Appendix 7 Flood Hydrology and Geomorphology

Bowmans Creek Diversion

Appendix 7

Flood Hydrology and Geomorphology

05 October 2009

FLUVIAL SYSTEMS

GEOMORPHOLOGY • CATCHMENT HYDROLOGY
RIVER REHABILITATION • ENVIRONMENTAL FLOWS

Fluvial Systems Pty Ltd
PO Box 49
Stockton N.S.W. 2295
Australia

Tel: +61 2 49284128
Fax: +61 2 49284128
Mobile: 0404 472114
Email: chris.gippel@bigpond.com
ABN: 71 085 579 095

Document History and QA

Client: **Ashton Coal Operations Pty Ltd**

Document: Appendix 7: Flood Hydrology and Geomorphology

Date: 05 October 2009

Author: Dr Chris Gippel

Revision History:

Revision	Revision Date	Details	Authorised	
			Name	Signature
A	31/08/2008	Preliminary Draft	Christopher Gippel	
B	24/09/2009	Draft	Christopher Gippel	
C	05/10/2009	Final	Christopher Gippel	

Table of Contents

1 INTRODUCTION ... 1

1.1 Context of this Report ... 1

1.2 Director General's Requirements Relevant to the Geomorphological Assessment of the Proposal ... 1

1.3 Relevant Laws, Policies, Guidelines or Plans ... 2

1.4 Definition of Channel Stability and Morphological Resilience ... 3

1.5 Objectives of this Report ... 4

2 HISTORICAL AND EXISTING ENVIRONMENT ... 5

2.1 Flood Hydrology of Bowmans Creek ... 5

2.1.1 Data availability ... 5

2.1.2 Flood frequency analysis ... 6

2.1.3 Previous flood frequency analyses ... 8

2.1.4 Frequency and durations of overflows for 5 year ARI events ... 12

2.1.5 Relative influence of the Hunter River water levels on flooding of Bowmans Creek ... 13

2.2 Previous Investigations - Geomorphology ... 17

2.2.1 Geomorphic history of the Upper Hunter River and tributaries ... 17

2.2.2 Description of Bowmans Creek fluvial geomorphology by Patterson Britton & Partners (2001) ... 19

2.2.3 Description of Bowmans Creek fluvial geomorphology by ERM (2006) ... 20

2.2.4 Description of Bowmans Creek fluvial geomorphology by Maunsell Australia (2008) ... 21

2.2.5 Summary of previous geomorphological investigations of Bowmans Creek and their relevance to the present study ... 21

2.3 Geomorphological setting and state of Bowmans Creek ... 22

2.4 Characterisation of Existing Geomorphological Processes ... 25

2.4.1 Approach taken to Geomorphological Assessment ... 25

2.4.2 2008 survey data ... 26

2.4.3 Field measurement of low flow channel width and depth ... 27

2.4.4 Field Measurement of Bed Material Particle Size ... 30

2.4.5 Assessment of Bed Stability Based on Bed Shear Stress ... 32

2.4.6 Assessment of Bank Stability Based on Maximum Permissible Velocity ... 35

2.4.7 Types of scour and scour depth prediction ... 37

2.4.8 Bed scour in the existing channel ... 40

2.4.9 Summary of existing channel geomorphic condition ... 42

3 GEOMORPHOLOGICAL DESIGN ASPECTS OF THE PROPOSAL ... 43

3.1 Brief Description of the Proposed Diversion Concept ... 43

3.2 Design Principles ... 43

3.3 Design Method for Basic Channel Form ... 44

3.4 Design of Channel Features 45

4 GEOMORPHOLOGICAL IMPACTS OF THE PROPOSAL........ 47

4.1 Brief Description of Implementation and Operation of the Proposed Diversions........ 47

4.2 Diversion Channels........ 47

4.2.1 Assessment of bed stability based on bed shear stress........ 47

4.2.2 Assessment of bank stability based on maximum permissible velocity 47

4.2.3 Modelled bed scour........ 51

4.3 Existing Channel and Terrace........ 53

4.4 Implications of Natural Incision Trajectory for Diversions 54

4.5 Probability of Avulsion 55

5 MITIGATION MEASURES........ 55

6 SUGGESTED MONITORING PROGRAM 56

7 CONCLUSION 57

8 REFERENCES........ 58

List of Figures

Figure 1.1: Geomorphic dynamic equilibrium concept. Source: Sear (1996). 5

Figure 2.1: Data availability for the two gauges on Bowmans Creek 6

Figure 2.2: Relationship between peak flows at the two gauges on Bowmans Creek (Polynomial relationship used for Q> 775 ML/d (9 m^3/s) and power function for Q< 775 ML/d (9 m^3/s) 7

Figure 2.3: Gauged flows at the two gauges on Bowmans Creek for the month of August 1998. 10

Figure 2.3: Duration of spells exceeding the 5 Year ARI event, when the diversion would overflow into the existing Bowmans Creek. 13

Figure 2.4: River gradient between Liddell and Singleton. Mean gradient is 0.000594 m/m. (Data from 1972 to 2005). 14

Figure 2.5: Data availability for the Hunter River gauge at Singleton 15

Figure 2.6: Flood frequency curve for Singleton converted to stage height at Bowmans Creek junction (Based on data from 1913 to 2005) 16

Figure 2.7: Predicted extent of inundation of the floodplain in vicinity of Bowmans Creek, as influenced only by Hunter River water levels. (These levels correspond to contours at the predicted Hunter River water levels for the given ARI events as given in Figure 2.6.) 17

Figure 2.8: Example Hydrographs from Hunter River and Bowmans Creek, August 2008 (Water levels estimated from available hydraulic model information. On this occasion Hunter River water did not reach the site of the proposed Eastern diversion, but at the proposed Western diversion site the level of Hunter River water exceeded that of Bowmans Creek on some days. This is equivalent to a 1 in 5 to 1 in 7 year ARI Hunter River event.) 18

Figure 2.8: Topography of Bowmans Creek and the Hunter River in the vicinity of their confluence. 23

Figure 2.9: Profile of the floodplain near the confluence of Bowmans Creek and the Hunter River. 24

Figure 2.10: Downstream pattern of morphology of Bowman's Creek as indicated by cross-sections surveyed by Pegasus Technical in 2008. (Water level is on days of survey in 2008; terrace level sometimes corresponded to the ground elevation at the lateral limit of the cross-section rather than the actual highest level of the terrace in that vicinity) 26

Figure 2.13: Monthly pattern of median flow at D/S Bowmans Creek Bridge gauge, also showing the inter-quartile range (between the 25^{th} percentile and 75^{th} percentile). 27

Figure 2.11: Downstream pattern of width of low flow channel in Bowman's Creek. (Top plot is the section of Bowmans Creek that would be replaced by the Western diversion, and the lower plot is the section that would be replaced by the Eastern diversion.) 28

Figure 2.12: Downstream pattern of depth of water in low flow channel in Bowmans Creek (Top plot is the section of Bowmans Creek that would be replaced by the Western diversion, and the lower plot is the section that would be replaced by the Eastern diversion.) 29

Figure 2.16: Sites where bed material was sampled for particle size distributions in August 2009. 31

Figure 2.13: Particle size distributions of riffle crest bed material sampled in August 2009. 32

Figure 2.14: Existing Bowmans Creek, Bed Stability Index for a range of ARI events 35

Figure 2.15: Existing Bowmans Creek, Bank Stability Index for a range of ARI events 36

Figure 2.16: Calculated reach median values of a range of active layer and general scour predictions for the existing Bowmans Creek in the study area. 41

Figure 2.17: Predicted number of pools with potential for velocity reversal [relationship of Caamaño et al. (2009)] and number of pools showing velocity reversal in 1-D model for the existing Bowmans Creek in the study area. 41

Figure 3.1: Long profiles of the existing channel reach that would be diverted by the proposed Eastern diversion. (The bank top and bank toe elevations refer to the low flow channel. In the proposed diversion plan, the top pool would be retained in the backwater of block bank E1). 45

Figure 3.2: Oblique depiction of the proposed diversion channels and the existing channels. 46

Figure 4.1: Proposed Eastern Diversion Bed Stability Index for a range of ARI events, compared with values for the existing channel in the reach to be diverted 48

Figure 4.2: Proposed Western Diversion Bed Stability Index for a range of ARI events, compared with values for the existing channel in the reach to be diverted 49

Figure 4.3: Proposed Eastern Diversion Bank Stability Index for a range of ARI events, compared with values for the existing channel in the reach to be diverted 50

Figure 4.4: Proposed Western Diversion Bank Stability Index for a range of ARI events, compared with values for the existing channel in the reach to be diverted 51

Figure 4.5: Calculated reach median values of a range of active layer and general scour predictions for the proposed Eastern Diversion. 52

Figure 4.6: Calculated reach median values of a range of active layer and general scour predictions for the proposed Western Diversion. 53

Figure 4.7: Predicted number of pools with potential for velocity reversal [relationship of Caamaño et al. (2009)] and number of pools showing velocity reversal in 1-D model for the proposed Eastern and Western Diversion channels. 54

List of Tables

Table 2:1: Magnitude of floods for a range of ARI for the gauge downstream of Bowmans Creek Bridge. 8

Table 2:2: Predicted magnitudes for reported ARIs as a proportion of the magnitude of the 100 year ARI flood 12

Table 2:3: Magnitude of floods for a range of ARI for Hunter River at Singleton gauge. 15

Table 2:3: Average dimensions of reach of existing channel associated with the proposed Eastern diversion 29

Table 2:4: Average dimensions of reach of existing channel associated with the proposed Western diversion 30

Table 2:5: Locations of bed sediment sampling points, and median and standard deviation of particle size 32

1 INTRODUCTION

1.1 Context of this Report

Bowmans Creek, (officially known as Foy Brook at the flow gauging stations), rises in the foothills of the Mount Royal Range about 50 km north-west of Singleton. The creek generally flows in a southerly direction until it joins the Hunter River. At its junction with the Hunter River, Bowmans Creek has a total catchment area of 265 km^2, of which 254 km^2 are located upstream of the New England Highway. The reach of relevance to this report comprises the lower 6 km of the creek between the New England Highway and the Hunter River.

This report is a contribution to the Environmental Assessment of Application number DA 309-11-2001 MOD 6, the proposal that includes: two short re-alignments and associated rehabilitation of Bowmans Creek over sections of the western portion of the ACP (Ashton Coal Project) underground mine to optimise minable reserves over four seams and maintain the economic viability of the operation; and updating some of the existing conditions of consent.

The focus of this report is on assessment of flood hydrology and fluvial geomorphology. The assessment of flood hydrology is included with the assessment of fluvial geomorphology because the important geomorphic processes are active during storm events, so geomorphic assessment relies critically on proper characterisation of flood hydrology. Flood hydraulics (which describes the distribution of water level, velocity and bed shear stress) are also relevant to geomorphic processes, and this report utilises results of hydraulic modelling undertaken by Hyder Consulting and Evans and Peck (detailed elsewhere in this Environmental Assessment).

1.2 Director General's Requirements Relevant to the Geomorphological Assessment of the Proposal

The Director General's Requirements with respect to Section 75F of the Environmental Planning and Assessment Act 1979 specifically mentions fluvial geomorphology as a component of the "Soil and Water" Key Issue as follows:

"- *plans for the proposed realignments of Bowmans Creek including:…*

- *A detailed assessment of the environmental, hydrogeological, hydrological and geomorphic considerations of the final alignment; and….*"

The following General Requirements are also relevant to the geomorphological assessment:

"*The Environmental Assessment of the proposal must include:…*

- *a detailed assessment of the key issues specified below, and any other significant issues identified in this risk assessment, which includes:*
  - *a description of the existing environment, using sufficient baseline data;*
  - *an assessment of the potential impacts of all stages of the proposal on this environment, including any cumulative impacts, taking into consideration any relevant laws, policies, guidelines and plans; and*
  - *a description of the measures that would be implemented to avoid, minimise, and if necessary offset the potential impacts of the proposal;*
  - *a statement of commitments, outlining the proposed environmental management and monitoring measures;…*"

1.3 Relevant Laws, Policies, Guidelines or Plans

The law, policy, guideline or plan most relevant to this assessment is DIPNR (2005) *Stream/Aquifer Guidelines - Management of stream/aquifer systems in coal mining developments, Hunter Region* (the *Guidelines*). These Guidelines were written taking into account the statutory regime established by the *Water Act 1912* (WA), and the *River and Foreshores Improvement Act 1948* (RFIA). The Water Management Act 2000 (WMA) was passed by Parliament in December 2000 and will eventually replace both the WA, and the RFIA. DIPNR (2005) noted that the *Guidelines* will be amended at a later date to take into account the WMA (an amended version was not available at the time of preparation of this report, so the *Guidelines* were assumed to remain relevant). The relevant outcome for the *Guidelines* is:

> *"Maintenance of stable stream systems, including stream channels, floodplains and alluvial groundwater aquifers in the vicinity of mining developments."*

According to the *Guidelines*:

> "*The general outcome for any mining development should be a transparent and accountable process to:*
>
> - *identify where likely adverse impacts on stream systems may be anticipated*
> - *develop management programs to maintain streams to agreed geomorphological and ecosystem outcomes*
> - *monitor and identify changes within the stream system due to mining impacts*
> - *develop agreed remediation outcomes and timeframes to achieve stability, flow maintenance and ecosystem resilience*"

The specific objective for the *Guidelines* most relevant to this geomorphological assessment is:

> "*1. The protection of riverine integrity, which involves retention of environmental and use values, maintenance of the river system within its geomorphic boundaries and of its geomorphic character, and protection of dependent ecosystem values*."

In describing Schedule 2 streams (Bowmans Creek is a Schedule 2 stream), the *Guidelines* noted:

> "*Schedule 2 streams in the Hunter Region exhibit complex forms, often with abandoned meander channels, perched groundwater tables, channel avulsion patterns and interactions with the surrounding vegetative, geological and flood boundary controls. They require a high level of understanding of the hydrologic regime and ecosystems in engineering design and management to provide flexible stability (dynamic equilibrium).*"

The *Guidelines* list information requirements for the Environmental Impact Assessment process in relation to development of a mine. The current proposal is for construction of two creek diversions, so not all of the listed information requirements are relevant. These information requirements were applicable to the original conditions of the ACP Development Consent (Ref DA No. 309-11-2001-i). Geomorphological surveys were undertaken by ERM (2006) and Maunsell Australia (2008) to address these requirements.

Though not a formal guideline, Hancock (2001) put forward a view of the then Department of Land and Water Conservation (now NSW Office of Water) regarding remediation of streams in mining-affected areas. Although the Bowmans Creek diversion proposal is not a remediation, the recommendations of Hancock (2001) could apply equally to construction of diversion channels [Hancock (2001) cited two cases of diversions, Bayswater Creek and Goulburn River, as examples of unacceptable remediation efforts]. According to Hancock (2001, p. 22):

> "*Acceptable remedial works can include hard engineering structures only if those structures have a defined lifespan and someone accepts responsibility to replace those structures with longer term systems*"

Also (Hancock, 2001, p. 22):

> "*Remedial works, to maintain a long term stability must have the following design elements within them:*
>
> - *Maintenance of the degrees of freedom of the stream – that is the ability of the stream to migrate in its channel boundaries, to incise to a stable bedrock/armoured gravel/vegetation control which will not transmit upstream*
> - *Provision of flow variability along the stream channel (pool/riffle sequences)*
> - *Provision of meanders as part of the degrees of freedom of the stream*
> - *Use of indigenous vegetation to form controls on the system – schedules 1 and 2 streams*
> - *Mixed bed controls (woody debris or competent rock at spacing) on larger defined streams*
> - *Use of vegetation to form the bank controls, and ecosystem structure*
> - *Provide as much diversity in channel design and vegetation system as the site allows!*"

This report has been prepared in accordance with the Director General's Requirements, the *Guidelines* of DIPNR (2005), and also takes into account the recommendations of Hancock (2001).

The *Guidelines* of DIPNR (2005) and recommendations of Hancock (2001) mention variability, stability, ecosystem resilience and dynamic equilibrium, so it is important to first define what is meant by these concepts.

1.4 Definition of Channel Stability and Morphological Resilience

The discipline of fluvial geomorphology is the scientific study of river landforms and the processes that shape them. The processes are concerned with the movement and deposition of sediment by flowing water to form characteristic morphological features that may be of significance as habitat for certain aquatic biota. The study of geomorphology is usually undertaken within a time-perspective, because current forms are often at least partly inherited from processes acting at previous times.

Rivers are naturally dynamic, so temporal variability in geomorphological forms is to be expected, and the dynamic nature of river geomorphology could be critically important for maintenance of stream health (Florsheim et al., 2008). Temporal environmental variability and disturbances that force communities away from a static or near-equilibrium condition create gaps for colonization by new organisms (Karr and Freemark, 1985; Levin and Paine, 1974). Numerous studies provide evidence of the importance of hydrological disturbance and related cyclic geomorphic perturbation in regulating stream community structure (Ward and Stanford, 1983; Resh et al., 1988; Townsend, 1989; Lake, 1995; Poff and Allan, 1995; Poff, 1997; Poff and Ward, 1989; Lake, 2000; Montgomery, 2002; Benda et al., 2004; Lisle, 2005; Poff et al., 2006).

There is a general belief among river ecologists that high physical heterogeneity (high diversity of morphology) delivers great diversity of habitats (Kemp et al., 1999), and maintenance of this heterogeneity requires a degree of ongoing disturbance. Riverine biota and ecosystems have evolved in the context of natural channel instabilities, so that in many cases the processes associated with the instability (e.g. channel scour), or the landforms produced by instability (e.g. bare sand and gravel bars and undercut banks), are required for ecosystem maintenance or the survival of particular species (Petts and Calow, 1996; Shields et al., 2000). For example, Petts et al. (1992) found that lack of geomorphic instability (in regulated rivers in this case) led to succession of vegetation units to mature stages with the loss of pioneer and early successional units.

An alluvial channel that is stable in the geomorphic sense is not static, but in a condition of dynamic stability. Dynamic stability covers the range of adjustments of the system that lie within the natural range of variability over the time period being considered (in this report, the management time scale of ~50 – 100 years). Channels change position shape and other morphological characteristics in response to variations in the main controlling factors: discharge, sediment supply and size, and boundary conditions (relative resistance of the channel to change as imparted by vegetation, bank material characteristics, and wood in the channel; and base-level). Base-level refers to the downstream control on the bed level of the stream, which in the case of Bowmans Creek in the vicinity of Camberwell is the bed level of the Hunter River.

Sear (1996) illustrated the concept of dynamic stability (**Figure 1.1**). Under conditions of no major perturbations in the controlling factors, the morphology will undergo minor adjustments of scour and fill of the bed, and areas of bank erosion and deposition. A perturbation, as might be caused by a major flood of 1 in 50 -100 year ARI magnitude, could lead to major changes to channel morphology in the form of realignment, or significant scour or deposition due to the natural resistance of the channel being overcome (i.e. vegetation being stripped from the surface). Resilience is the ability of a system to withstand major disturbances without significant change (Holling, 1973). A resilient channel will return to its previous state of dynamic equilibrium, while a non-resilient channel will shift to a new morphological state (**Figure 1.1**). Over the long time scale of ~1000 years, such threshold changes can be expected (**Figure 1.1**). Brierley and Fryirs (2009) referred to this concept using the terms "*river behaviour*" (geomorphic adjustments in response to flow events of differing magnitude, duration, and recurrence, whereby the distribution of erosional and depositional processes may be altered but the river retains the same morphological state) and "*river change*" (when a reach experiences a wholesale shift in form-process relationships, whether induced by natural or human disturbance, such that the river adopts a different morphology and behavioural regime).

In order for ecosystem resilience to be defined, the ecosystem must be in a stable state prior to the perturbation. Resilience cannot be defined for an ecosystem if this condition is not met (Holling, 1973). It is argued here (see later) that the creek is not in a dynamically stable state, but on a trajectory of recovery from incision. A fundamental principle adopted for the design of the proposed diversions was that that the diversions should be on the same geomorphic trajectory as the existing creek, which means that they were designed to be deformable so that they could evolve in harmony with the rest of Bowmans Creek.

1.5 Objectives of this Report

This report has four main sections structured around objectives that correspond to the relevant Director General's Requirements:

1. To provide a detailed description of the historical and existing environment of the lower 6 km of Bowmans Creek with respect to its flood hydrology, its hydrological interaction with the Hunter River, and its fluvial geomorphological processes and forms.
2. To use the characterisation of the existing geomorphological state of the creek as the rational basis of the geomorphological design elements of the proposal.
3. To make an assessment of the potential impacts of the proposal on the geomorphological processes and forms of the system, including any potential cumulative impacts.
4. To provide a description of the measures that would be implemented to avoid, minimise, mitigate, rehabilitate/remediate, monitor and/or offset the potential impacts of the proposed modification

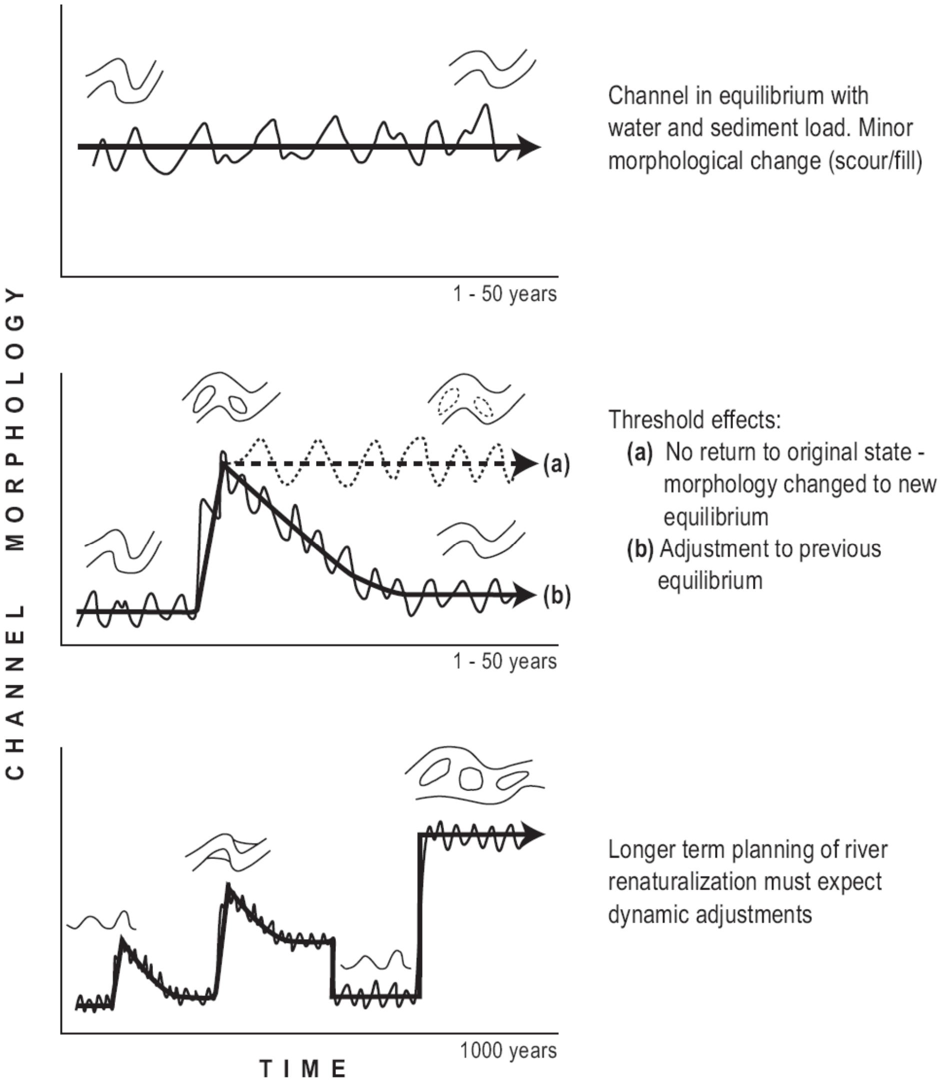


Figure 1.1:
Geomorphic dynamic equilibrium concept. Source: Sear (1996).

