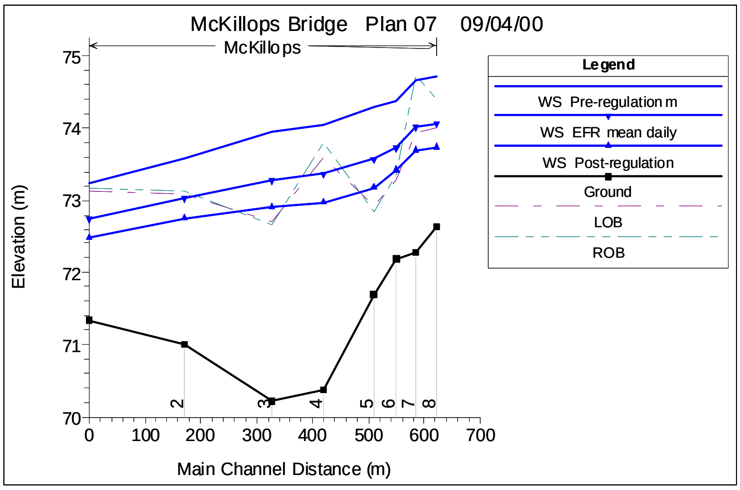


Snowy River downstream at McKillops Bridge (site 7) - MeAN daily snow melt discharges



Snowy River downstream at Mckillops Bridge (site 7) – Pre-regulation and EFR Mean daily snow melt discharges, (A) surface water profiles (B) shear stress and (C) mean velocity.

A



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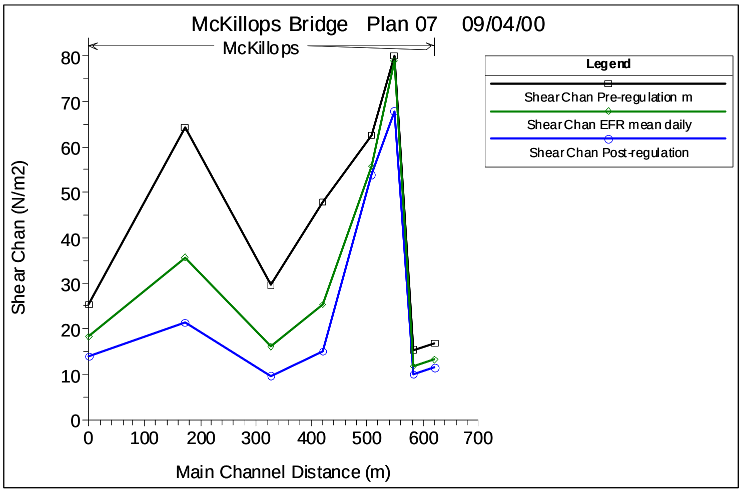