2 HISTORICAL AND EXISTING ENVIRONMENT

2.1 Flood Hydrology of Bowmans Creek

2.1.1 Data availability

Men daily discharge, peak daily discharge and stage height data to 2005 were obtained from PINEENA V9 (DNR, 2006) and flow data post-2005 were supplied on request by the Office of Water. A gauging station comprising a concrete weir and telemetered water level recorder is located approximately mid-way between the New England Highway and the Hunter River. This gauging station, known as Foy Brook Downstream of Bowmans Creek Bridge (Station 210130), has been operated since 1993 by the Office of Water and its predecessors. An upstream gauge at Ravensworth (210042), which has a catchment area of 170 km^2, operated from 1956 to 1999. As shown in **Figure 2.1**, the Ravensworth gauge had a relatively high proportion of years with complete records while the record from the gauge at downstream of Bowmans Creek Bridge

(210130) had a high proportion of missing values. Analysis of peak daily discharge records for the period of coincident records shows that the daily peak discharge at Ravensworth was closely correlated with the daily peak discharge at downstream Bowmans Creek Bridge (see **Figure 2.2**), which allowed the shorter and incomplete record at downstream Bowmans Creek Bridge to be extended.

2.1.2 Flood frequency analysis

The length of record for gauge at downstream Bowmans Creek Bridge is too short for reliable estimates of flood frequency. The record at Ravensworth is long enough to estimate the 100 year event or less frequent with an error of less than 25 percent (Gordon et al., 2004, p. 205).

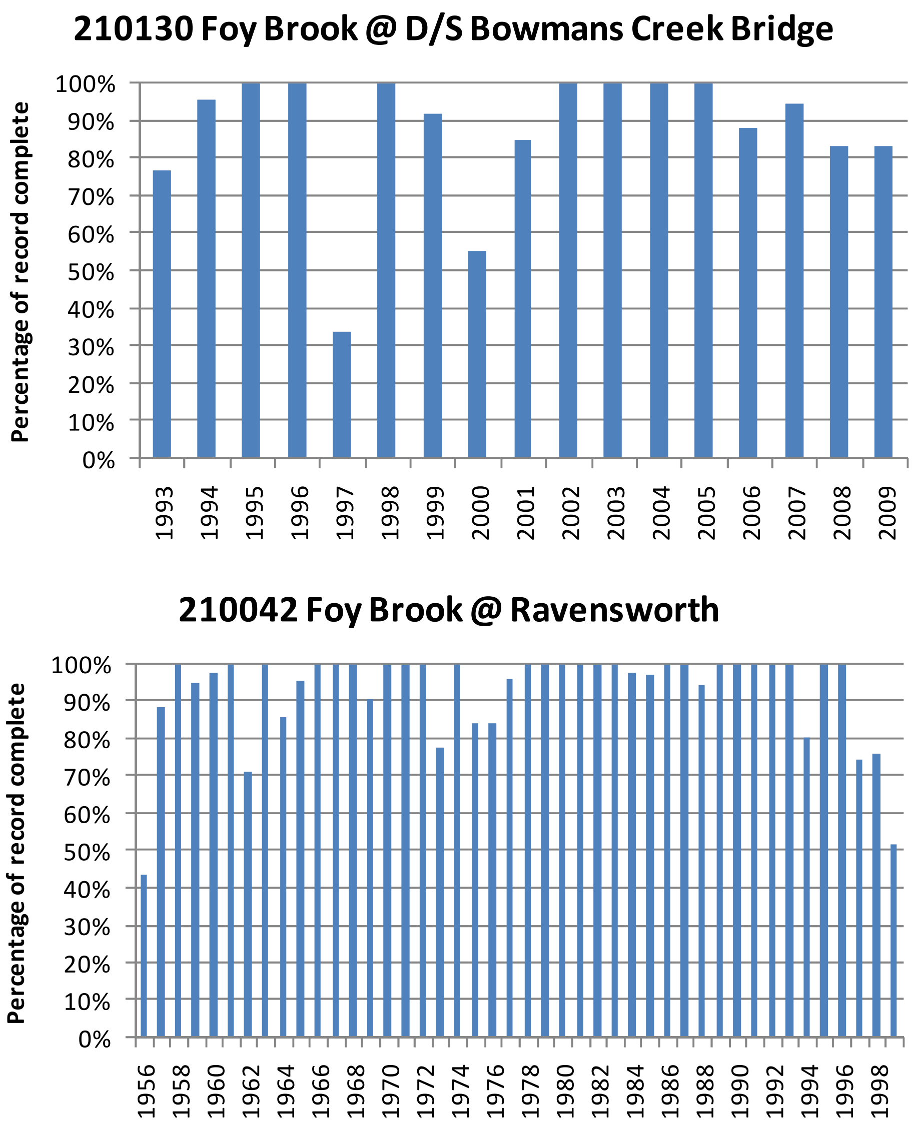


Figure 2.1:
Data availability for the two gauges on Bowmans Creek

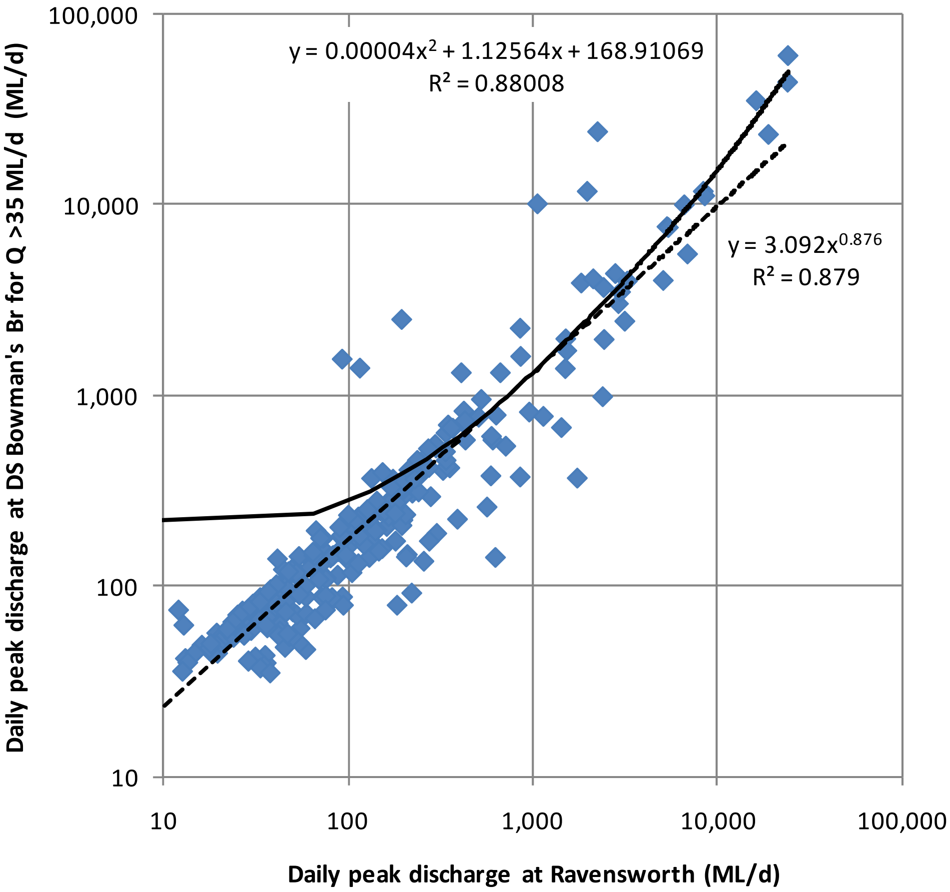


Figure 2.2:
Relationship between peak flows at the two gauges on Bowmans Creek
(Polynomial relationship used for Q> 775 ML/d (9 m^3/s) and power function for Q< 775 ML/d (9 m^3/s)

Two methods were used to generate flood frequency estimates for the site at D/S Bowmans Creek Bridge on the basis of the record from Ravensworth. The first method was to factor the flood frequency curve established for Ravensworth using the relationships in **Figure 2.2**. The second method was to first factor the flow data from Ravensworth, and combine this series (1957 to 1998) with that from downstream Bowmans Creek Bridge (1994 to 2008). Where the two series overlapped (1994 to 1998), the downstream Bowmans Creek Bridge data were used, unless data were missing, in which case Ravensworth data were used. A flood frequency curve was then established for this extended time series (1957 to 2008).

The partial duration curve was used for ARI <10 years, and the annual series for ARI >10 years (as suggested by Australian Rainfall and Runoff) (Gordon et al., 2004, p. 215; Kuczera and Franks, 2006). The partial duration curves were fitted using polynomials on log transformed data. The partial duration series curves fitted well to the range of data covering ARI <10 years (R^2 > 0.95).

The selection of distribution has a major impact on the resulting ARI estimates. Log Pearson 3-parameter (LPIII) is often used as a standard in Australia, although it is not always the best fit. Generalised Extreme Value (GEV) and Generalised Pareto (GPO) are good alternatives (Kuczera and Franks, 2006). In a comparison of goodness of fit (Kolmogorov Smirnov, Anderson-Darling and Chi-Squared tests) to the Bowmans Creek data, the GPO and GEV distributions were ranked in the top three of 41 distributions.

The Bowman's Creek gauged data are characterised by a distribution that has most values grouped within a relatively low band of peak discharge, and two years with peak discharge values twice as high as the rest. This means that no distribution is a particularly good fit to all of the data. Curves established for the Ravensworth gauge were a better fit to the gauged data. However, it is still the case that the distribution is characterised by two particularly high values. The largest Hunter River flood on record was 1955, and this flood is not included in the Bowmans Creek record.

The preferred flood frequency series was the extended downstream Bowmans Creek Bridge series (1956 – 2009) (**Table 2:1**).

Table 2:1: Magnitude of floods for a range of ARI for the gauge downstream of Bowmans Creek Bridge.
(Based on extended D/S Bowmans Creek Bridge series (1957 – 2008)

Flood (ARI)	Q (m^3/s)
0.25	9.8
0.33	13.1
0.5	24.8
1.0	62.2
1.25	75.4
2	98.8
5	152.5
10	218.8
20	323.5
30	400.0
50	516.6
75	628.8
100	720.9

2.1.3 Previous flood frequency analyses

There are three main methods of estimating flood peak frequency: (i) flood frequency analysis, (ii) runoff-routing model using design rainfall, and (iii) Probabilistic Rational Method (PRM). Flood frequency analysis refers to procedures that use gauged flood data to select and fit a probability model of flood peaks at the site of the gauge. Runoff-routing models develop a flood hydrograph from either an actual event (recorded rainfall time series) or design storm utilizing Intensity-Frequency-Duration data together with dimensionless storm temporal patterns as well as standard data from Australian Rainfall & Runoff (Institution of Engineers Australia, 1987). If the site of interest is located near a gauging station, flood frequency analysis is the preferred method, provided the data series is long enough (predictions should not extend beyond the length of the series) and does not have significant missing data that cannot be filled. Runoff-routing models and the PRM are used where gauged data are inadequate and for ungauged sites.

ERM (2006) used flood frequency analysis to estimate that the 2 yr ARI event was approximately 7 m^3/s and the 10 yr ARI event was approximately 38 m^3/s. It was estimated that a flow of 120 m^3/s would overflow from the banks of Bowmans Creek (where this overflow would occur was not stated). These flood frequency estimates are unrealistic, as they were based on mean daily discharge, not daily peak instantaneous discharge, and were derived using a short record with significant un-filled gaps.

In developing the RAFTS (runoff-routing) model, Paterson Britton & Partners (2001, p. 12) noted that:

> "*Continuous rainfall data for specific storms is required for the calibration and verification of hydrologic computer models. This data is usually obtained from pluviometers located within the catchment being modelled. Pluviometers generate pluviographs which are plots of the instantaneous variation in rainfall with time.*
>
> *Unfortunately, there are no pluviometers within the Bowmans Creek catchment. Nor are there any close enough to the catchment to provide a reliable representation of catchment rainfall during storms that have caused major flooding*."

Paterson Britton & Partners (2001, p. 13) tabulated the major floods recorded at Ravensworth gauge, and also noted the highest flow recorded at D/S Bowmans Creek Bridge. Three of the six events for Ravensworth gauge indicate a date for the flood peak that is one day later than the date given in PINEENA (DNR, 2006). Referring to the flows at the D/S Bowmans Creek Bridge, it is noted that "*the only flow of note being that recorded in August 1998 when a peak discharge of 350 m^3/s was recorded*." The peak instantaneous discharge given in PINEENA for the storm that peaked on 08/08/1998 is 703 m^3/s (**Figure 2.3**), so Paterson Britton & Partners (2001) assumed a value that was half that of the recorded peak discharge.

The rainfall loss is an important parameter in the RAFTS model. Paterson Britton & Partners (2001, p. 14) noted that "*no definitive loss rate data is available for the Bowmans Creek catchment*", so they used an estimated value.

Due to the lack of rainfall data, "pseudo-calibration" of the RAFTS model was undertaken using runoff data from Ravensworth. It was noted by Paterson Britton & Partners (2001, p. 15) that:

> "*Although there is no evidence of a major flood occurring in the catchment over the period of record (i.e. a 100 year recurrence flood), the 1990 flood has been identified as a moderate flood and stream flow records for this event can be compared against model outputs for design storms*."

It was later (also p. 15) stated that:

> "*The comparison indicates that the 1990 flood was of the order of a 5 year recurrence flood. This is in keeping with anecdotal reports of the frequency of the 1990 flood elsewhere in the Upper Hunter, and confirms that results from the hydrologic modelling are consistent with expected peak discharges.*"

The assumption that the 3-4/02/1990 flood in Bowmans Creek was in the order of a 1 in 5 year event needs to be questioned. On the Hunter River this event was a 1 in 2.6 year event at Liddell, 1 in 2.4 year event at Singleton gauge, 1 in 6.2 year event at Greta and 1 in 5.9 year event at Wollombi Brook at Warkworth, which suggests that in the main stem of the Hunter, and in Wollombi Brook, the February 1990 event was of a moderate size. However, it cannot be assumed that the relative magnitudes of all flood events are consistent across the Upper Hunter. For example, the largest event in the Hunter River in 1990 occurred not in the first week of February, but in the third week of April and was a 1 in 8.3 year event at Liddell, 1 in 3.7 year event at Singleton gauge and 1 in 11.8 year event at Greta. In Bowmans Creek, this flood was only a 0.5 year event. Many other examples of poor correlation between flood peak magnitudes in Bowmans Creek and other Upper Hunter River gauges can be cited. For example, in the first week of March 1977, there was a large flood event in the Hunter River at Singleton gauge where it was a 1 in 30 year event. At Liddell it was only a 1 in 3.8 year event, and on Wollombi Brook at Warkworth it was a 1 in 9.9 year event. In Bowmans Creek this event was relatively small, being only a 1 in 2.1 year event. There are other years where Bowmans Creek had a significantly higher annual flood compared to other gauges.

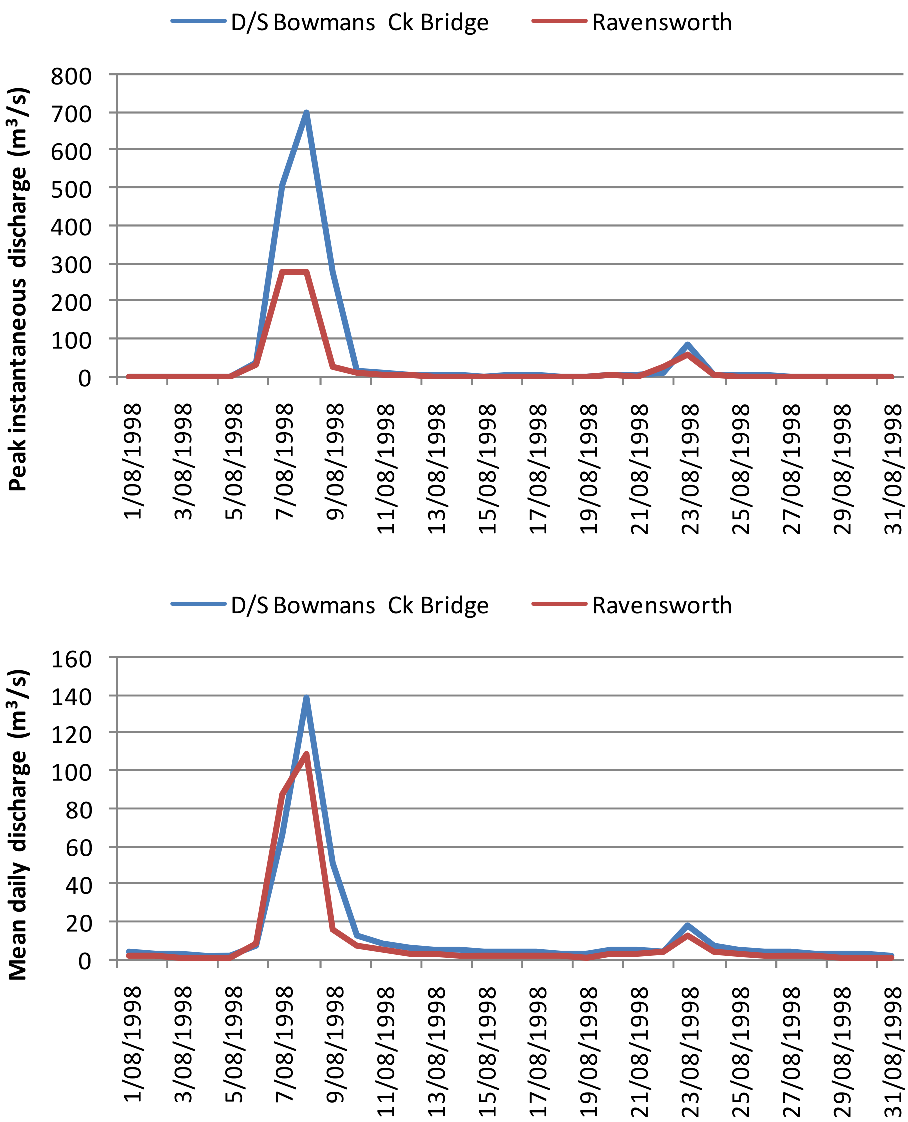


Figure 2.3: Gauged flows at the two gauges on Bowmans Creek for the month of August 1998.

If the 1990 event recorded at Ravensworth gauge was a 5 year ARI event, as claimed by Patterson Britton & Partners (2001), then over the 42 year period of record there should have been ~7 events with a higher discharge. In fact there were none (the 1990 event was the largest flood in 42 years). Using the RAFTS model, Patterson Britton & Partners (2001) estimated that the 1 year ARI event at Ravensworth was ~110 m /s (from their Figure 6). If this was the case, it would be expected that events of this size or larger would occur in most years of record. In fact, this flow was exceeded in only 6 years out of the 42 years on record. This apparent lack of flood peaks in the record cannot be explained by missing data (**Figure 2.1**), as only one significant flood peak that appears in the records for other upper Hunter gauges is missing from the Ravensworth gauge (14/05/1962, which was ~5 year ARI event elsewhere).

It is worth noting that the flood frequency analysis for the extended Bowmans Creek at D/S Bowmans Creek Bridge series (**Table 2:1**) predicted that the June 2007 event was a 34 year ARI event; in the Hunter River at Singleton this was a 50 year ARI event; in Wollombi Brook at Warkworth this was a 25 year ARI event. Although the recurrence interval of this event varied from site to site in the Hunter Valley, it was clearly a large regional event. At the gauge at D/S Bowmans Creek Bridge the peak discharge recorded in June 2007 was 424 m^3/s, which is lower than the peak recorded in August 1998 (**Figure 2.3**). Yet the August 1998 flood in Bowmans Creek at Ravensworth was lower in magnitude than the 1990 event to which Patterson Britton & Partners (2001) assigned a 5 year ARI. By this reckoning, the 2007 event would have had a recurrence interval <5 years in Bowmans Creek, which is unlikely.

To summarise, the relative size of the 1990 event in Bowmans Creek cannot be inferred by the relative size of the same event in other Upper Hunter streams. It is not clear how much influence this assumption might have had on the way Paterson Britton & Partners (2001) set up their RAFTS model. The main argument against their results is that flows recorded in the creek do not match the frequency predicted by the RAFTS model.

The Probabilistic Rational Method (PRM) is known to have error (see Institution of Engineers Australia 1987). A study by Rijal and Rahman (2005) of a selection of catchments from SE Australia found that the 75th percentile values of the relative errors in design flood estimates for the average recurrence intervals of 2, 5, 10, 20, 50 and 100 years ranged from 61% to 80% for the Probabilistic Rational Method. These errors were relative to the estimates made using standard flood frequency analysis performed on gauged data (as undertaken here for Bowmans Creek). In the study of Rijal and Rahman (2005) the gauges had record lengths ranging from 24 to 59 years, and the catchments ranged in size from 3 to 950 km^2.

Rijal and Rahman (2005) also found that there is a chance of about 10% that the error in design flood estimates will exceed 100% with the Probabilistic Rational Method. They warned that "*the users of these techniques should be aware of this large error and provision should be made accordingly*".

One of the problems with the Probabilistic Rational Method is that the preparation and use of the contour maps of dimensionless runoff coefficient values in the Australian Rainfall & Runoff (Institution of Engineers Australia, 1987) assumes a smooth variation of these coefficient values over geographical space. A study by Rahman and Hollerbach (2003) on 104 small to medium-sized catchments in southeast Australia showed that the dimensionless runoff coefficient values exhibit little spatial coherence and many nearby catchments showed quite different dimensionless runoff coefficient values.

The predicted magnitudes for the reported ARIs were calculated as a proportion of the magnitude of the 100 year ARI (**Table 2:2**). These show consistent percentages for the flood frequency analysis method, for three gauges of very different catchment areas, and different lengths of record (Singleton – 95 years, Wollombi –100 years, Bowmans Ck – 52 years). The RAFTS model and the PRM give similar proportions but the proportions were much higher than the values calculated using real flow data.

To conclude, there are serious doubts about the reliability of the predictions of magnitudes of floods of given ARIs based on RAFTS model output and the Probabilistic Rational Method. Events of the size indicated by these methods do not appear with the expected frequency in the gauged record. While the February 1990 event was a moderate event in the Hunter River, flood frequency analysis suggests that in Bowmans Creek it was a ~75 year ARI event.

Table 2:2: Predicted magnitudes for reported ARIs as a proportion of the magnitude of the 100 year ARI flood

ARI (Years)	Flood Frequency Analysis			RAFTS	Probabilistic Rational
	Hunter River (Singleton)	Wollombi Brook (Warkworth)	Bowmans Ck (D/S Bowmans Ck Br)	Bowmans Ck (D/S Bowmans Ck Br)	Bowmans Ck (D/S Bowmans Ck Br)
0.25	1%	0.2%	1%		
0.33	2%	0.3%	1%		
0.5	3%	1%	3%		
1	6%	3%	7%	14%	16%
1.25	8%	4%	8%		
2	12%	7%	10%		24%
5	22%	21%	16%	40%	37%
10	30%	34%	27%		47%
20	45%	44%	43%	65%	63%
30	56%	64%	54%		
50	72%	79%	71%		81%
75	88%	91%	87%		
100	100%	100%	100%	100%	100%

2.1.4 Frequency and durations of overflows for 5 year ARI events

The diversion channels are to be designed to ultimately allow events greater in magnitude than the 1 in 5 year ARI (152 m^3/s, from **Table 2:1**) to overflow into the existing Bowmans Creek channel (this will be staged, such that initially smaller events will overflow into the existing creek). A peak daily discharge series was generated for downstream Bowmans Creek Bridge by extending the gauged record using the regression established for data from Foy Brook at Ravensworth gauge. A regression with data from Wollombi Brook at Warkworth gauge was used to infill a small number of missing values. The low flow data were filtered out.

A spells analysis was undertaken to determine the frequency and duration of events that would overflow into the existing Bowmans Creek. Over the 54 year long modelled period, there were 15 spells that would likely have created overflow from the diversion into the existing channel (**Figure 2.4**). Most of these events would have been large enough and of sufficiently long duration to fill the void of the existing channel (after allowing for predicted subsidence). The data shows that the series is represented by relatively long periods between events (7 - 8 years) interspersed with several events in close succession.

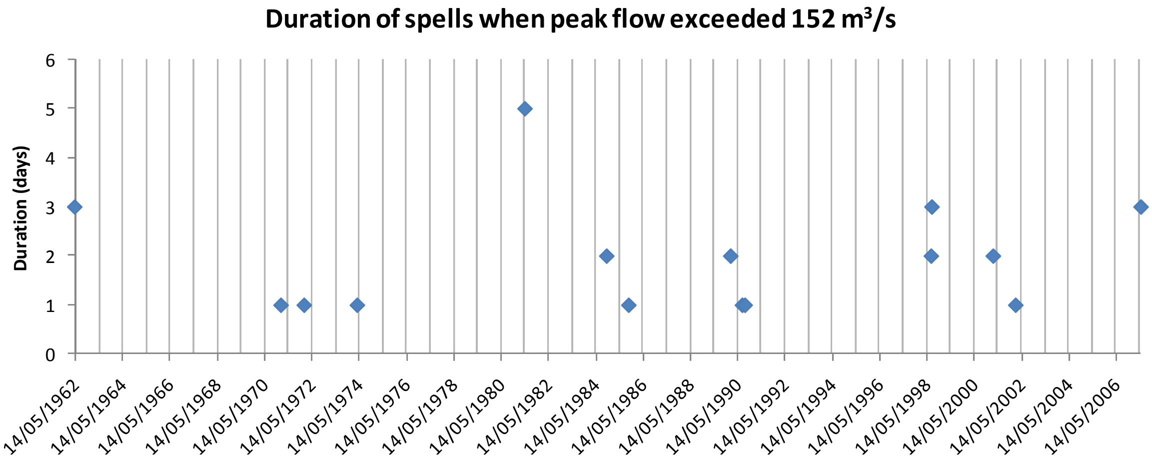


Figure 2.4: Duration of spells exceeding the 5 Year ARI event, when the diversion would overflow into the existing Bowmans Creek.

2.1.5 Relative influence of the Hunter River water levels on flooding of Bowmans Creek

The lower 6 km of Bowmans Creek is known to be within the range of influence of the Hunter River. Although Patterson Britton & Partners (2001) partially characterised this influence, the main problem is that the levels in the Hunter River near Bowmans Creek are not known to Australian Height Datum (AHD). The two Hunter River gauges (one just upstream of Bowmans Creek, 210126 Hunter River @ U/S Foy Brook and one just downstream, 210127 Hunter River @ U/S Glennies Creek) in the vicinity are not tied to AHD, and their record is relatively short (from 1993).

The two Hunter river gauges closest to Bowmans Creek having stage data tied to AHD are 210083 Liddell (25 km upstream) and 210001 Singleton (38 km downstream). An analysis of the river gradient between these gauges indicated a relatively narrow range of river gradient (**Figure 2.5**). Of course, local morphology and hydraulics means that the water surface is not likely to be even along this 62.3 km of river, but as a first approximation, the slope of the river surface can be used to predict water surface elevation at Bowmans Creek junction, for the length of common record at Liddell and Singleton. The full (longer) Singleton record can be used by using a single (mean) value of river gradient for days when Liddell data are not available.

Patterson Britton & Partners (2001, p. 10) noted that the 1955, 1893, 1913, and 1971 floods were "*considered to be of 20 year recurrence or rarer, at Singleton*…[and that]…*In the upper Hunter, the 1955 flood is often regarded as being of similar magnitude to the design 100 year recurrence flood*", although no reference was cited for these assumptions. Certainly, further downstream at Maitland, the 1955 flood is considered to be rarer than the 100 year ARI event. Utilising two previous flood studies [New South Wales, Dept. of Public Works (1990) and Webb, McKeown & Associates Pty Ltd (1998)], Parsons Brinkerhoff Pty Ltd (2003, p. 22) noted the following:

> "*The 1998 Supplementary Flood Study did not determine the probable maximum flood (PMF) discharge along the Hunter River. Rather, an 'extreme flood', approximating the PMF, was allowed for. The extreme flood discharge was 24,000 m^3/s, compared with 10,300 m^3/s for the 1955 flood and 8,000 m^3/s for the modelled 1% AEP event.*" [Note: The 1% AEP event is equivalent to the 1 in 100 year ARI event].

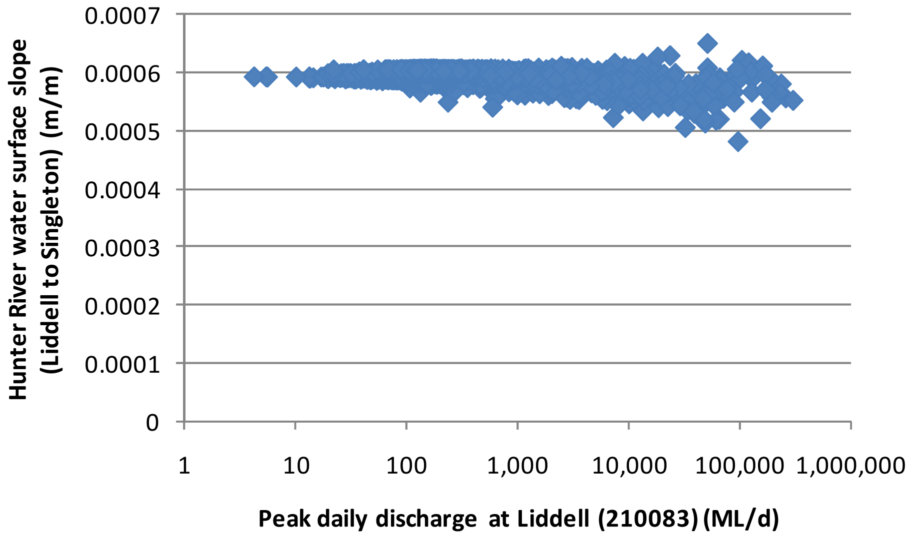


Figure 2.5:
River gradient between Liddell and Singleton. Mean gradient is 0.000594 m/m.
(Data from 1972 to 2005).

Thus, according to Parsons Brinkerhoff Pty Ltd (2003), at Maitland the 1955 flood peak was 1.29 times that of the 100 year ARI event.

Flood frequency analysis was undertaken for the Singleton gauge, which as a reasonably complete record from 1913 to the current day (**Figure 2.6**). Examination of records form gauges on the Hunter River at Liddell and Wollombi Brook at Warkworth revealed that significant flood events that would have impacted the Singleton flood distribution did not occur on any of the days with missing values. Various distributions were fitted to the Singleton data. The best fit distributions were Generalized Pareto (GP), Log-Pearson III (LPIII) and Generalized Extreme Value (GEV), and they gave similar results (**Table 2:3**). Overall, the GP was considered the best fit to the data. At Singleton, the 1955 flood peaked at 13,123 m^3/s, which is 1.66 times the estimated 100 year ARI event. The flood distribution predicts that the 1955 flood was a 166 year ARI event. Although this should be regarded as a highly uncertain estimate because it is an extrapolation, the evidence points to the 1955 flood event having an ARI greater than 100 years at Singleton in the context of the period from 1913 up to the present day.

A complete flood frequency curve was developed for Singleton gauge using a partial duration curve for ARI <10 years (polynomial on log transformed data), and the annual series for ARI >10 years (Generalized Pareto distribution). Expressing the flood frequency curve for Singleton in terms of predicted stage height at Bowmans Creek junction (based on assumed river gradient), revealed that the Hunter River is not often at an elevation that has significant impacts on the hydraulics of Bowmans Creek (**Figure 2.7** and **Figure 2.8**).

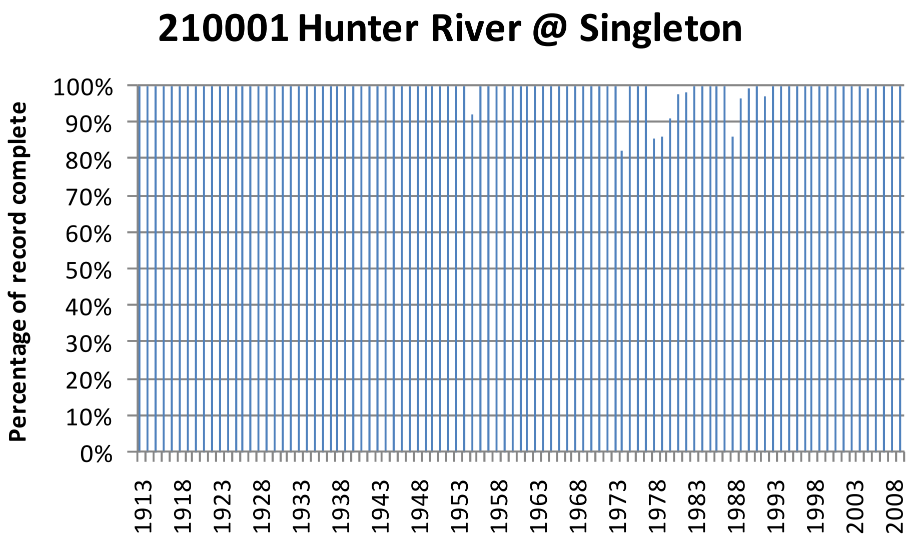


Figure 2.6:
Data availability for the Hunter River gauge at Singleton

Table 2:3: Magnitude of floods for a range of ARI for Hunter River at Singleton gauge.
(Based on data period 1914 – 2008; LPIII = Log-Pearson III; GEV = Generalized Extreme Value; GP = Generalized Pareto)

Flood (ARI)	LPIII Q (m^3/s)	GEV Q (m^3/s)	GP Q (m^3/s)
10	2,501	2,193	2,360
20	3,789	3,329	3,564
30	4,668	4,182	4,426
50	5,911	5,516	5,710
75	7,008	6,827	6,917
100	7,846	7,923	7,889

Patterson Britton & Partners (2001, p. 10) noted that "*during the 1955 flood, the Hunter River reached a peak level of 64.2 mAHD in the vicinity of the Ashton Mine site (pers. comm. DLWC, 2001)*". Patterson Britton & Partners (2001) indicated that this level was determined by interpolation of recorded peak flood levels made for the 1955 flood. Patterson Britton & Partners (2001) interpolated flood levels for the 20 and 5 year ARI events for the junction of Bowmans Creek with the Hunter River from flood frequency distributions estimated for Singleton and Denman [using flood studies by Singleton Shire Council (1984) and Sinclair Knight & Partners, 1981) – neither of these reports were sighted in the preparation of this report]. Stage height data are not available for the Denman gauge in 1955, but the mean water surface slope between Denman and Singleton (**Figure 2.5**) predicts a water level of 64.6 mAHD at Bowmans Creek junction at the peak of the flood in 1955, which is comparable with the value cited by Patterson Britton & Partners (2001, p. 10).

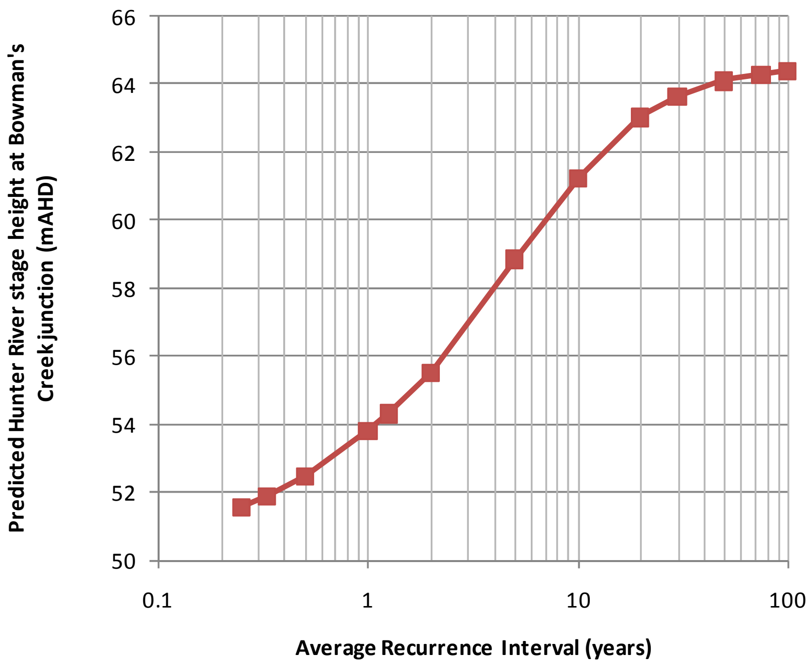


Figure 2.7:
Flood frequency curve for Singleton converted to stage height at Bowmans Creek junction
(Based on data from 1913 to 2005)

The high-level Bowman's Creek floodplain just downstream of the highway bridge is significantly inundated at about 64 - 65 mAHD, and this is a very rare event to be caused by the Hunter River alone (**Figure 2.7** and **Figure 2.8**). These data were also analysed on an event (spells) basis. This revealed that there were relatively few events on record when the area of the proposed Eastern diversion would be inundated by the Hunter River (bed of the lower end inundated 57 days in 93 years, median spell duration 2 days). The area of the proposed Western diversion channel would be influenced by the Hunter River more frequently, but for a relatively small proportion of the time (bed of the lower end inundated 342 days in 93 years, median spell duration 3 days).

Under conditions of very large Hunter River floods, Bowman's Creek will be inundated by Hunter River water. However, Bowmans Creek typically peaks one day before the Hunter River, so the Creek will still experience the hydraulic conditions imposed by high flows in Bowmans Creek itself (**Figure 2.9**).

The analysis of the interaction between floods in the Hunter River and Bowmans Creek indicated that Bowmans Creek floods most often acts independently of floods in the Hunter River, even if it is only for the first day of the flood event (after which the Hunter River backwater may affect Bowmans Creek flood hydraulics). Thus, the analysis of hydraulic-geomorphic stability of Bowmans Creek must assume conditions without a Hunter River backwater being present.

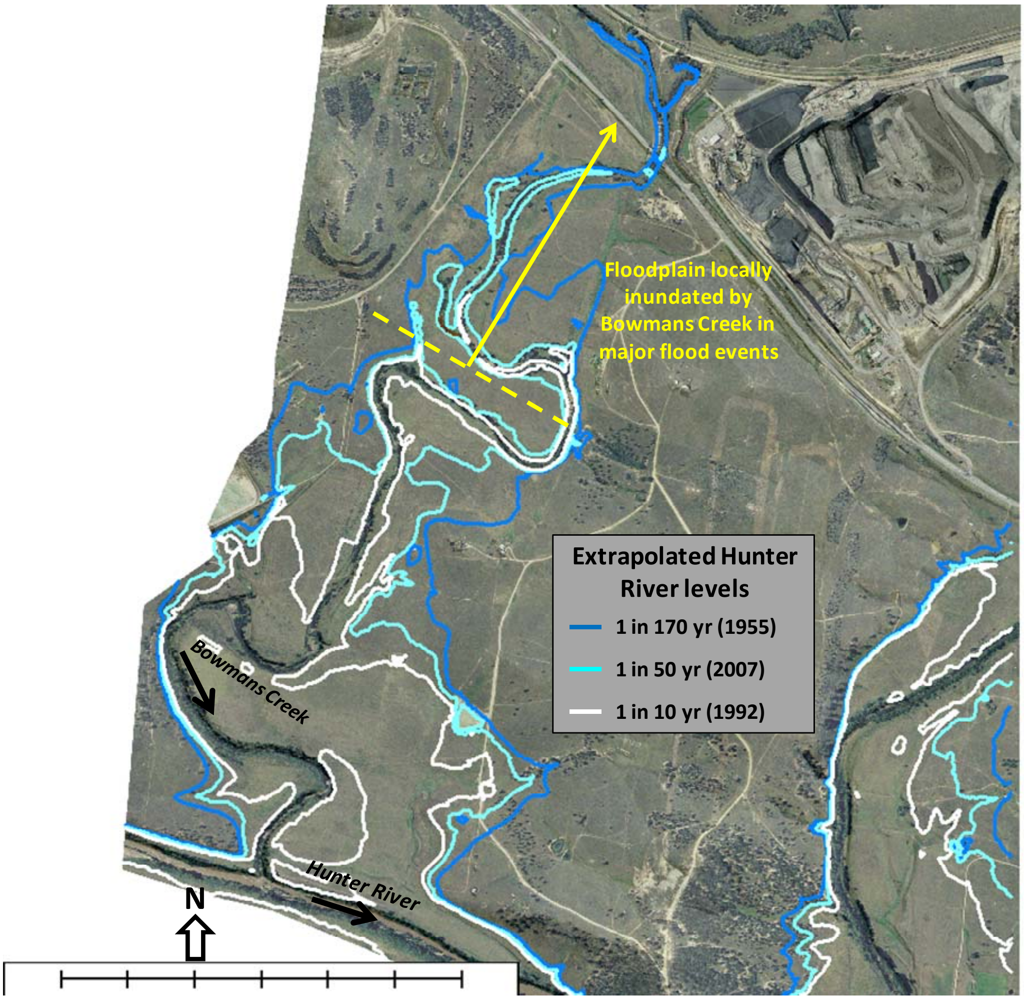
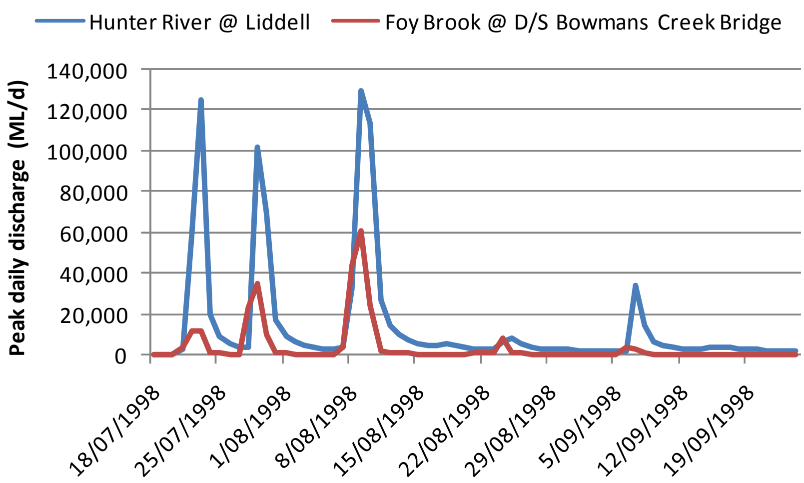


Figure 2.8:
Predicted extent of inundation of the floodplain in vicinity of Bowmans Creek, as influenced only by Hunter River water levels.
(These levels correspond to contours at the predicted Hunter River water levels for the given ARI events as given in **Figure 2.7**.)

2.2 Previous Investigations - Geomorphology

2.2.1 Geomorphic history of the Upper Hunter River and tributaries

Erskine and Bell (1982) reviewed evidence for channel change in the Upper Hunter River in historical times. They proposed that most of the change since 1949 was due to cyclical change in climate - a theme that was followed up by Erskine (1986) and Erskine and Warner (1988). Reddoch (1957) noted that between 1946 and 1955, along the 82 km section of the Hunter River between the site of Glenbawn Dam and Alcheringa (near Branxton), 250 ha of floodplain and terrace were destroyed by bank erosion. Bowmans Creek enters the Hunter River within this section.



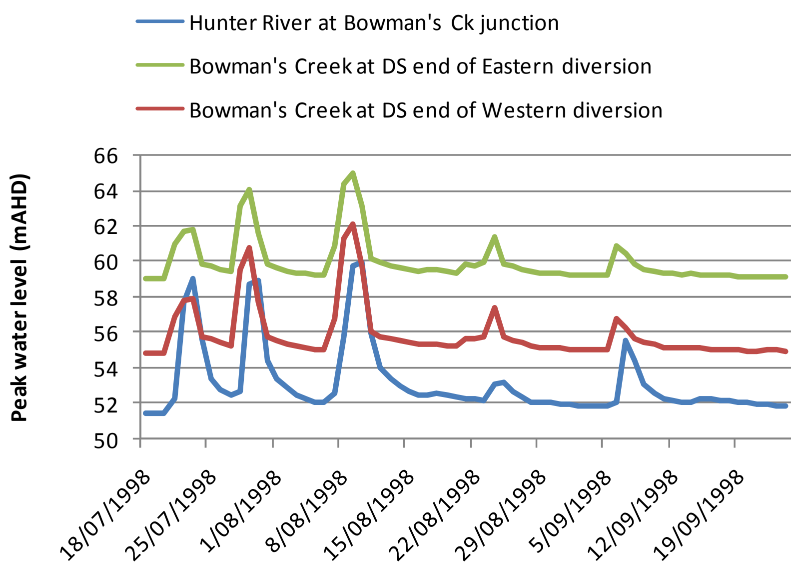


Figure 2.9:
Example Hydrographs from Hunter River and Bowmans Creek, August 2008
(Water levels estimated from available hydraulic model information. On this occasion Hunter River water did not reach the site of the proposed Eastern diversion, but at the proposed Western diversion site the level of Hunter River water exceeded that of Bowmans Creek on some days. This is equivalent to a 1 in 5 to 1 in 7 year ARI Hunter River event.)

Erskine and Bell (1982) argued that while it is often assumed that such changes are largely the result of forest clearing, grazing, agriculture, urbanisation and other human activities in the stream catchments, in the case of the Hunter River, the changes were due predominantly to changes in rainfall and their consequent effect on floods and sediment yields. Bell and Erskine (1981) recorded a high percentage increase in summer rainfall, average rainfall intensities of frequent storms, and annual runoff at Singleton after 1946. In contrast, catchment disturbances that could have altered hydrology and sediment supply (forest clearing, ringbarking, rabbit plagues and excessive grazing) occurred mainly in the previous century. An additional historical disturbance was the construction of Glenbawn Dam which has modified streamflows since 1958. However, as the catchment area of Glenbawn Dam comprises less than 8 percent of the total Hunter River catchment at Singleton, only minor effects on flood peaks due to this factor would be expected in the Singleton area.

Erskine and Bell (1982) argued that a sequence of large floods between 1949 and 1956 (11 floods were recorded at Singleton in excess of 1,000 m^3/s during this period) was effective as a landforming agent in the Upper Hunter. This was due, in large part, to the exceptionally short inter-arrival time between each event. Also, these floods marked the onset of a flood dominated regime, with no trend of recovery of channel morphology noted through the 1960s and 1970s because of the repeated occurrence of large floods (Erskine and Bell, 1982). This climatic evidence does not rule out the likelihood that human impact has increased the frequency, or risk, of floodplain erosion and channel enlargement (Prosser et al., 2001). Some systems in NSW were observed to erode within a decade of clearing of riparian vegetation, and this led Raine and Gardiner (1995) to argue that erosion experienced during the 1950s in northern NSW would not have occurred without that clearing.