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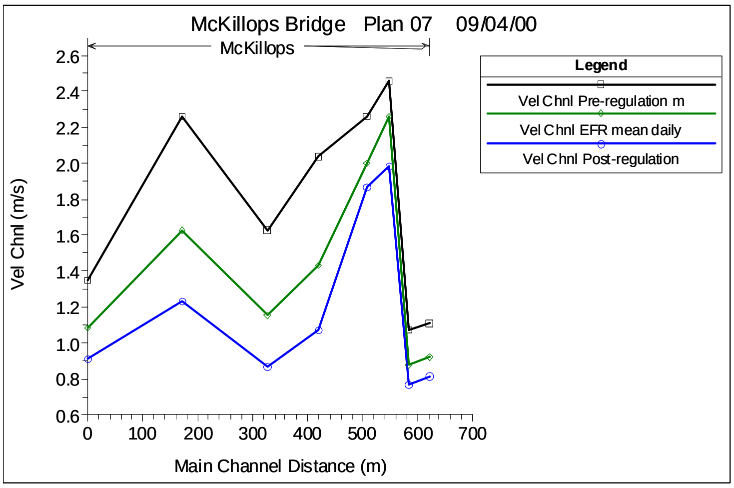
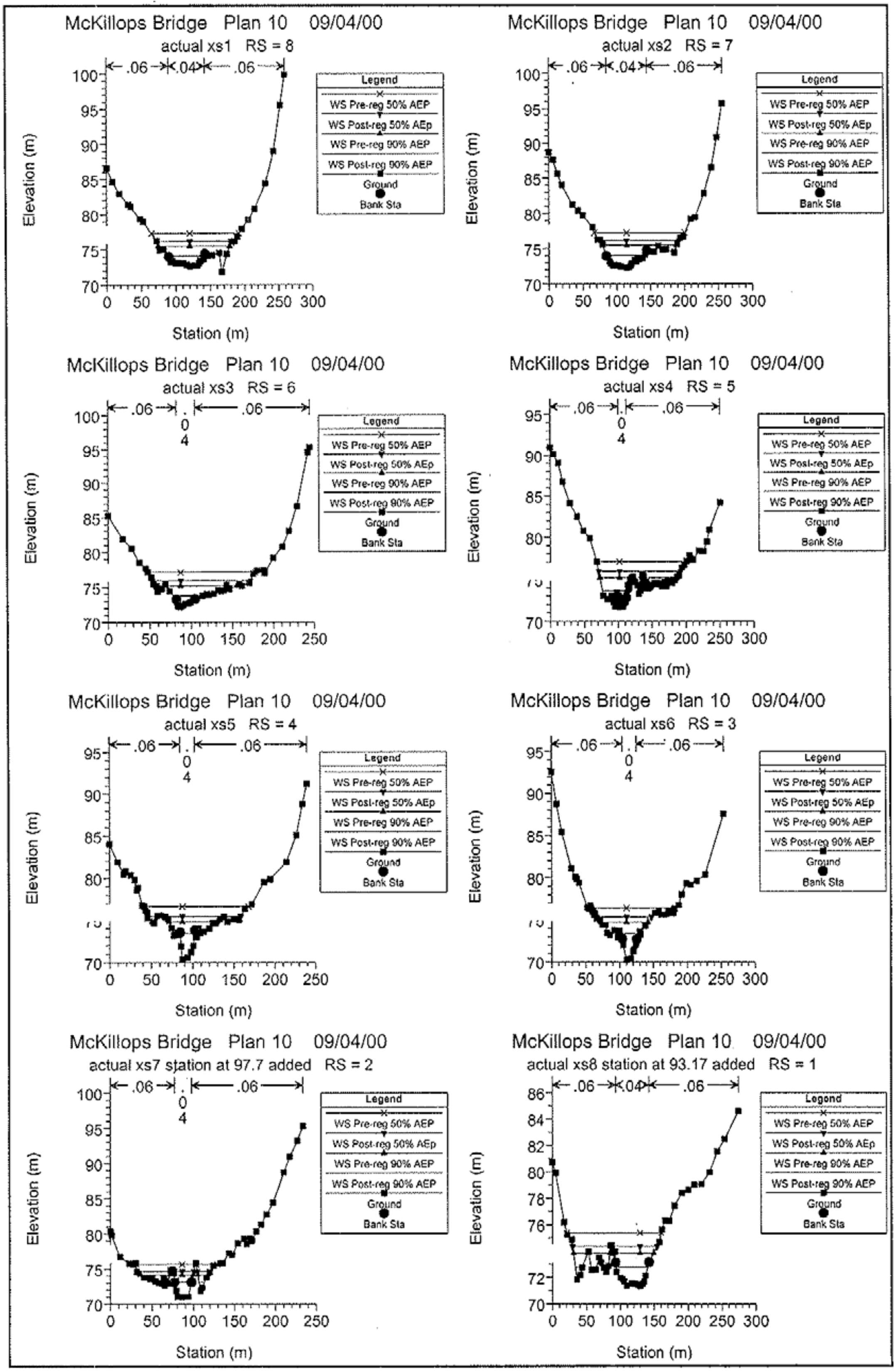
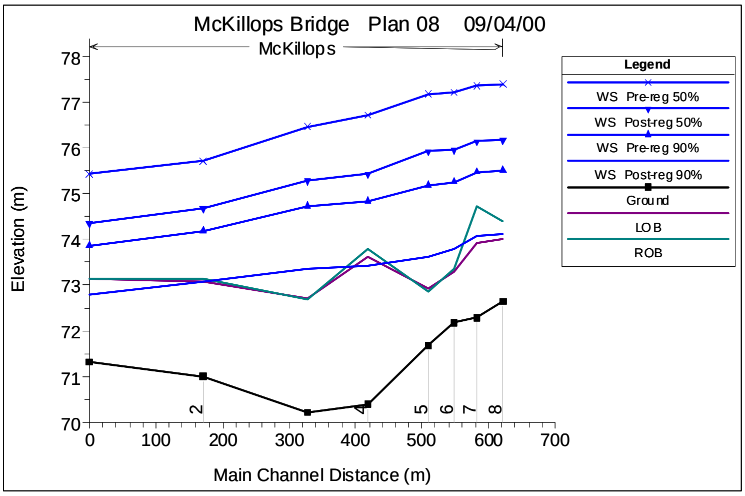


Snowy River downstream at Mckillops bridge (site 7) – 90% and 50% annual exceedence probabiliy floods.



Snowy River downstream of Mckilliops bridge (site 7) –under EFR and Pre-regulation 90% and 50% annual exceedence floods (A) water Surface profiles (B) Shear Stress and (C) Mean channel velocity.

A



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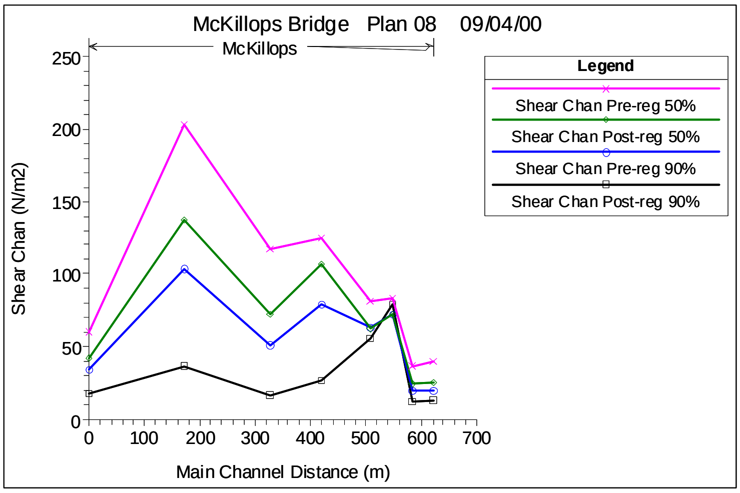

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