Spink et al. (2007) evaluated 517 riverwork projects that were implemented in the upper Hunter catchment over the period 1952 to 2000. Projects were largely implemented after major phases of geomorphic river change. From 1952 until 1980, projects were heavily influenced by engineering techniques. One example of this approach is concrete block and cable, which can be found in Bowmans Creek. Across the catchment, from 1952 to 2000, no bed control structures were established to address channel incision. Projects attempted to address planform channel adjustments through bank stabilisation techniques. However, according to Spink et al. (2007), these planform adjustments were river responses to channel incision.

Recent Riverstyles mapping (Cook and Schneider, 2006) confirms the extent of degradation, with 100% of the Hunter regulated river rated as being in poor geomorphic condition and with 83% having only a moderate recovery potential. Poor condition was defined as containing one or more of the following characteristics:

- Abnormal or accelerated geomorphic instability (reaches are prone to accelerated and/or inappropriate patterns or rates of planform change and/or bank and bed erosion).
- Excessively high volumes of coarse bedload which blanket the bed, reducing flow diversity.
- Absent or geomorphically ineffective coverage by vegetation relative to the reference reaches (allowing most locations to have accelerated rates of erosion) or the reach is weed infested.

The above literature suggests the possibility that the Hunter River in the vicinity of Bowmans Creek incised after 1949, and has not recovered its pre-incision morphology. Incision of the Hunter River would necessarily mean incision of Bowmans Creek, due to lowering of its baselevel.

2.2.2 Description of Bowmans Creek fluvial geomorphology by Patterson Britton & Partners (2001)

Patterson Britton & Partners (2001) was engaged by White Mining Limited to investigate options for realignment of the Bowmans Creek in association with the then proposed Ashton Mine Project. The findings of these investigations were documented as Appendix N to the Environmental Impact Statement (EIS) for the then proposed Ashton Mine Project. Although this diversion was not constructed, the report contains some relevant information concerning the existing creek.

Patterson Britton & Partners (2001) noted that downstream of the New England Highway Bridge the channel of Bowmans Creek becomes deeply incised within the alluvial floodplain of the Hunter River. Twenty-three cross-sections surveyed at the time showed the low flow channel was typically 15 – 20 m wide, with an invert level up to 6 m below the adjoining floodplain. An in-channel "terrace" adjacent to the low flow channel was noted in many areas. Patterson Britton & Partners (2001, p. 5) considered that in its lower reaches the creek had an in-channel capacity of between 1 and 2 years average recurrence interval (ARI). As will be demonstrated later in this report, this is an incorrect assumption. Patterson Britton & Partners (2001) realised that the lower section of the channel (within the lowest 1,250 m at least), contained all flows within bank (as indicated by an annotation on their Figure 3).

Patterson Britton & Partners (2001) reported some limited data concerning particle size of the bed material, critical bed material size for initiation of movement, and bedload transport rates. The methodology employed to derive these values was not provided by Patterson Britton & Partners (2001). The summary in the following paragraph incorporates an adjustment of the chainages used by Patterson Britton & Partners (2001) to match those used in this study.

Patterson Britton & Partners (2001) reported median particle diameters of 50 – 70 mm immediately downstream of the highway bridge, with fining further downstream. This bed material was predicted to be mobile (presumably under 100 year ARI flow conditions). At chainage 4,200 to 3,200 m the median particle size was reported to be 100 to 150 mm (maximum diameter 200 mm). Similarly coarse cobbles are also noted to occur between chainage 2,400 and 2,800 m (their Figure 3). This material was predicted to be stable (presumably under 100 year ARI flow conditions), so the bedforms were interpreted to be relict Pleistocene riffles (i.e. large size material transported at a previous time in geological history, and exposed when the channel incised in historical times). Figure 3 of Patterson Britton & Partners (2001) indicates that contemporary transport of bed material ceases at chainage 3,800 m (XS8), after which the bed material is of relict (Pleistocene) origins, and much of it is immobile under the current regime. In the lower part of the creek, from chainage 1,470 m to 810 m the bedrock pools were reportedly swept clear of gravels. The bed load transport rates just downstream of the highway bridge were estimated to be 500 m^3 per year, reducing to 50 – 100 m^3 per year further downstream. Patterson Britton & Partners (2001) did not indicate what method they used to derive this bed load transport rate.

2.2.3 Description of Bowmans Creek fluvial geomorphology by ERM (2006)

ERM (2006) was engaged by Ashton Coal Operations Limited to undertake a pre-mining baseline assessment of Bowmans Creek prior to the commencement of underground mining and to prepare a program for ongoing monitoring of fluvial geomorphology of Bowmans Creek.

ERM (2006) used field inspection, aerial photographs and field topographic survey to map channel characteristics, including channel bars, pools, riffles, bedrock outcrop, knick points, relic [sic] sand bars, relic [sic] cobble bars, vegetation, areas of erosion, terracing, and locations where aquatic fauna were observed.

Although ERM (2006) did not indicate that any bed material size measurements were undertaken, they reported that with downstream progression, the channel bed graded from cobble lining with a gravely silty substrate, to a silty sand substrate. Channel width, depth, cross sectional area, and width-to-depth ratios were calculated from survey data. The low flow channel was typically 12 to 20 m wide and 1.0 to 1.5 m deep.

ERM (2006) noted that Pegasus Technical identified and surveyed 44 pools in a ponding survey undertaken in March 2006. The presence of pools depends on the morphology (i.e. having a series of high points and depressions in the bed) and the hydrology. These pools were identified based on the presence of water, so the survey was sensitive to the hydrological conditions on the day of the survey. In a later survey, Maunsell Australia (2008, p. 15) noted that "*There were 44 distinct pools identified in the ponding survey by Pegasus Technical in March 2006 compared to 12 pools July 2008… In 2008, surface water flows were significantly greater and observations during site inspection by Maunsell noted continuous surface water was present for the entire length and that it was difficult to differentiate between pool and riffle in terms of stream depth or width. Visually, the only indications apparent were changes in surface velocity*". While these pool data are not useful for the current study, the long profile surveys undertaken by Pegasus Technical characterised the morphology of the thalweg, which allowed characterisation of potential pool depth and length.

ERM (2006, p. 15) provided general descriptions of the pools and riffles, and also provided detailed maps of all identified geomorphic features. ERM (2006) described the features "*Relic cobble bar (grassed)*" and "*Relic sand bar (grassed)*" [Note: the word "relic" is misused here; the intended word is "relict"]. Presumably these were interpreted to be formerly mobile bedforms that were not contemporaneous with the current hydraulics of the creek. While the grass covering would afford resistance to scour, this alone would not justify referring to them as relict.

2.2.4 Description of Bowmans Creek fluvial geomorphology by Maunsell Australia (2008)

In June 2007, high flows in Bowmans Creek and backwater flooding from the Hunter River occurred across the site. In response to observations of evidence of flood erosion on Bowmans Creek made by Marine Pollution Research (2008) during an ecological survey in late June 2008, Ashton Coal considered that additional geomorphological surveys were necessary to update the baseline survey information prior to underground mining of Bowmans Creek associated with longwalls and miniwalls 5 to 9. Maunsell Australia (2008) was commissioned by Ashton Coal Limited to undertake this survey.

Despite anecdotal observations of bank collapse and instability and channel scour as a result of the 2007 floods, survey monitoring of the cross sections in 2008 did not reveal significant changes in cross section geometry for most of the survey monitoring sections, compared to 2006 (Maunsell Australia, 2008, p. 13). In this sense, the term "*significant*" was used subjectively. Comparing the surveyed cross-sections, scour of the bed was up to 0.9 m and deposition was up to 0.4 m. Cross-sections with scour outnumbered those with deposition. While bank scour and erosion was visually apparent, Maunsell Australia (2008) concluded that the 2007 event did not materially alter the channel form or pool-riffle sequence. This conclusion did not appear to be based on a statistical analysis of the data, so it is not clear if the stream showed significant net deposition or incision, widening or narrowing.

2.2.5 Summary of previous geomorphological investigations of Bowmans Creek and their relevance to the present study

The previous studies of Patterson Britton & Partners (2001), ERM (2006) and Maunsell Australia (2008) reported on some aspects of the fluvial geomorphology of Bowmans Creek, but most of the information is not directly useful for this present study. The topographic survey data collected by Pegasus Technical as part of the geomorphological investigations are useful for this present study.

Geomorphological stability and resilience is best assessed through analysis of the hydraulics in the context of the bed and bank materials and their vegetative cover. This requires hydraulic modelling of the channel, reporting shear stress and stream power, and characterisation of the particle size distribution of the bed material. Hydraulic modelling was undertaken by Patterson Britton & Partners (2001) and later by ERM (2006) using a different set of cross-section data, surveyed in 2006 by Pegasus Technical. Neither of these studies reported bed shear stress or stream power distribution [ERM (2006) reported a single value of reach average stream power at two discharges, rather than at the required pool-riffle scale].

Bed shear stress ("*tractive stress*") is a function of the hydraulic radius (~depth) and energy slope. Knowledge of bed shear stress at certain discharges, on its own, does not enable an assessment of erosion potential, as this also depends on the bed material particle size, the bank material, and the vegetative cover. While Patterson Britton & Partners (2001) reported a few values of median bed material particle diameter, these data were inadequate in detail and coverage to use in an analysis of bed material mobility based on bed shear stress. Neither ERM (2006) nor Maunsell Australia (2008) sampled bed material particle size distributions.

In order to characterise the relative stability of Bowmans Creek, an investigation using modelled bed shear stress and measured particle size was undertaken as a component of the present study.

2.3 Geomorphological setting and state of Bowmans Creek

As a relatively small tributary of the Hunter River, it would be expected that Bowmans Creek would be incised to some extent into the floodplain of the Hunter River in the vicinity of their junction. However, the literature suggests that the Hunter River could have incised in this vicinity some time after 1949, and not recovered since then. Incision of the Hunter River would mean lowering the baselevel of Bowmans Creek, which would induce upstream migrating incision of the creek. This sort of incision is significant, because it leads to much greater confinement of flows within the channel, elevating shear stress for the same discharge, which results in enhanced bed scour and bank erosion. Such channels typically go through a cycle of incision, followed by a period of channel instability whereby the bed and banks frequently adjust, tending towards widening of the incised creek corridor. As the channel widens, the shear stresses are lowered and the channel becomes more stable. It is important to establish the existing state of Bowmans Creek (whether dynamically stable or on a trajectory of change – see **Figure 1.1**), as this will be used as the benchmark against which future change will be assessed. Any observed post-mining changes in the geomorphology of the creek need to be evaluated in the context of any pre-existing trajectory of change.

The geomorphic state of the Hunter River near Bowmans Creek was examined using discharge data from the Singleton and Liddell gauges, and a Lidar-derived digital elevation model (DEM) supplied by Ashton Coal Limited. The DEM was not of sufficient resolution to characterise the morphology of the channel of Bowmans Creek in detail, and any morphological detail that was under water at the time of the Lidar flight was not characterised on the DEM.

At their junction, Bowmans Creek has incised down to the bed level of the Hunter River (**Figure 2.10**). The thalwegs of these channels are about 11 - 12 metres below the surrounding floodplain level. Bowmans Creek is incised down to the bed level of the Hunter River only near its lower end (**Figure 2.11**). The floodplain is relatively flat laterally for a perpendicular distance of about 1,500 m north from the Hunter River, and then it slopes upstream. To a perpendicular distance north of 1,500 m from the Hunter River, the floodplain geomorphic processes are controlled entirely by the Hunter River, while further away from the Hunter River Bowmans Creek becomes the dominant control. These data suggest that the morphologically-defined bankfull level of the Hunter River (where it just reaches the top of the banks) is at ~61 m AHD. The interpolated river profile data (using Denman and Singleton gauged data) indicate that this level corresponds to a 1 in 10 year ARI event at Singleton (**Figure 2.7**). This suggests that the Hunter River is incised, as the frequency of bankfull in an unincised river would be expected to be within the range 1 to 3 years ARI (Gordon et al., 2004).

It would appear then that over the past approximately 60 years, the lower reaches of Bowmans Creek have been on a trajectory of incision. This would have involved the channel tending towards deepening and widening. At some point the channel would widen sufficiently that the shear stresses would be low enough that the bed and banks would be dynamically stable. Given the narrow and deep morphology of the creek, it is doubtful that this point in the channel's evolution has been reached. Certainly, Bowmans Creek is delivering coarse bedload to the Hunter River, as evidenced by the large tributary confluence bar in the Hunter River (**Figure 2.10**). This contradicts the suggestion of Patterson Britton & Partners (2001) that Bowmans Creek does not deliver bed material to the Hunter River, and that the bed deposits in the lower reaches of the creek are immobile paleo-features.

The evidence suggests that Bowmans Creek is currently an unstable stream, tending towards widening. The tendency towards further incision would appear to be at least partly constrained by a number of bedrock outcrops that would control the bed level of certain sections of the creek. Thus, it is hypothesised that the bed shear stresses and velocities in the creek during flood events would likely have the potential to scour the bed and banks and transport bed material through the creek.

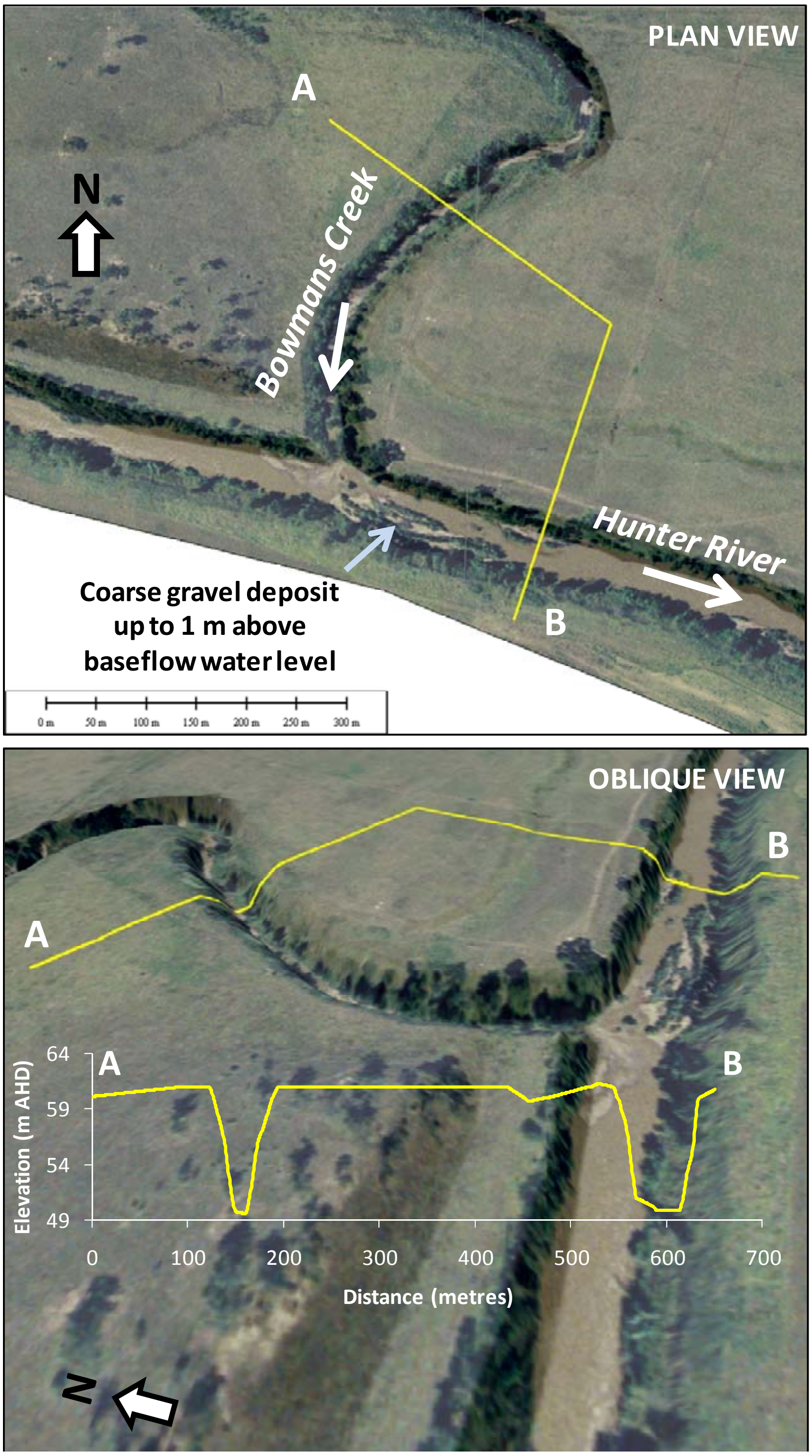


Figure 2.10:
Topography of Bowmans Creek and the Hunter River in the vicinity of their confluence.

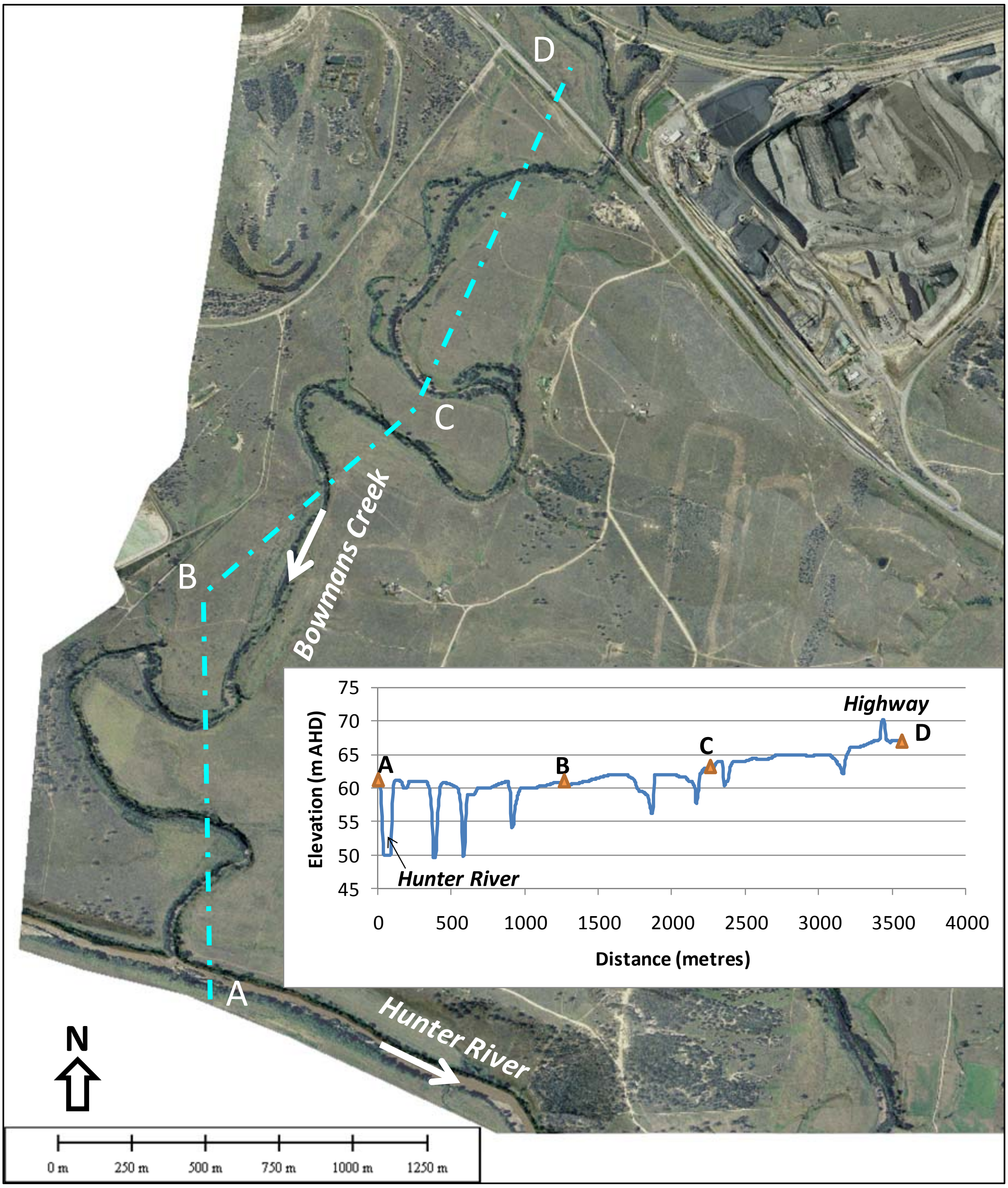


Figure 2.11:
Profile of the floodplain near the confluence of Bowmans Creek and the Hunter River.

2.4 Characterisation of Existing Geomorphological Processes

2.4.1 Approach taken to Geomorphological Assessment

The geomorphology of the existing Bowmans Creek was characterised using five methods:

- Examination of 51 transects and several thalweg long profiles surveyed by Pegasus Technical in 2008;
- Field measurement of channel width and depth undertaken for this project;
- Field measurement of bed particle size undertaken for this project;
- Assessment of bed stability and bank stability based on HEC-RAS (1-D hydraulic model) predicted bed shear stress and velocity (i.e. hydraulics); and
- Assessment of modelled bed scour potential.

The HEC-RAS hydraulic model was run for the discharges corresponding to the 1, 2, 5, 10 and 20 year ARI events. Events over the range 1 to 5 year ARI would be expected to include the main channel forming events, which are large enough to mobilise and transport sediment (the process that builds and destroys channel forms), and frequent enough to keep vegetation in check (vegetation growth can stabilise channel forms). Smaller events are not usually effective in sediment transport, and larger events are too infrequent to be the main controlling influence. The exception is when a series of large events occurs within a short space of time, occurs during a flood dominated regime period (FDR) (Erskine and Warner, 1988). For this reason the 10 and 20 year ARI events were modelled. The 100 year ARI event was not included because such an event is too large to be much impacted by management decisions. The geomorphic impacts of a 100 year ARI event can be catastrophic, but over a long time frame, it is the more frequent events that exert the most control over channel form.

Stream power was not used as an index of stream stability, as there was no reference value of stream power available from which to gauge relative stability.

Bed material sediment yield by the creek over a period of time depends on the:

- pattern of hydrology;
- sediment supply;
- distribution of shear stress or stream power (i.e. hydraulics) within the channel;
- particle size distribution of the bed material; and
- extent and density of riparian and in-stream vegetation cover.

The bed load transport can be modelled on the basis of available data, but the hydrological data from the gauge within the study reach is too patchy and too short to provide a good characterisation of bed load. Of the variables listed above, the hydrology and the sediment supply are not affected by operation of the mine. The hydraulics of the channel for a given discharge depend on the channel morphology (cross-section and long profile shape) and roughness, which may change over time, but not necessarily related to mining activity. The same can be said for vegetation cover. Thus, analysis of the channel hydraulics (shear stress and velocity distribution) over time will indicate any likely change in the sediment load (for a given hydrological regime).

It is very difficult to directly measure hydraulic variables in the field, so the hydraulics are usually characterised by modelling. The models are driven by cross-section data and roughness data. The roughness data are estimated by the modeller, and if there are no calibration data available (as is the case for Bowmans Creek), then these estimates are nothing more than expert opinion. A change in cross-section morphology, with all other things being equal, will generate a change in the distribution of the hydraulic variables. A change in the bed particle size will also alter the hydraulics of sediment movement. Thus, superficially at least, it appears that the hydraulics of the channel can be "monitored" through this modelling approach. The problem is that the model results are very sensitive to the values of roughness selected by the modeller. The modeller usually partitions the cross-section into three sections, and each may be assigned a different roughness value. The subjective selection of the partitions and the roughness values by the modeller can have much more influence on the results than small changes in the cross-section shape or the particle size distribution. In practice, this means that the modelling approach would only be able to detect relatively large changes in the hydraulics of a channel.

2.4.2 2008 survey data

Detailed surveys of 51 cross-sections of Bowmans Creek were undertaken by Pegasus Technical in 2006 and 2008. These cross-sections were not equally spaced, nor were they located to characterise all of the pools and riffles present. Rather, they were concentrated at riffle sites, with less being located at pool sites. A distinctive downstream pattern emerged from the 2008 channel survey data (**Figure 2.12**). The elevation of the terrace was highly variable, which reflected the variable topography of the terrace, plus limitations in the data due to variable transect length.

The bed of Bowmans Creek appears to steepen in grade from about chainage 2,500 m to the Hunter River, as it cuts through the Hunter River floodplain to reach the Hunter River bed level at the junction (**Figure 2.12**). The creek is more incised in this area, with valley walls of up to 11 m high.

The channel bank top level was defined in this report as corresponding to the top of the bank of the low flow channel. Its elevation was variable, but generally followed a downstream grade similar to the water surface and the thalweg (**Figure 2.12**).

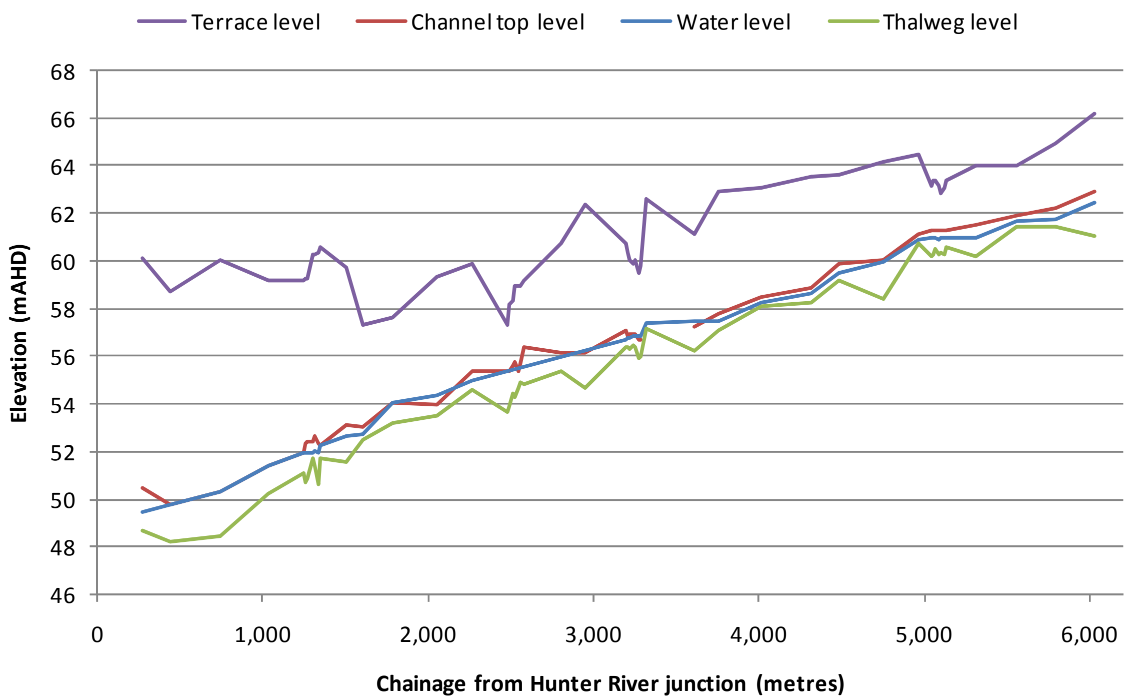


Figure 2.12:
Downstream pattern of morphology of Bowman's Creek as indicated by cross-sections surveyed by Pegasus Technical in 2008.
(Water level is on days of survey in 2008; terrace level sometimes corresponded to the ground elevation at the lateral limit of the cross-section rather than the actual highest level of the terrace in that vicinity)

2.4.3 Field measurement of low flow channel width and depth

On 29/07/2009 a survey was undertaken in Bowmans Creek to measure the water depth (at thalweg, on day of survey), water width (edge to edge for day of survey) of the low flow channel width (bank edge to bank edge – independent of flow). Mean flow for the day was 0.25 m^3/s (21.8 ML/d), which was equivalent to the flow exceeded 20% of the time for all months for the available record. For July, this flow was equivalent to the flow exceeded 28% of the time (i.e. 72 percentile flow) (**Figure 2.13**). The flow statistics for this gauge are uncertain because of the high percentage of missing data. The percentage of missing data ranged from 13 – 20% for the months February to July, and 3 to 9% for the remaining months. Regardless of uncertainty, the flow on the day of survey can be considered a higher than average baseflow for that time of year, but the flow was fully contained within the low flow channel. Depth of water was 0.2 – 0.3 m at riffle sites, which control the pool depth, so under median baseflow conditions the pool depths would be about 0.2 m shallower than were measured during the survey.

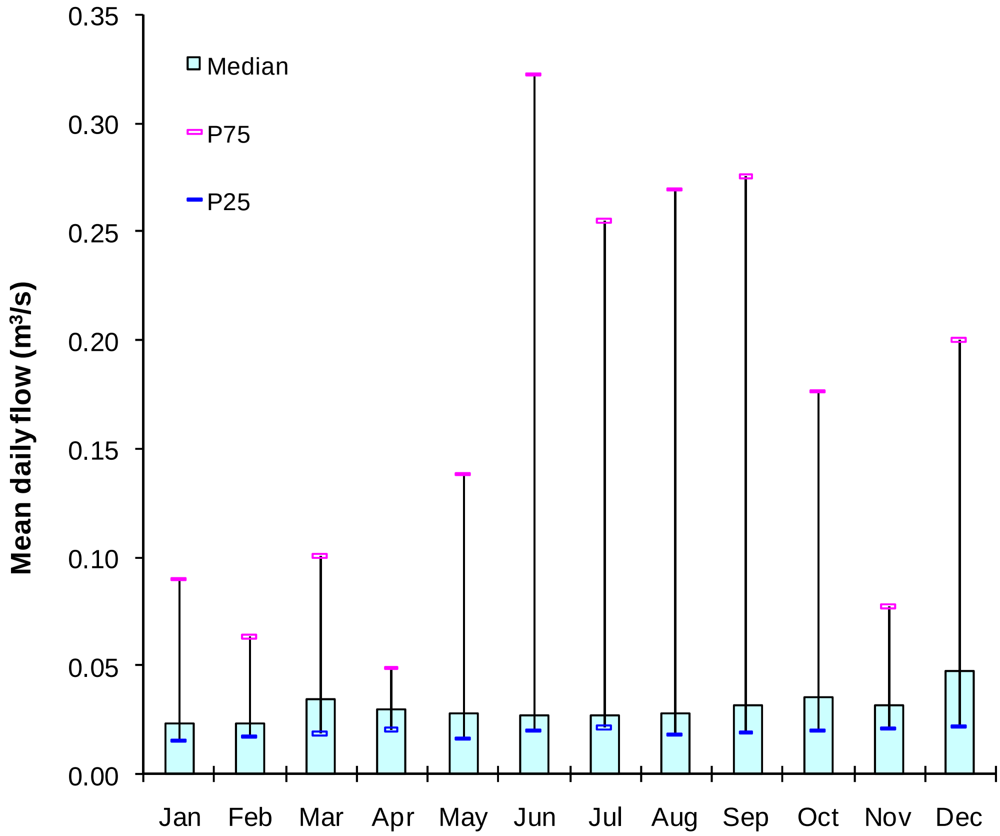


Figure 2.13: Monthly pattern of median flow at D/S Bowmans Creek Bridge gauge, also showing the inter-quartile range (between the 25th percentile and 75th percentile).

A total of 29 measurements were taken along the reach corresponding to the proposed Western diversion, and 34 measurements along the reach corresponding to the proposed Eastern diversion (i.e. the lengths of stream that are proposed to be diverted). The purpose of this survey was to characterise the variability in the form of the low flow channel, so measurements were made through all riffle and pool sections. The measurement locations were not equally spaced, but selected to characterise the expansion and contraction of the channel. These data (**Figure 2.14** and **Figure 2.15**) generally corresponded with the values interpreted from the 2008 cross-section survey data, although direct comparison was not possible, as the measurement points were not coincident.

On the basis of the cross-section data, and the field survey, the main cross-sectional dimensions of the two sections of existing creek that would be diverted by the proposed Eastern and Western diversions were characterised in terms of mean and standard deviation (**Table 2:4** and **Table 2:5**). These data formed a basis for the design of the diversion channels. The water depth and width data are provided here as part of a comprehensive assessment of the channel characteristics, but these hydraulic data were not used in designing the morphology of the diversions. The design was based on the morphology data – the water widths and depths for any flow conditions would be controlled by the morphology.

The data indicated that the upper (Eastern) section of creek corridor was broader and less incised than the lower (Western) section. The Western section was characterised by more variable width and depth of the low flow channel compared to the Eastern section (i.e. there were relatively more pools and shorter pools in the Western section).

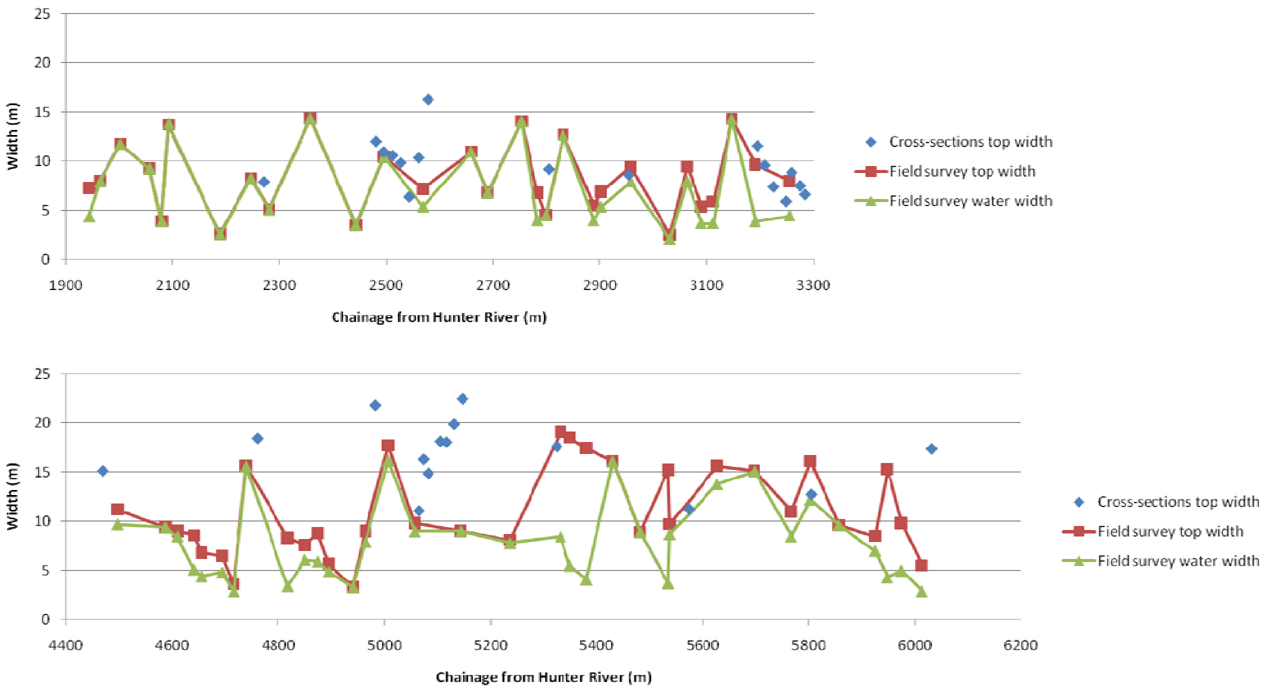


Figure 2.14:
Downstream pattern of width of low flow channel in Bowman's Creek.
(Top plot is the section of Bowmans Creek that would be replaced by the Western diversion, and the lower plot is the section that would be replaced by the Eastern diversion.)

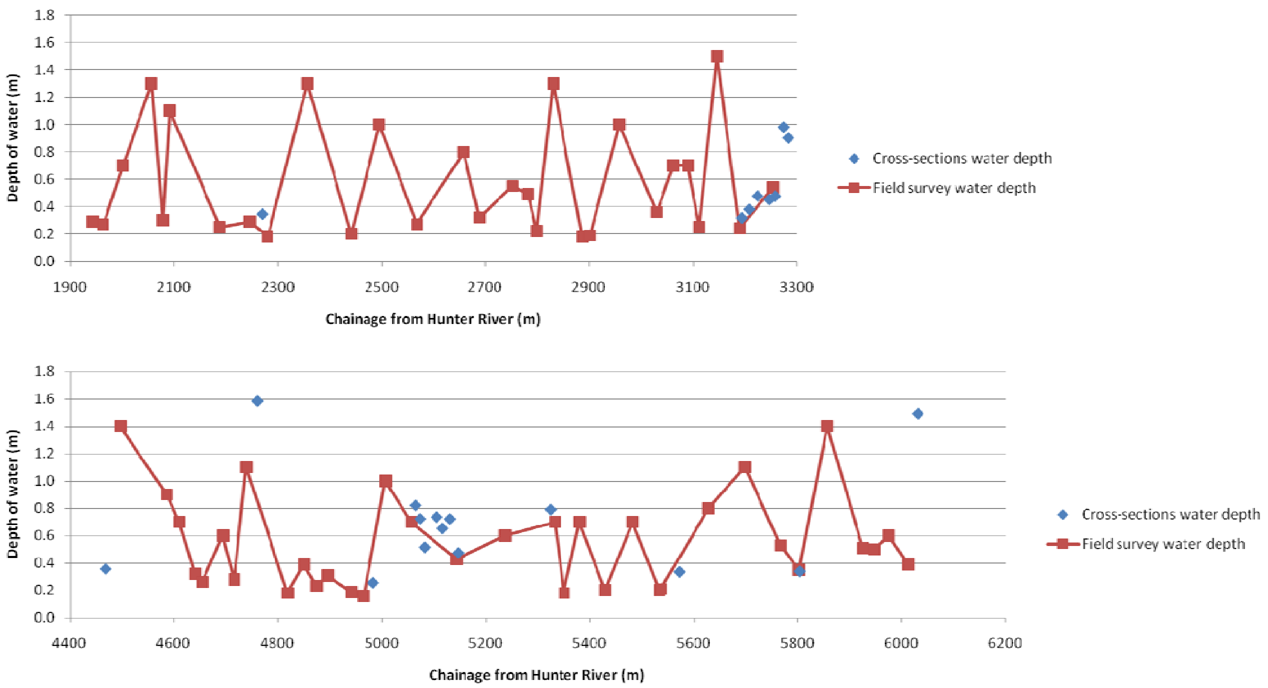


Figure 2.15:
Downstream pattern of depth of water in low flow channel in Bowmans Creek
(Top plot is the section of Bowmans Creek that would be replaced by the Western diversion, and the lower plot is the section that would be replaced by the Eastern diversion.)

Table 2:4: Average dimensions of reach of existing channel associated with the proposed Eastern diversion

Variable	Source of Data	Mean	Standard Deviation
Side slope (m/m)	Cross-sections	1:7.3	3.8
Side slope height (m)	Cross-sections	2.3	1.8
Top width of macro-channel at terrace level (m)	Cross-sections	62	15
Width of base of channel across low active floodplain from base of side slopes (m)	Cross-sections	27	8
Width of low flow channel at pools, between bank edges (m)	Field survey	11.0	3.7
Width of low flow channel at riffles, between bank edges (m)	Field survey	10.6	5.3
Depth of low flow channel from bank top to thalweg (m)	Cross-sections	1.1	0.4
Height of vertical bank to bank toe (m)	Cross-sections	0.4	0.1
Low flow water depth pool (m)	Field survey	0.7*	0.3
Low flow water depth riffle (m)	Field survey	0.3*	0.2

* The water depth on the day of survey was about 0.2 m greater than for average baseflow conditions.

Table 2:5: Average dimensions of reach of existing channel associated with the proposed Western diversion

Variable	Source of data	Mean	Standard deviation
Side slope (m/m)	Cross-sections	1:3.4	2.2
Side slope height (m)	Cross-sections	3.1	1.0
Top width of macro-channel at terrace level (m)	Cross-sections	43	16
Width of base of channel across low active floodplain from base of side slopes (m)	Cross-sections	17	5
Width of low flow channel at pools, between bank edges (m)	Field survey	11.3	2.3
Width of low flow channel at riffles, between bank edges (m)	Field survey	5.7	2.0
Depth of low flow channel from bank top to thalweg (m)	Cross-sections	0.9	0.4
Height of vertical bank to bank toe (m)	Cross-sections	0.5	0.3
Low flow water depth pool (m)	Field survey	0.9*	0.4
Low flow water depth riffle (m)	Field survey	0.3*	0.1

* The water depth on the day of survey was about 0.2 m greater than for average baseflow conditions.

2.4.4 Field Measurement of Bed Material Particle Size

Bed material particle size was measured on 25/08/2009 at 10 locations on Bowmans Creek (**Figure 2.16**) using the Wolman Pebble Count technique, measuring the B-axis dimension of 100 particles selected at random from the surface of riffle crests. The particles were selected from a number of traverses across the entire width of the riffle crest area, which included the channel under water at the time of survey and dry channel bed where bed material was exposed (traverses were made until 100 particles were sampled). The grass covered sections of the bed of the macro-channel (i.e. low flow channel and including the low floodplain within the macro channel) were judged qualitatively to have a similar particle size distribution as the exposed bed material that was sampled. Ten sites were sampled, as this corresponded with the number of sites that could be reasonably sampled in one day. The sites were

The particle size data were converted to distributions of percent finer by weight (in phi classes), corrected for bias in sampling using the method of Leopold (1970) (**Figure 2.17**). The riffles at 1,120 m and 1,948 m (sample sites 2 and 3) were significantly coarser than at the other sites, while the other sites had similar particle size distributions (**Table 2:6**). The median particle diameter was very coarse gravel, but cobble-sized material down to fine gravel and coarse sand was present at all sites. The Folk and Ward (1957) sorting coefficient indicated that all samples except samples 2, 5 and 10 were moderately sorted (coefficient = 0.71 – 1.0). Sample 10 was moderately well sorted (coefficient = 0.50 – 0.71) and samples 2 and 5 were poorly sorted (coefficient = 1.0 – 2.0). These particle size data conflict with the observations reported by Patterson Britton & Partners (2001) of bed material with median diameter 100 – 150 mm in the lower 4 km of Bowmans Creek. A detailed comparison of particle size data cannot be made because Patterson Britton & Partners (2001) did not detail their sampling method, number of samples, sampling locations, method of analysis or size distribution data. It is possible that the bed material has altered since the time of the observations made by Patterson Britton & Partners (2001).

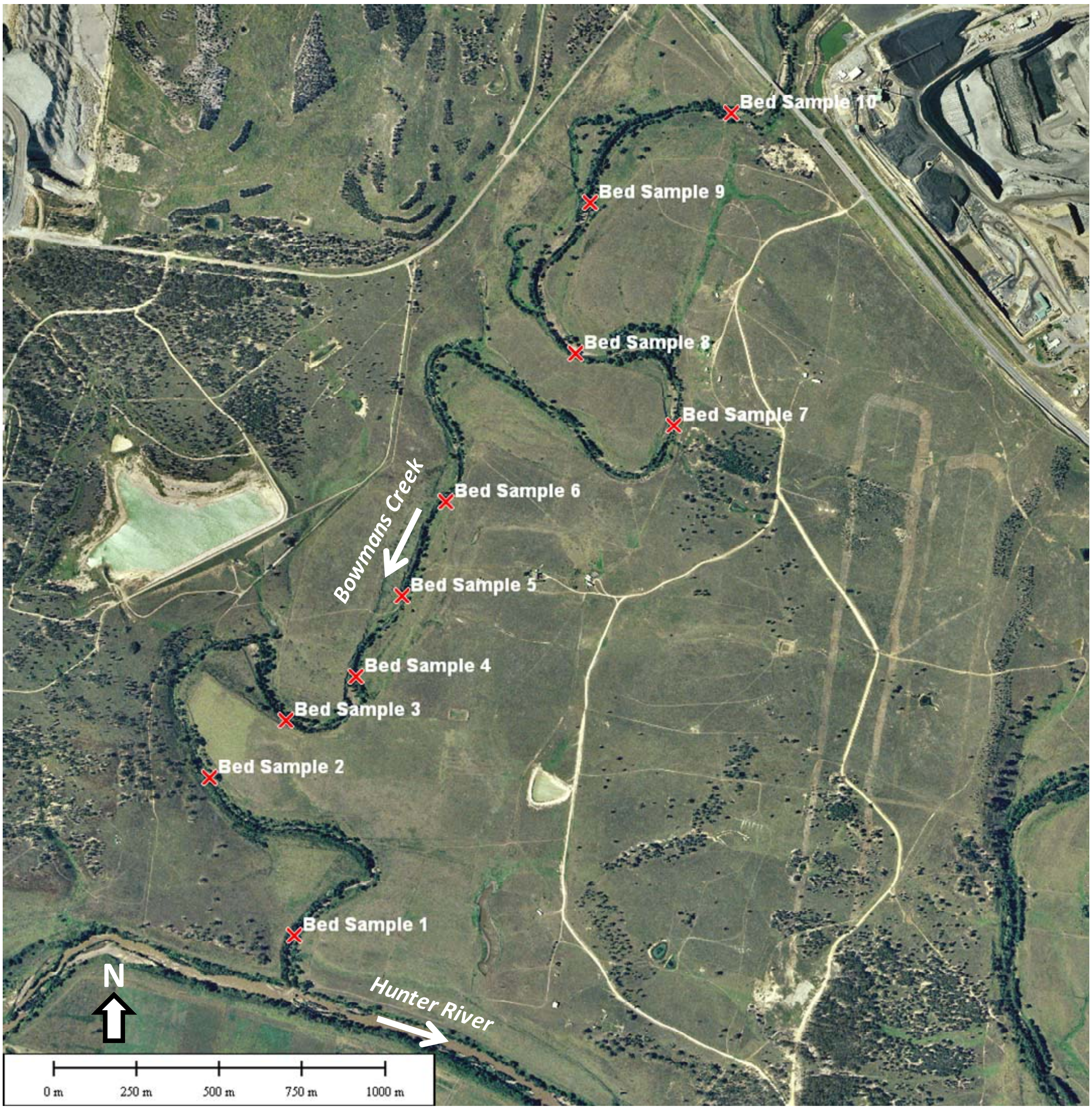


Figure 2.16:
Sites where bed material was sampled for particle size distributions in August 2009.

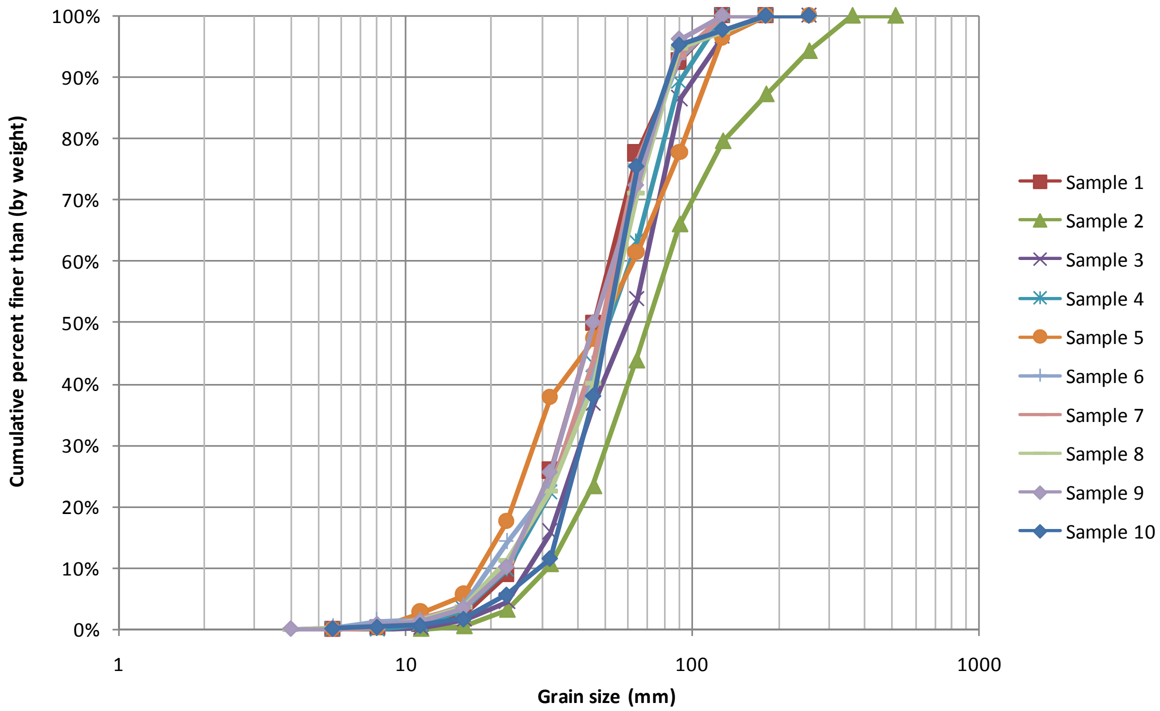


Figure 2.17:
Particle size distributions of riffle crest bed material sampled in August 2009.

Table 2:6: Locations of bed sediment sampling points, and median and standard deviation of particle size

Sample Number	Chainage (m from Hunter River)	Median Size (mm)	Arithmetic Standard Deviation (mm)	Median Class
1	188	45.3	24.0	Very coarse gravel
2	1,120	70.5	59.8	Small cobble
3	1,948	59.3	28.0	Very coarse gravel
4	2,280	50.9	28.7	Very coarse gravel
5	2,574	48.3	40.0	Very coarse gravel
6	2,900	49.1	25.7	Very coarse gravel
7	4,329	48.2	24.2	Very coarse gravel
8	4,834	50.5	25.6	Very coarse gravel
9	5,404	45.3	25.0	Very coarse gravel
10	5,990	50.6	20.2	Very coarse gravel

2.4.5 Assessment of Bed Stability Based on Bed Shear Stress

Transported sediment is comprised of bed load and suspended load. Suspended load is sourced mainly from the catchment, and also locally from bank erosion. Bed load is in almost continuous contact with the bed, carried downstream by rolling, sliding or hopping motions. The initiation of particle movement on the bed depends on the hydraulics of the near bed region. As determination of velocity near the bed is difficult, bed shear stress is a commonly used method of determining incipient motion. Shear stress at the bed (τ_b) is represented by:

$$\tau_b = \gamma RS$$

where:

γ = Unit weight of water

R = Hydraulic radius

S = Energy slope

Bed shear stress (units of N/m^2) is readily calculated at cross-sections through a 1-D hydraulic modelling approach, and is one of the standard outputs of the HEC-RAS model.

In natural cobble and gravel bed streams with a range of particle sizes present, such as Bowmans Creek, the theory of equal mobility predicts that most of the grain sizes begin moving at nearly the same discharge. This does not imply that the entire bed surface moves at the one time, but that, at any instant, the bed load may consist of a range of particle sizes, and the bed selectively unravels from different locations as discharge increases (Gordon et al., 2004, p. 190). The critical shear stress (τ_c) is the shear stress required to set the bed particles in motion, represented by the Shields equation:

$$\tau_c = \theta_c g d(\rho_s - \rho)$$

where,

θ_c = dimensionless critical Shields stress

g = acceleration due to gravity (9.8 m/s^2)

d = representative particle size (m)

ρ_s = particle density (2,650 kg/m^3)

ρ = water density (1,000 kg/m^3)

For particles to move, the actual shear stress (τ_b) must exceed the critical shear stress (τ_c). Lorang and Hauer (2003) defined the mobility ratio, or stream stability index (ξ):

$$\xi = \tau_b/\tau_c$$

whereby threshold entrainment for the full range of particle sizes composing the bed material is achieved when $\xi \geq 1$.

There is considerable debate in the literature concerning the appropriate values of θ_c and d to use in the Shields equation (Gordon et al., 2004, p. 194). Buffington and Montgomery (1997) compiled 8 decades of flow-competence work and found that θ_c values ranged from 0.03 to 0.07. Reviews by Miller et al. (1977) and Yalin and Karahan (1979) both reported that θ_c approaches a constant value of 0.045 for coarse particles (diameter > 10 mm). The median diameter (D_{50}) is often used as the representative diameter. However, Komar (1987) modified the original Shields entrainment expression to account for a natural mixed-particle size bed, to derive the flow-competence equation

$$\tau_c = 0.045g(\rho_s - \rho)D_{50}^{0.6}\, D_{max}^{0.4}$$

where D_{max} is the maximum diameter and the exponent values 0.6 and 0.4 come from data obtained in streams where $D_{max}/D_{50} \leq 22$ and particle diameter ranges were 10 to 100 mm.

The condition of bed instability defined by $\xi \geq 1$ should not be interpreted as harmful to stream ecology, as occasional bed instability is necessary for proper ecosystem functioning. Mobilisation of bed material would be expected to be associated with bankfull (channel maintenance) flow conditions, which might occur on average every 1 to 3 years in a dynamically stable stream. Thus, the threshold of entrainment ($\xi = 1$) would correspond with flows of about bankfull level. When Lorang and Hauer (2003) applied the equation of Komar (1987) to 33 high gradient (≥ 0.002 m/m) gravel/cobble bed (D_{84} = 35 – 1,000 mm) rivers in New Zealand [using data from Hicks and Mason (1991)], they found that the value of 0.045 for the dimensionless critical Shields stress (θ_c) predicted that the beds of most streams would be stable at bankfull, and a more appropriate value of θ_c was 0.02. This corresponds with the minimum value of θ_c suggested by Andrews (1983) for gravel bed rivers. On the basis of this evidence, we assumed that 0.02 was the appropriate value of θ_c for Bowmans Creek (which has a water surface gradient of 0.0022 – 0.0024 m/m for the 1 – 20 year ARI events, and a gravel/cobble bed with D_{84} = 74 – 157 mm). For the present study of Bowmans Creek, the absolute value of θ_c was important, but not critical. This is because the main objective was to compare the estimated value of the stream stability index (ξ) in the existing stream under the existing hydrology/hydraulics situation with that modelled for the situation with the proposed diversion channels in place. That is, the comparison of the values of estimated stability index was more important than the accuracy of the values of the stability index, provided the accuracy of the estimate was similar for both situations (which was the case).

Using a HEC-RAS model, bed shear stress (τ_b) was predicted at each of the cross-sections in the existing creek surveyed by Pegasus Technical in 2008. Each cross-section was partitioned into a central channel area, and a left and right area. This was done by defining the central channel area as between the inset-benches (i.e. containing the low flow channel and low floodplain). The model was run for 1 yr, 2 yr, 5 yr, 10 yr and 20 yr ARI events. Each cross-section was assigned a bed particle size distribution on the basis of the closest sample. The relationship of Komar (1987) was used to predict τ_c, with the modification of θ_c = 0.02. Bed mobility was assessed as a threshold phenomenon defined by the stream stability index ($\xi = \tau_b/\tau_c$).

The analysis of potential bed particle mobility indicated a low likelihood of bed material mobility on the sides of the channel for the 1 yr ARI event, but higher floods had the potential to scour areas of exposed bed material in the side sections of the channel (**Figure 2.18**) [note that this discussion applies to gravel/cobble bed material which covered the bed of the macro-channel, not the fine-grained cohesive alluvium which comprised the walls of the macro-channel – here analysed as banks (see later)]. For the 1 yr ARI event, in the central channel area the shear stress was above the threshold for entrainment at more than half of the cross-sections. The relative instability of the bed increased with increasing discharge, such that at the 5 yr ARI event the majority of the channel bed had potential for particle mobility (**Figure 2.18**). This suggests that the bed of the existing channel is active at events with a frequency of 1 to 3 years ARI (as would be expected in a dynamically stable stream). The bed material on in the side sections (comprising gravel/cobble bars and low-level floodplain) was more stable due to lower shear stress there. The stability of this material was enhanced where it was vegetated, which constituted the majority of the bed of the macro channel excluding the low flow channel.

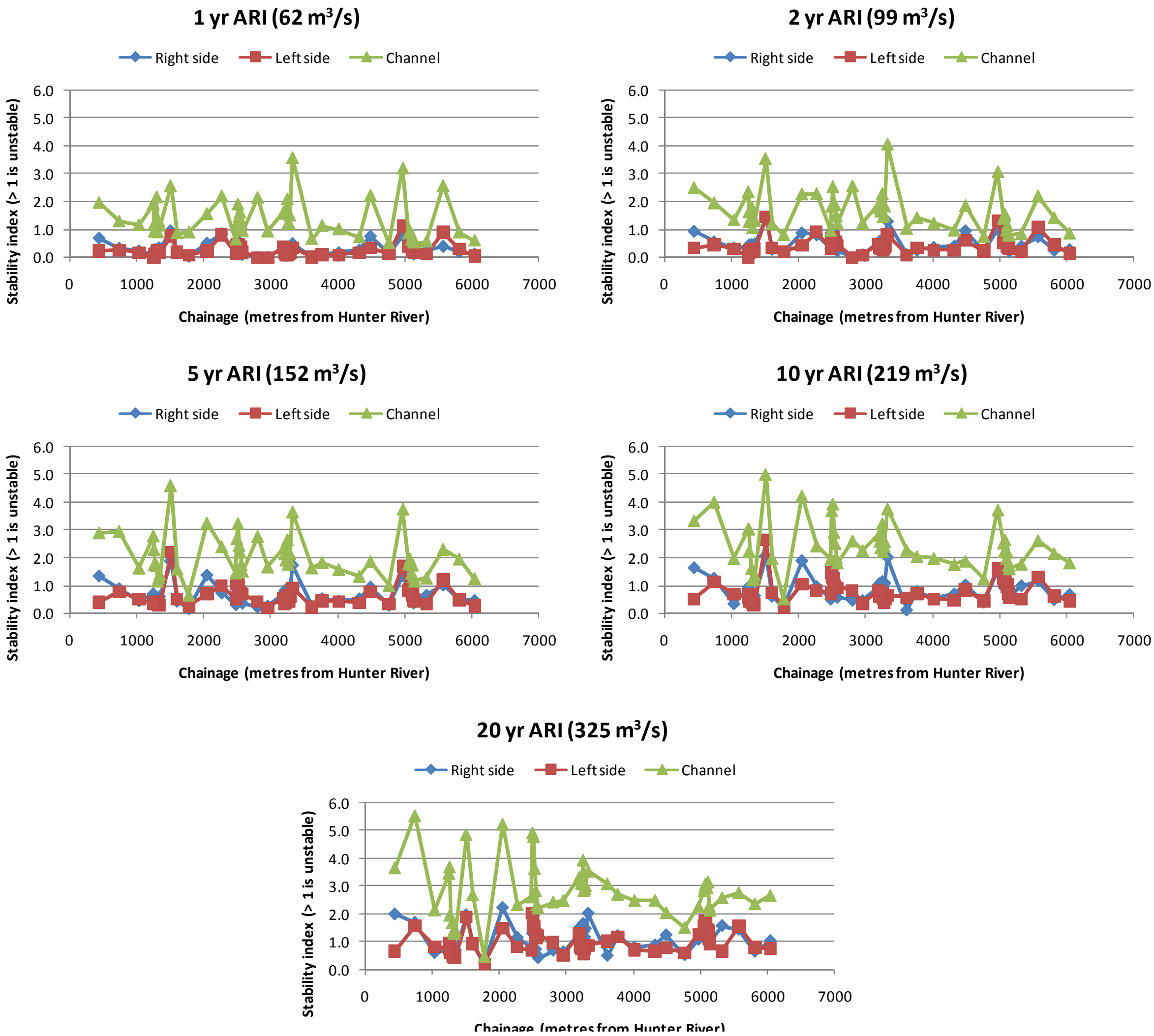


Figure 2.18:
Existing Bowmans Creek, Bed Stability Index for a range of ARI events

2.4.6 Assessment of Bank Stability Based on Maximum Permissible Velocity

The maximum permissible velocity (U_{max}) is the greatest mean channel velocity (U) that will not cause fluvial erosion of the channel body. A channel is stable when:

$$U < U_{max}$$

Tables of maximum permissible velocity appear in many channel design, engineering and hydraulics publications (e.g. Chang, 1988). These values assume a bare channel surface (i.e. no grass or other lining or vegetation). Vegetation failure usually occurs at much higher levels of flow intensity than for soil (Fischenich, 2001).

For the alluvium in the upper banks of Bowmans Creek, the values of maximum permissible velocities in the literature suggest that bare bank material would be at risk of fluvial erosion under conditions of velocity exceeding 0.8 m/s for short duration events, and conditions of velocities exceeding approximately 0.4 m/s for long duration events (longer than half a day). A grass covered surface would be at risk of erosion for velocities exceeding 2 m/s for short duration events and conditions of velocities exceeding approximately 1.5 m/s for long duration events (longer than half a day). In this analysis, the bank stability was assessed using 2 m/s as the threshold index of stability, as the majority of the banks were grassed, and the majority of flood events would be relatively short lived.

Using a HEC-RAS model, bank velocities were predicted at each of the cross-sections in the existing creek surveyed by Pegasus Technical in 2008. Each cross-section was partitioned into a central channel area, and a left and right area, and only the predictions for the left and right areas were used in this analysis. The model was run for 1 yr, 2 yr, 5 yr, 10 yr and 20 yr ARI events.

The analysis of bank stability potential indicated a low likelihood of bank instability from fluvial erosion for the 1, 2 and 5 year ARI events (**Figure 2.19**). At the 10 yr ARI event and the 20 yr ARI event some sections of the banks had potential for instability (**Figure 2.19**). This suggests that the channel banks can erode in places during the higher flood events. Bare banks would be unstable for events with a frequency of 1 to 3 years ARI (and larger events). Some sections of bare banks were observed on Bowmans Creek, and it is the occasional erosion of these banks that explains the process of widening of the incised creek corridor over time.

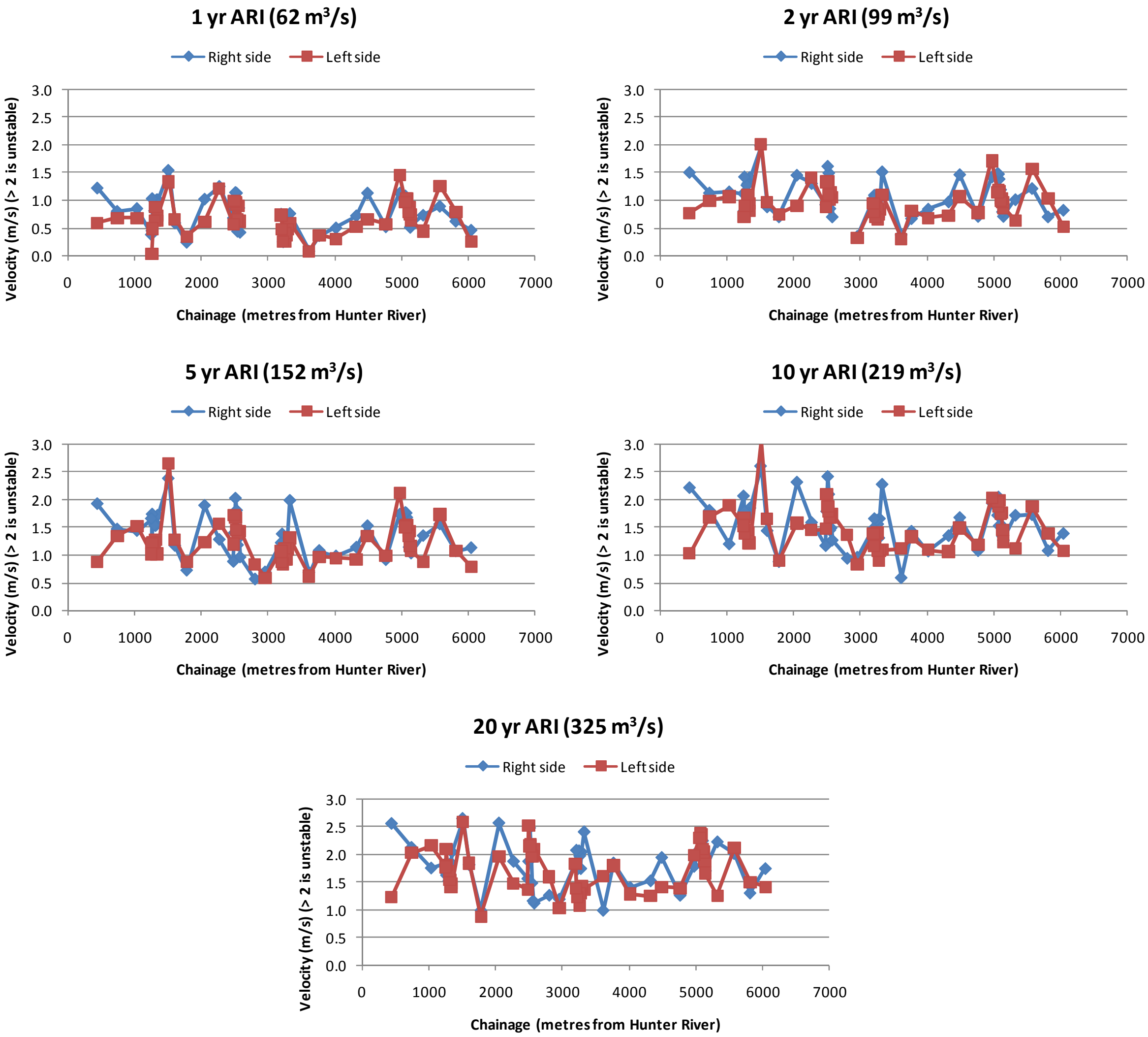


Figure 2.19:
Existing Bowmans Creek, Bank Stability Index for a range of ARI events

Bank erosion can also occur through mechanical mass wasting. The most common mechanisms are toppling of banks that are undercut from fluvial erosion, toppling of banks due the surcharging effect of trees (can be in association with wind) and slumping due to rapid drawdown of water level under conditions of saturated banks. Channels that are not subject to excessive fluvial erosion generally have well vegetated and sloping banks, and therefore generally have low rates of mechanical bank failure. Bowmans Creek showed evidence of mechanical bank failure, which would be expected in an incised channel with high and steep banks. Thus, although mechanical failure was not analysed here, it can be assumed that in Bowmans Creek this form of failure occurs in certain locations in association with fluvial erosion.

2.4.7 Types of scour and scour depth prediction

The process of bed scour is introduced here, not because it is particularly relevant to characterising the existing conditions in Bowmans Creek, but because it is relevant to the proposed diversions. Bed scour processes are natural, whereby the bed levels change during flood events if the bed material is mobile, and the bed morphology can be different after a flood event compared to before the event. While bed scour processes can be modelled to a certain extent, the change in bed morphology caused by a flood event is not predictable. Bed scour processes are characterised for the existing channel in this section so that the existing bed scour processes can later in this report be compared with those predicted for the proposed diversions.

There are four main bed material scour processes that occur in Bowmans Creek:

- Active layer bed scour (also called disturbance depth, live bed scour, or moving layer depth);
- General scour (longitudinally local contraction scour and bend scour affecting the entire cross-section)
- Local-scale scour immediately adjacent to obstructions (here, large woody debris); and
- Maintenance of pool-riffle morphology by scour

2.4.7.1 *Active layer bed scour*

Active layer bed scour refers to the thickness of the layer of bed material that is mobilised when the incipient motion[1] threshold is exceeded under certain flood events. Under conditions of undisturbed sediment supply, the bed level returns to its pre-flood event level. This process has been examined extensively in the literature, and only some key papers are referred to here. Wilcock et al (1996), Wilcock (1997) and May et al. (2007) related the depth of the active bed layer to the dimensionless shear stress (Shields stress) (τ^*):

$$\tau^* = \frac{\tau_b}{g(\rho_s - \rho)D_{50}}$$

where:

τ_b = bed shear stress (N/m^2)

g = acceleration due to gravity (9.8 m/s^2)

D_{50} = median particle diameter (m)

ρ_s = particle density (2,650 kg/m^3)

ρ = water density (1,000 kg/m^3)

[1] The flow condition of incipient motion of the bed material particles is such that the particles just start moving.

May et al. (2007) developed an empirical equation (r^2 = 0.81, N = 11) that related τ^* to the active layer mean thickness (δ_{av}) as a function of the 90th percentile particle size (D_{90}), which is generally assumed to represent the size of the particles making up the armour layer:

$$\frac{\delta_{av}}{D_{90}} = 9301\,\tau^{*3.291}$$

Wilcock (1997) derived an equation of a similar form that was a function of the median particle size (D_{50}):

$$\frac{\delta_{av}}{D_{50}} = 7963\,\tau^{*2.61}$$

DeVries (2002) suggested that plane bed transport of coarse heterogeneous mixtures in gravel bed streams involves the disturbance of a relatively thin layer of the bed. DeVries (2002) concluded that the maximum scour depth (δ_{max}) was related to the size of the coarser mobile grains. The relationship of Wilcock and McArdell (1997) ($\delta_{max} = 2D_{90}$) and the relationship suggested by DeVries (2002) ($\delta_{max} = 1.5D_{max}$) enveloped the data similarly. Field data indicated that only a fraction of the active bed area experienced disturbance to the limits suggested by these relationships. The maximum disturbance depth was invariant with flow strength once the largest grains present were mobilized. Disturbance depth did not scale with grain sizes smaller than D_{50} when larger grains were mobilized. Thicker traction carpets were not predicted to occur because much larger shear stresses than observed naturally were needed to mobilize two or more layers of the bed simultaneously (DeVries, 2002).

2.4.7.2 *General scour*

General scour includes (i) contraction scour, which occurs when the flow cross section is reduced by natural features, such as stone outcrops, ice jams, or debris accumulations, or by constructed features such as bridge abutments, and (ii) bend scour, which is associated with the helical pattern of flow through channel meander bends that moves sediment from the outside (concave bank) to the inside of the bend, which is often a point bar. Blodgett and McConaughy (1986) measured general scour at 21 sites on streams with a range of bed material sizes (sand to cobble-size median diameter). The sites were free of obstructions that might cause local scour. Monthly or annual measurements of thalweg level were made over a period of time. Scour depth was defined as the depth of scour below a reference plane, which was set at the highest thalweg elevation measured during the period of observation. From these data, Blodgett and McConaughy (1986) derived the following best fit relationships:

$$\delta_{max} = 3.8{D_{50}}^{-0.115}$$

$$\delta_{av} = 0.84{D_{50}}^{-0.115}$$

Pemberton and Lara (1984) suggested that regime equations provided by Blench (1970) and Lacey (1931) could be used to predict a value of maximum general scour in natural channels. For a stream with a moderate bend (appropriate for Bowmans Creek) the relationship based on Lacey's equation is:

$$\delta_{max} = 0.059Q^{0.333}W^{0}{D_{50}}^{-0.167}$$

and the relationship based on Blench's equation is:

$$\delta_{max} = 0.162Q^{0.667}W^{-0.667}{D_{50}}^{-0.1092}$$

where,

Q = the discharge of interest (m^3/s)

W = the flow top width at Q (m)

D_{50} = median particle diameter of bed material

2.4.7.3 *Local scour adjacent to woody debris*

Scour pools are known to be associated with large woody debris in streams, and these pools make a significant contribution to habitat heterogeneity (Gippel, 1995; Lester and Boulton, 2008). Most of the work on scour associated with wood has been in relation to engineered log jams (ELJs) but the same principles apply to natural accumulations of large wood in streams. An abrupt change in boundary conditions exists at the tip of logs, where there is a point of flow separation and associated turbulent flow. This turbulent flow propagates downstream from the tip of the log producing a scour pool with a point of maximum depth just downstream from the tip of the log. Scour pools also form by the process of jetting of flow under the log. A proportion of the flow is directed under the log, producing a slightly elevated shear stress compared to the upstream conditions. The rate of sediment movement in the higher shear stress region is higher than elsewhere in the stream, hence a local increase in depth downstream and parallel to the log results. For single logs, the maximum depth of scour due to the flow separation was found by Marsh et al. (2001) to be similar to the scour due to flow jetting under the log.

The scour forming processes for complex log jams (such as ELJs) were not investigated by Marsh et al. (2001), however, it is likely that the scour process would be analogous to that at engineered structures such as groynes or bridge abutments. For bridge abutments the scour forming process is principally one of flow separation at the tip of the structure with the additional scouring action due to the constriction of flow at the abutment. The porous and hydraulically complex nature of log jams would result in less scour than one would expect at bridge piers or bridge abutments. Abbe and Montgomery (1996) predicted maximum scour at two ELJs using the equation of Liu et al. (1961) for groynes at 4.4 m and 4.2 m. These values were clearly an over-estimate. By correcting the values for constriction scour, grain size standard deviation, and bed armouring the estimated scour depth was 1.3 m for both log jams. This estimation compared favourably with the observed depths of 1.4 m and 1.1 m. Wallerstein (2003) presented an initial attempt to determine the rate and depth of scour associated with a large woody debris channel obstruction based upon considerations of changes in specific head through the section, a flow resistance equation, the sediment continuity equation and a sediment transport equation.

2.4.7.4 *Scour associated with maintenance of pool-riffle channel form*

Pool-riffle sequences can be viewed as quasi-stable features for typical flood events in gravel-bed rivers. At low flows the velocity over the steep downstream face of the riffle is higher than through the pool, but it has been hypothesized that velocity increases with discharge at a faster rate through the pool, causing it to exceed the velocity over the riffle as high flows drown out the riffle's control on the water surface slope of the pool (Keller 1971). This condition, known as velocity reversal, has been proposed as a mechanism for the maintenance of pool-riffle features, whereby reversal of velocity causes corresponding reversal of shear stress and transport capacity that scours sediment previously deposited in the pool (Caamaño et al., 2009).

Caamaño et al. (2009) presented a simple one-dimensional criterion that unified and explained previous disparate findings regarding the occurrence of velocity reversals. Results showed that reversal depends critically on the ratio of riffle-to-pool width, residual pool depth, difference between pool and riffle elevations, and on the depth of flow over the riffle. The velocity reversal threshold is given by:

$$\frac{W_R}{W_P} - 1 = \frac{D_Z}{h_{Rt}}$$

where,

W_R = pool water surface width

W_P = riffle water surface width

D_Z = residual pool depth (difference between the pool and riffle thalweg elevations)

h_{Rt} = riffle thalweg water depth

Reversal occurs where $\frac{W_R}{W_P} - 1 > \frac{D_Z}{h_{Rt}}$. For a given width ratio ($\frac{W_R}{W_P}$) and residual pool depth (D_Z), the water depth over the riffle thalweg (h_{Rt}) will indicate whether reversal occurs, with deeper flows required for reversal. Furthermore, the riffle must be wider than the pool ($\frac{W_R}{W_P} > 1$) for velocity reversal to occur. As the residual depth of the pool becomes smaller relative to the riffle thalweg depth it is more likely that velocity reversal will occur and conversely a very deep pool may never achieve reversal. Hence, velocity reversal may be less important for maintaining established large pools, than for scouring pools that have aggraded and are in danger of filling in completely. Pool-riffle sequences plotting close to the velocity reversal threshold represent reaches in which reversal occurrence is particularly susceptible to changes in stream sediment delivery and stream morphology. The equation of Caamaño et al. (2009) provides a direct means of predicting the sustainability of pools.

2.4.8 Bed scour in the existing channel

Mean and maximum active bed layer scour depth, and mean and maximum general scour depth was estimated using a range of equations. Some of these were discharge or shear stress dependent, and therefore varied with discharge, while others were largely dependent on particle size of the bed material and were invariant with discharge (**Figure 2.20**). Active layer scour depth was less than general scour depth. General scour depth would be expected to be of the same order as the observed natural variations in bed elevation, and this was the case, with pool depths in Bowmans Creek being observed to vary up to about 1.4 m and having a mean depth of 0.7 – 0.9 m (**Figure 2.15**). Active layer scour depth was predicted to be shallow, of the order of 0.1 – 0.3 m at most.

Using the relationship of Caamaño et al. (2009), not all of the 12 pools identified by the channel cross-section survey data had potential for velocity reversal (velocity in the pool higher than that in the downstream riffle at high flow) (**Figure 2.21**). However the 1-D HEC-RAS model predicted that most pools would have velocity reversal. There would be considerable uncertainty in these results, but they do indicate that pools in the creek have the capacity to be self-sustaining.

Local scour at large woody debris was not investigated in detail on Bowmans Creek. Inspection of large woody debris in the creek revealed that local scour features were associated with all items of large woody debris. Where scour pools were visible, they were variable extent and depth. Although all of those viewed in the field were less than 0.4 m deep and very localised. Some items of large woody debris were located in pools that were part of the pool-riffle morphology, in which case it was not possible to identify a separate local scour pool.

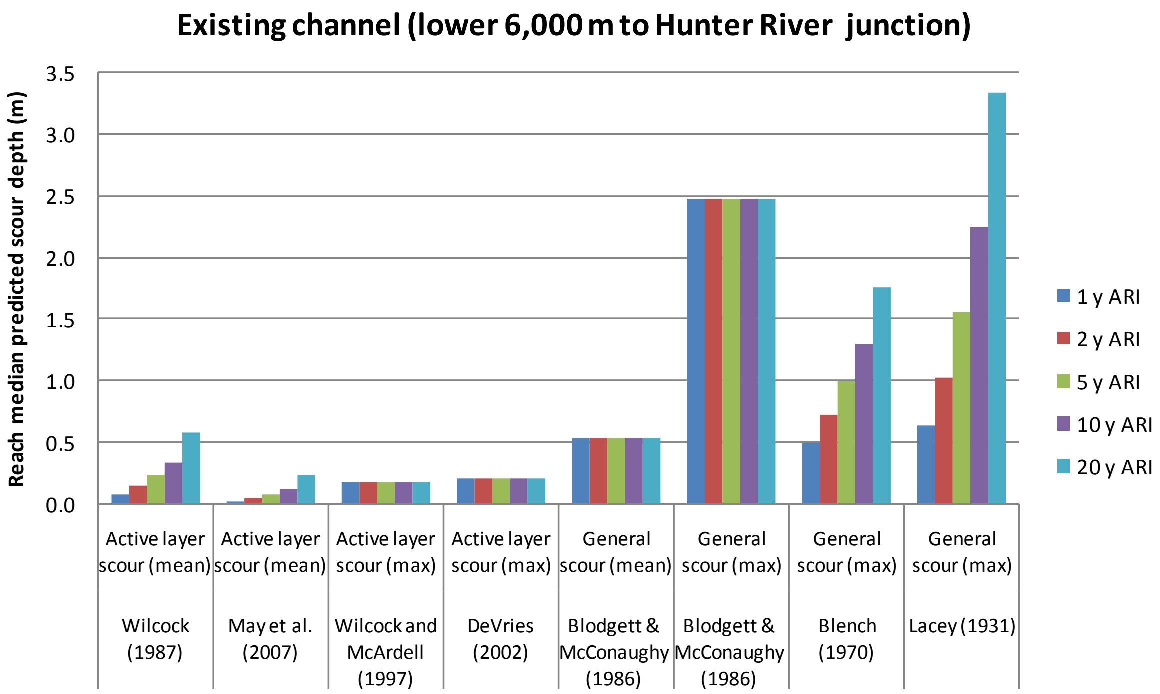


Figure 2.20:
Calculated reach median values of a range of active layer and general scour predictions for the existing Bowmans Creek in the study area.

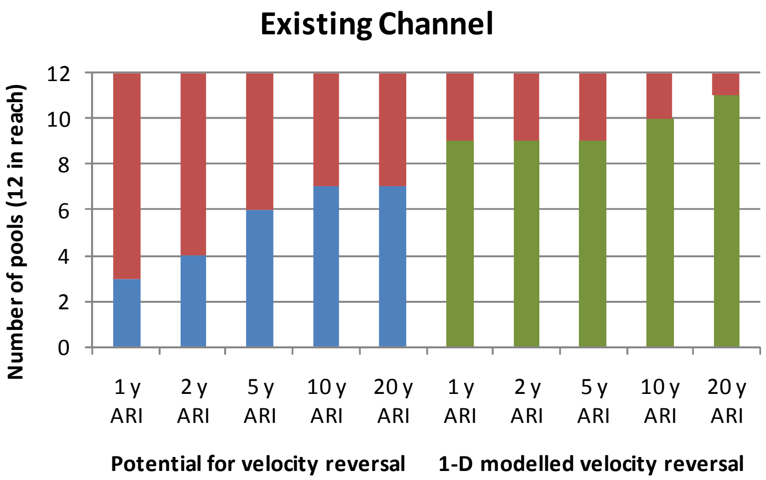


Figure 2.21:
Predicted number of pools with potential for velocity reversal [relationship of Caamaño et al. (2009)] and number of pools showing velocity reversal in 1-D model for the existing Bowmans Creek in the study area.

2.4.9 Summary of existing channel geomorphic condition

Bowmans Creek remains on a trajectory of incision and widening, which probably began up to 60 years ago. The rate of incision has been slowed by exposure of a number of bedrock outcrops. At their junction, Bowmans Creek has incised down to the bed level of the Hunter River. The thalwegs of the creek is about 11 - 12 metres below the surrounding floodplain level. Bowmans Creek is incised down to the bed level of the Hunter River only near its lower end. At a creek distance of 4 - 6 km from the Hunter River junction, Bowmans Creek is incised about 4 m into the floodplain.

The macro channel of Bowmans Creek has steeper and higher sideslopes in the lower 3 km compared to the upper 3 km. The walls of the macro channel are fine grained alluvium. The macro channel width (where macro channel meets the terrace level) is narrower in the lower half (around 30 - 60 m wide) compared to the upper half of the study reach (around 45 – 75 m wide). Within the macro channel there is a discontinuous inset depositional bench (composed of sand/gravel/cobble material and covered with grass), and a lower bed formed in gravel/cobble that comprises a low-level floodplain, gravel bars, and a distinct low flow channel with pool-riffle morphology. The low flow channel varies in width, being narrower at riffles (particularly in the lower half of the study reach). The bank top level of the low flow channel is about 0.5 – 1.5 m above the level of the thalweg. Pools at median low flow conditions were 0.5 – 0.7 m deep on average, and up to 1.2 m deep. The upper half of the study reach was characterised by more variable width and depth of the low flow channel compared to the lower half (i.e. there were relatively more pools and shorter pools in the lower half).

The median particle diameter was very coarse gravel, but cobble-sized material down to fine gravel and coarse sand was present at all sites. Eight of the ten sampled sites had similar particle size distributions (median diameter 45 – 50 mm), and two sites towards the lower end of the study area were noticeably coarser (median diameter 60 – 70 mm).

Bed material in the channel is predicted to be mobile during flood events of ≥ 1 – 3 yr ARI, while the grass covered bars and benches are mostly stable. The bed stability index was highly variable along the study reach, but overall, the channel was less stable in the lower half of the study reach.

The grassed banks are predicted to be generally stable for floods up to the 5 year ARI event, but for higher events the banks are likely to be subject to fluvial erosion in places. Bare banks are likely to erode during flood events of ≥ 1 – 3 yr ARI. There was no downstream pattern to the fluvial erosion bank stability index, but it is likely that mass wasting erosion would be more prevalent in the downstream, more incised, half of the study reach.

Active layer scour depth was predicted to be shallow, of the order of 0.1 – 0.3 m at most, while predictions of general scour depth matched the observed variations in bed level. Scour holes associated with large woody debris were observed to be highly localised and relatively small (<0.4 m deep). Modelling suggested that pools in the creek have the capacity to be self-sustaining through the process of velocity reversal under high flow conditions. Direct observations of these scour processes have not been made in this or previous studies, but the field observations did not contradict these model predictions.

Flood frequency analysis undertaken for this study suggested that the June 2007 flood was a 34 year ARI event in lower Bowmans Creek. In an event of this magnitude, the bed material would be expected to be mobile, bedforms would be expected to change, and areas of bank erosion would be expected. Observations consistent with these expectations were made by Marine Pollution Research (2008) during an ecological survey in late June 2008. At the surveyed cross-sections, compared to surveys made in the year prior to the flood of 2007, scour of the bed was up to 0.9 m and deposition was up to 0.4 m (Maunsell Australia, 2008). Cross-sections with scour outnumbered those with deposition, but Maunsell Australia (2008) did not analyse the data statistically so a firm conclusion cannot be drawn. Maunsell Australia (2008) also observed areas of bank erosion and deposition. Although Maunsell Australia (2008) did not regard the changes as "significant", the magnitude of the changes provides some indication of the expected rates of change. As a result of this high magnitude event, even though bed scour and bank erosion processes would have been active, there was no observed catastrophic channel change. Thus, although the channel is unstable during high flow events, in terms of the bed stability and bank stability indices used here, the channel has an inherent high resistance to gross change. This resistance is imparted by good vegetation cover, the presence of rock bars, the bed material containing a fraction of cobble size material, and presumably, a supply of bed material into the reach from upstream.

3 GEOMORPHOLOGICAL DESIGN ASPECTS OF THE PROPOSAL

3.1 Brief Description of the Proposed Diversion Concept

The proposal involves diversion of two lengths of the existing channel (the Eastern diversion) and the Western diversion). All flows <5 year ARI would flow down the diversion channels – as controlled by block banks constructed across the existing channel. For larger events the creek would overflow the block banks and flow would be split between the existing channel and the diversion channels, although the majority of the flow would pass down the diversion channels.

This section of the report is concerned with the design of the overall diversion channel morphology, in terms of length, plan form, long profile, cross-section shape and in-channel geomorphic features.

3.2 Design Principles

Approaches to channel design fall into three categories (Skidmore et al., 2001):

- Analog approach (adopts an existing stream as a template)
- Empirical approach (uses equations that relate channel characteristics derived from regionalised data sets, and assumes equilibrium conditions)
- Analytical approach (uses hydraulic models and sediment transport functions to derive equilibrium conditions)

The approach adopted in this study was the analog approach, also known as the carbon copy approach (FISRWG, 1998), with the two diversion channels being (as close a possible) carbon copies of the two sections of the existing channels that they would replace. The rationale for adopting this approach was that the diverted sections of Bowmans Creek should behave similarly to the existing sections that they would replace. Provision of near identical morphology and sediment transport processes would also mean minimal change to the availability of hydraulic habitat for biota.

In the long term, the diversions would not be expected to result in any interruption to bed material sediment supply from upstream, or from within the channel itself. The diversion channels will be deformable, allowing for natural adjustments of the bed and banks within the range of existing rates of change.

The diversion channels were designed to accept all flows up to the 1 in 5 year ARI event (although this would be staged to allow for establishment of vegetation). Larger floods would flow down both the existing and the diversion channels. Thus, for these larger floods, shear stresses in the diversion channels are expected to be lower than in the existing channel.

The low flow channel would be lined with a buried waterproof layer, and then overlain with approximately 600 mm depth of gravel/cobble bed material. The depth of this bed material would be expected to adjust over time. The liner may be located deeper in some sections underneath large woody debris structures, as these are likely to create scour holes.

For the purpose of modelling the geomorphic characteristics of the diversions channels, it was assumed that the bed material of the channels would be composed of a particle size distribution that represented an "average" of the 10 sampled bed particle distributions. The characteristics of the "average" distribution were calculated as the average of various percentile statistics.

3.3 Design Method for Basic Channel Form

Due to space limitations, it was not possible to design the proposed Eastern diversion to the same length as the existing channel it would replace, so it was shortened by about 36 percent. The proposed Western diversion would be 8 percent shorter than the existing channel that it would replace. The first step in channel design was to draw a plan shape. This was drawn to fit within the designated corridor that would not be impacted by future mining.

The 2008 thalweg and cross-section survey data provided by Pegasus Technical, plus the field measurements of width and depth undertaken for this study, were used to characterise the morphology of the sections of Bowmans Creek that would be diverted in terms of:

- Thalweg elevation,
- Low flow channel bed width,
- Low flow channel bank height,
- Extent of low-level active floodplain,
- Elevation and extent of higher level inset benches, and
- Width of top of macro channel

These data were used in algorithms to produce a carbon copy of these features of the channels within the corridor of the proposed diversion channels. This was done for each diversion, starting with three given lines that defined in planform the location of the:

- thalweg, and the
- left and right upper boundaries of the macro-channel, where it intersected the existing ground surface level (i.e. the upper Bowmans Creek terrace)

These sets of three lines (one set for each of the two proposed diversion channel) were supplied to Fluvial Systems by Evans and Peck and Hyder Consulting, after consultation with the design team. The elevation of the thalweg profiles was based on the surveyed thalweg profiles of the existing channels (from 2008 Pegasus Technical survey). These profiles were shortened by removing the lower 65 m from the Western diverted reach and removing 540 m from the Eastern diverted reach (**Figure 3.1**). This involved shortening the mid-reach shallow pool and not replicating the upstream pool in the diversion channel, but rather, retaining this pool in its current position as an active pool by locating the upper block bank at the downstream end of this pool.

The next step in the design process was to draw imaginary transect lines perpendicular to the thalweg at 0.5 m intervals. The location and elevation of the toes of the left and right banks of the low flow channel were then positioned on each transect by an interpolation algorithm that copied the width and elevation of the surveyed existing low flow channel. On the inside of bends, the algorithms automatically positioned the line of the bank toe further from the thalweg compared to the line of the bank of the outside of the bends. The tops of the low flow channel banks were then positioned, followed in a step-wise by the other morphological features that defined the channel. This process generated a series of data strings that defined the boundaries of the above features. These points were then imported to Global Mapper™, spatial analysis software that allowed editing of data where necessary, and creation of a digital terrain model (DTM) of the channels (**Figure**

3.2). Cross-sections were extracted from the DTM and used to develop HEC-RAS 1-D models of the hydraulics of the channels.

The positions of the in-set benches were modified so that they were located on the inside of bends, and the banks at the ends of the channels were shaped to merge with those of the existing channel. Otherwise, the resulting designed channels were as close as possible in geomorphological form to the existing channel sections that they would replace. They had almost identical variability of width and depth.

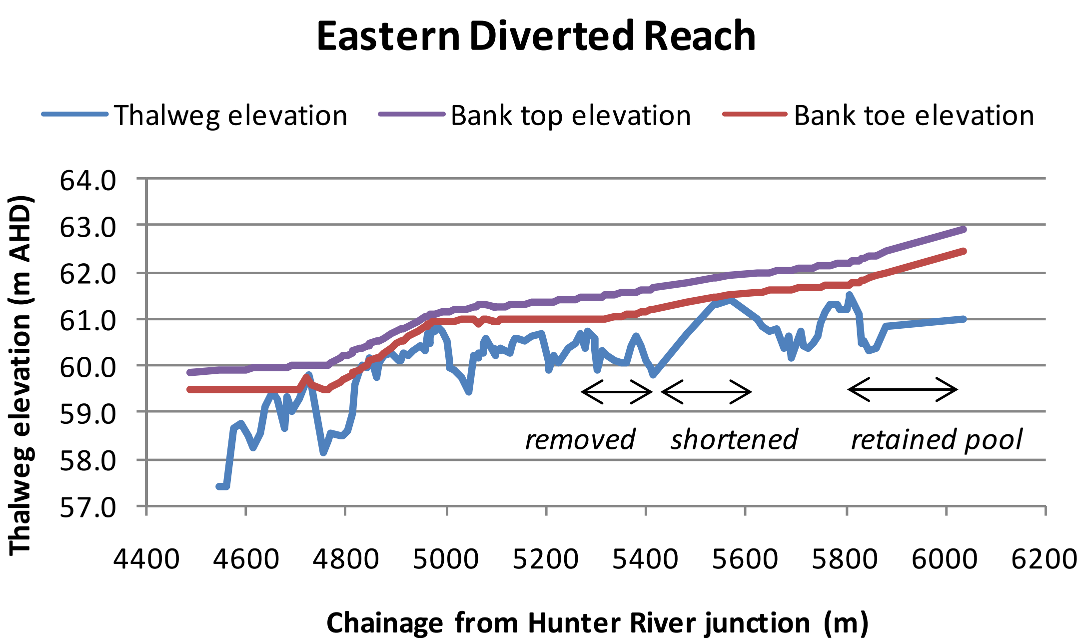


Figure 3.1:
Long profiles of the existing channel reach that would be diverted by the proposed Eastern diversion.
(The bank top and bank toe elevations refer to the low flow channel. In the proposed diversion plan, the top pool would be retained in the backwater of block bank E1).

3.4 Design of Channel Features

It was recommended to the design team that the diversions should contain large woody debris structures, rip-rap protection on the outside of the tighter bends, and large rock positioned within riffles to act as controls against incision. The detailed design of these features was not undertaken as part of the geomorphological design work.

The bed material would be composed of material similar in size to that found in the existing creek.

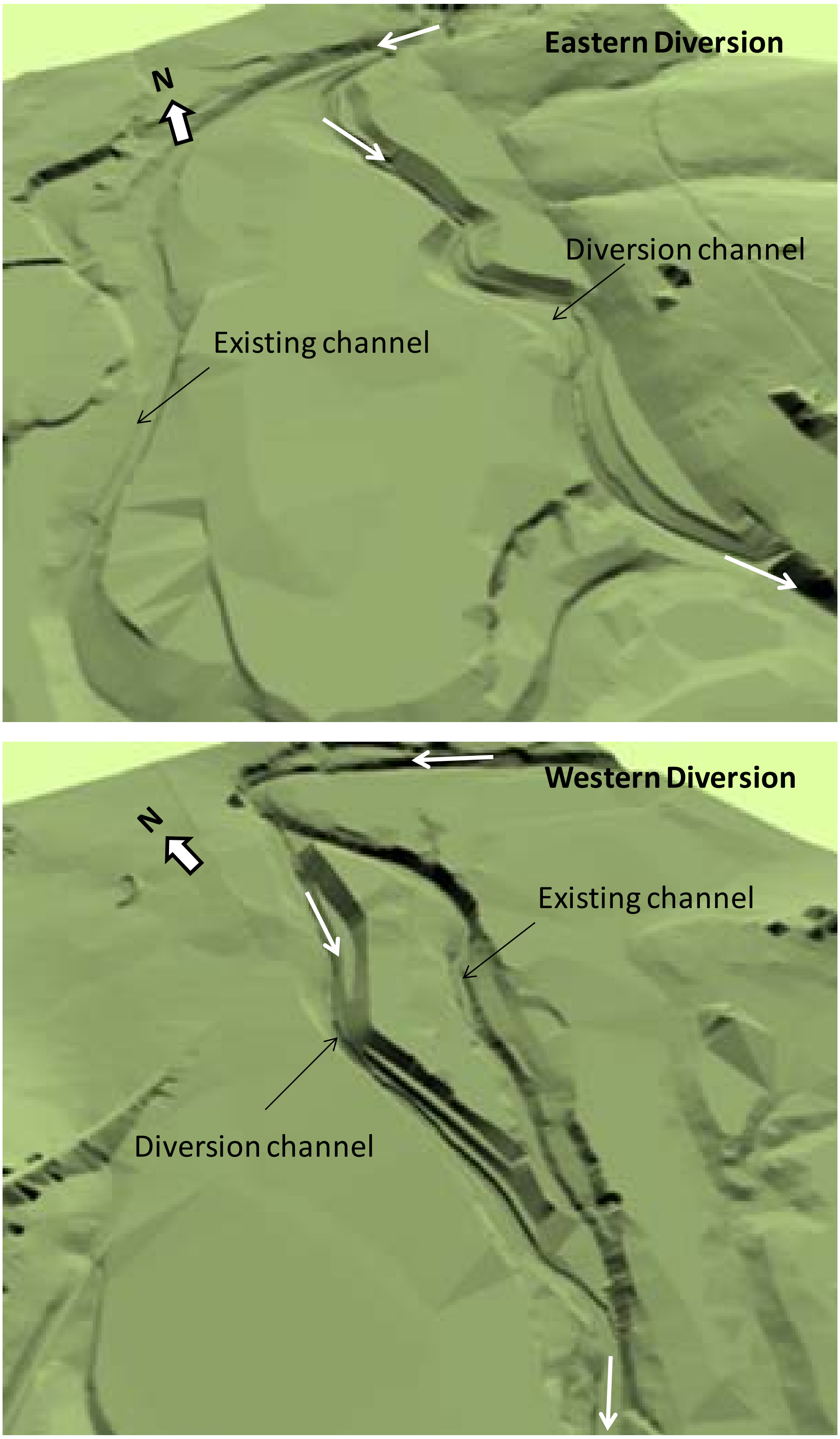


Figure 3.2:
Oblique depiction of the proposed diversion channels and the existing channels.

4 GEOMORPHOLOGICAL IMPACTS OF THE PROPOSAL

4.1 Brief Description of Implementation and Operation of the Proposed Diversions

The diversions will take all flows in Bowmans Creek lower in magnitude than the 1 in 5 year ARI event. This means that the existing creek will be deprived of these flows. For flows exceeding the 1 in 5 year ARI event, flows will be spilt between the diversion channels and the existing channel. Although the existing channel will be inundated by these higher events, the existing channel will convey a minor percentage of the discharge compared to that passing down the diversions. The diversion process will be staged, so that initially a greater proportion of the high flow events will be passed down the existing channel. This will allow time for the vegetation in the diversion channels to establish, after which time the diversion channels will be more stable.

The existing channel is expected to experience subsidence due to mining. This will modify the morphology of the channel, creating deeper pools than currently exist.

4.2 Diversion Channels

4.2.1 Assessment of bed stability based on bed shear stress

The analysis of potential bed particle mobility indicated a low likelihood of bed material mobility on the sides of the proposed Eastern diversion channel for most of its length (**Figure 4.1**). The stability of the bed to the sides of the diversion channel (gravel bars and low floodplain) would be enhanced by complete vegetative cover. For the 1 yr to 5 yr ARI events the central channel bed would be close to the threshold of entrainment or above the threshold (**Figure 4.1**). There was one predicted point of significantly higher bed instability on the crest and downstream side of the riffle at the lower end of the diversion, near where it would enter the existing channel (**Figure 4.1**). This area would need to be reinforced with a grade control structure to prevent excessive scour. Apart from this one point of high shear stress, the predicted relative stability of the bed of the channel of the proposed Eastern diversion was similar to that of the reach of the existing channel that would be diverted, although a direct comparison was not possible because fewer, and generally more widely spaced, transects were available for the existing channel (**Figure 4.1**).

The analysis of potential bed particle mobility indicated a high likelihood of mobility for exposed bed material on the sides of the proposed Western diversion channel for events ≥5 year ARI event (**Figure 4.2**). The stability of the bed to the sides of the diversion channel (gravel bars and low floodplain) would be enhanced by complete vegetative cover. For all modelled ARI events the central channel area would be unstable (**Figure 4.2**). The predicted relative stability of the bed of the channel of the proposed western diversion was similar to that of the reach of the existing channel that would be diverted, although a direct comparison was not possible because fewer, and generally more widely spaced, transects were available for the existing channel (**Figure 4.2**). The existing channel probably has a number of locations experiencing higher shear stress values than appeared in the modelled data – these values did not appear because transects were not available for these likely locations.

4.2.2 Assessment of bank stability based on maximum permissible velocity

The analysis of bank stability potential indicated a low likelihood of bank instability for the proposed Eastern diversion for all modelled flows (**Figure 4.3**). Bare banks would be unstable in some areas for events with a frequency of ≥5 years ARI. The banks of the channel of the eastern diversion were predicted to be more stable than those of the reach of the existing channel that would be diverted (**Figure 4.3**), although a direct comparison was not possible because fewer, and generally more widely spaced, transects were available for the existing channel.

The analysis of bank stability potential indicated a low likelihood of bank instability for the proposed Western diversion for all modelled flows (**Figure 4.4**). Bare banks would be unstable in some areas for events with a frequency of ≥5 years ARI. The banks of the channel of the western diversion were predicted to be generally more stable than those of the reach of the existing channel that would be diverted (**Figure 4.4**), although a direct comparison was not possible because fewer, and generally more widely spaced, transects were available for the existing channel.

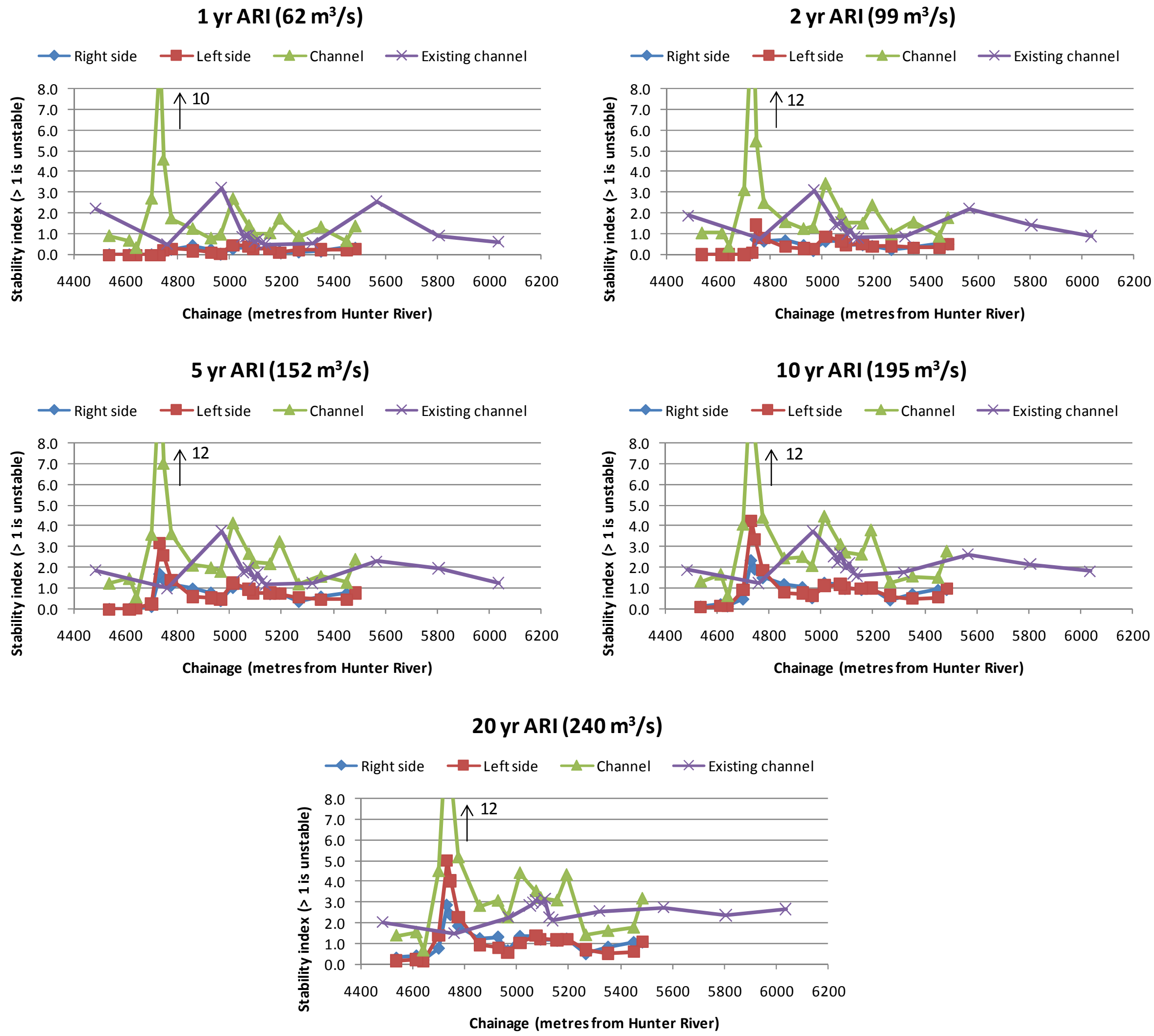


Figure 4.1:
Proposed Eastern Diversion Bed Stability Index for a range of ARI events, compared with values for the existing channel in the reach to be diverted

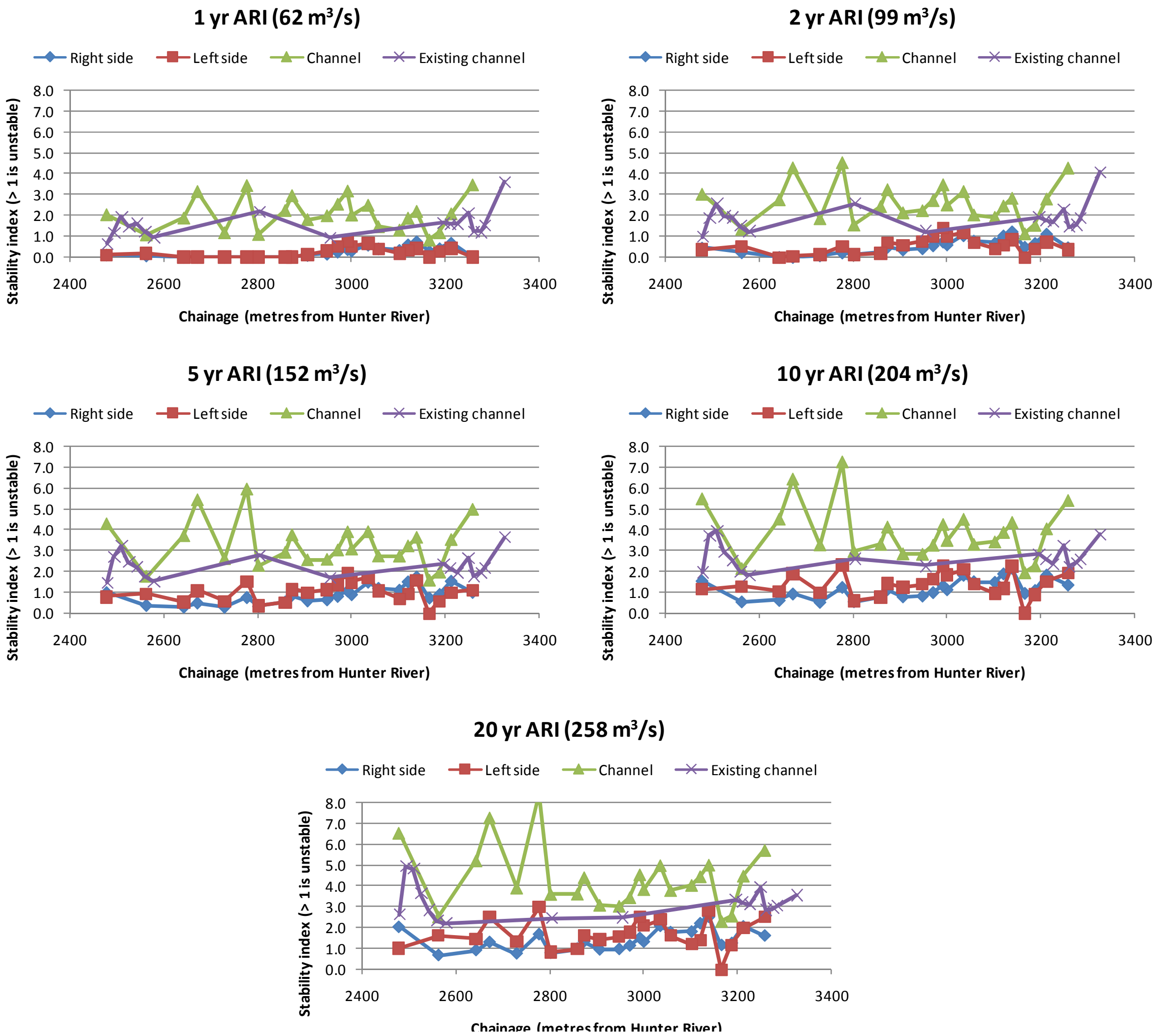


Figure 4.2:
Proposed Western Diversion Bed Stability Index for a range of ARI events, compared with values for the existing channel in the reach to be diverted

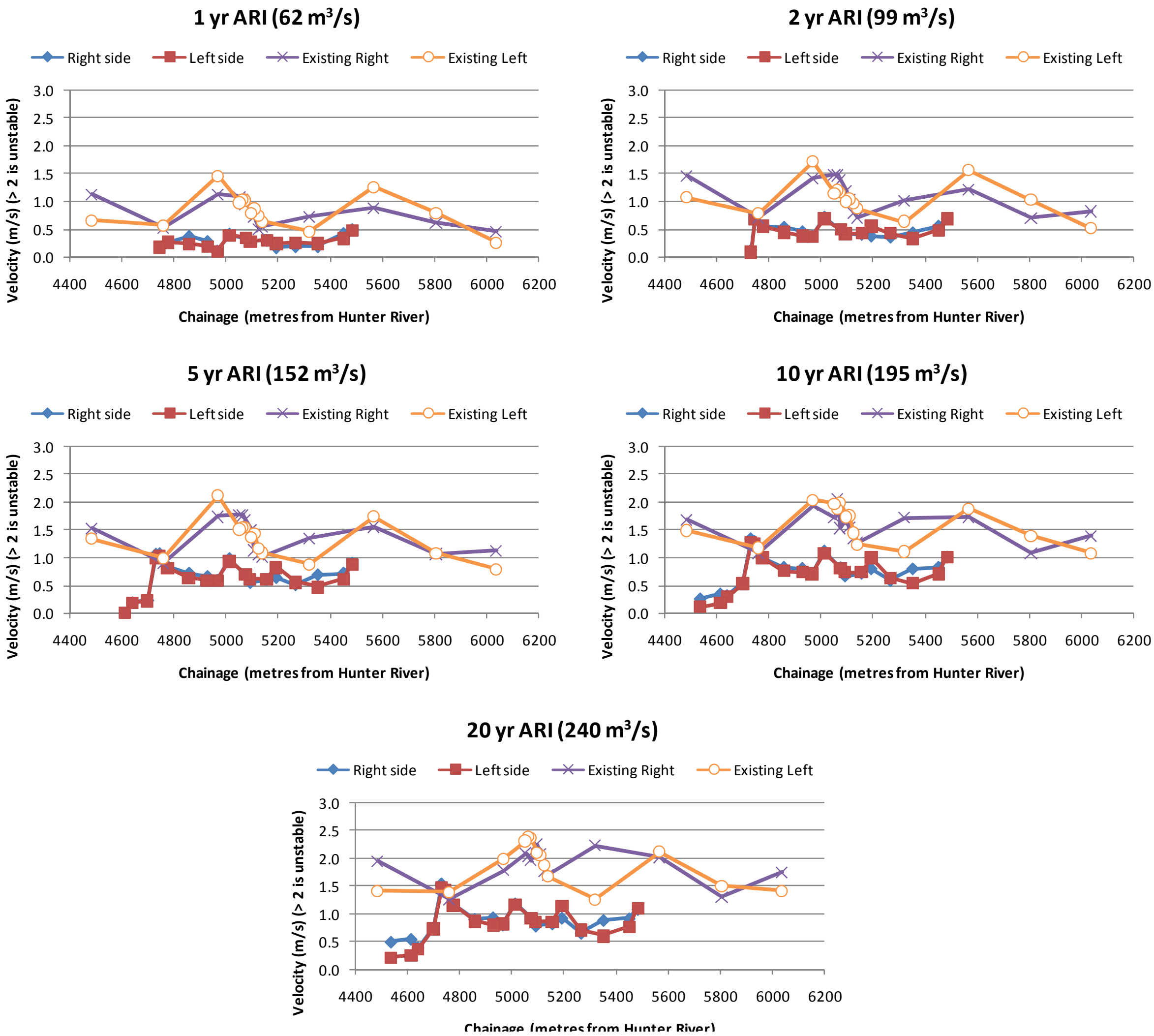


Figure 4.3:
Proposed Eastern Diversion Bank Stability Index for a range of ARI events, compared with values for the existing channel in the reach to be diverted

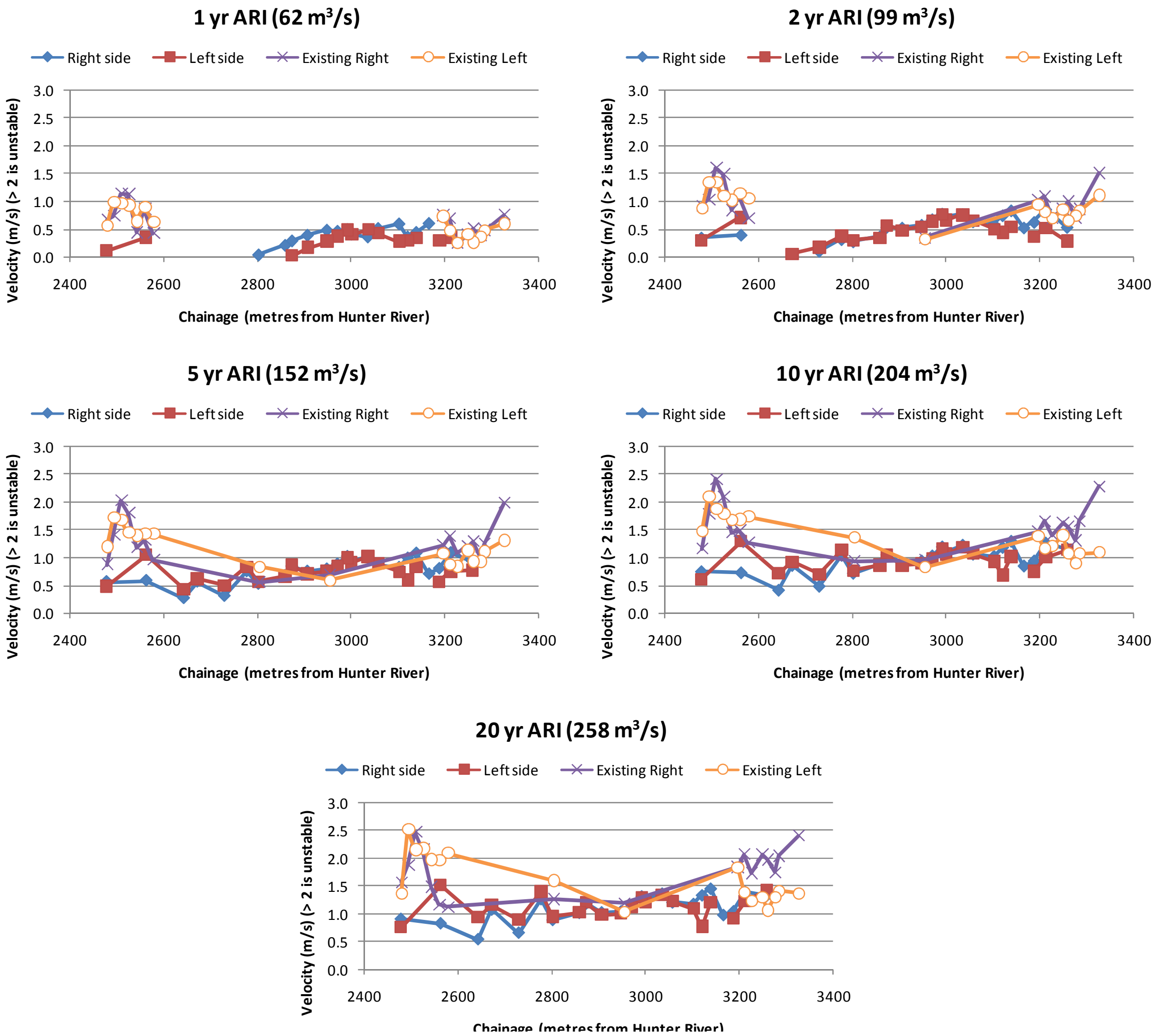


Figure 4.4:
Proposed Western Diversion Bank Stability Index for a range of ARI events, compared with values for the existing channel in the reach to be diverted

4.2.3 Modelled bed scour

An understanding of potential channel bed scour depth is an important consideration for the proposed diversion channels because the bed material of the channel would be of a finite depth (600 mm is proposed). Scour depths greater than this would be undesirable and result in the bed of the diversion being scoured down to the underlying geotextile layer and risking damage to the layer.

Mean and maximum active bed layer scour depth, and mean and maximum general scour depth was estimated using a range of equations. Some of these were discharge or shear stress dependent, and therefore varied with discharge, while others were largely dependent on particle size of the bed material and were invariant with discharge (**Figure 4.5** and **Figure 4.6**). Active layer scour depth was less than general scour depth. General scour depth was of the same order as the planned variations in bed elevation (**Figure 4.5** and **Figure 4.6**). Active layer scour depth was predicted to be shallow, of the order of 0.1 – 0.3 m at most, although some equations dependent of Shields shear stress predicted higher scour depths in the proposed western diversion for the higher discharges (**Figure 4.6**). A 600 mm depth of gravel/cobble bed material is generally appropriate for the diversion channels. The predicted scour depths in the diversion channels were similar to those predicted for the existing channel (**Figure 2.20**).

Using the relationship of Caamaño et al. (2009), not all of the 8 pools identified in both the Eastern and Western had potential for velocity reversal (velocity in the pool higher than that in the downstream riffle at high flow) (**Figure 2.21**). Compared to the relationship of Caamaño et al. (2009), the 1-D HEC-RAS model predicted a similar number of pools, or less pools, would have velocity reversal. There would be considerable uncertainty in these results, but they do indicate that pools in the creek have the capacity to be self-sustaining.

The pool depths reported by Abbe and Montgomery (1996) (1.1 – 1.4 m) were associated with ELJs of much greater size than those intended for the Bowmans Creek diversion channels, so the pool depths on Bowmans Creek would likely be less. The depth of the local scour pools will depend on the configuration of the ELJs. Scour depth is best estimated at the time when the detailed design of the ELJs is undertaken (the design will depend to some extent on the availability of logs). However, it is likely that the scour depth associated with ELJs on Bowmans Creek would be less than 1 metre (the structures can be sized to limit the scour to this, or any other, depth).

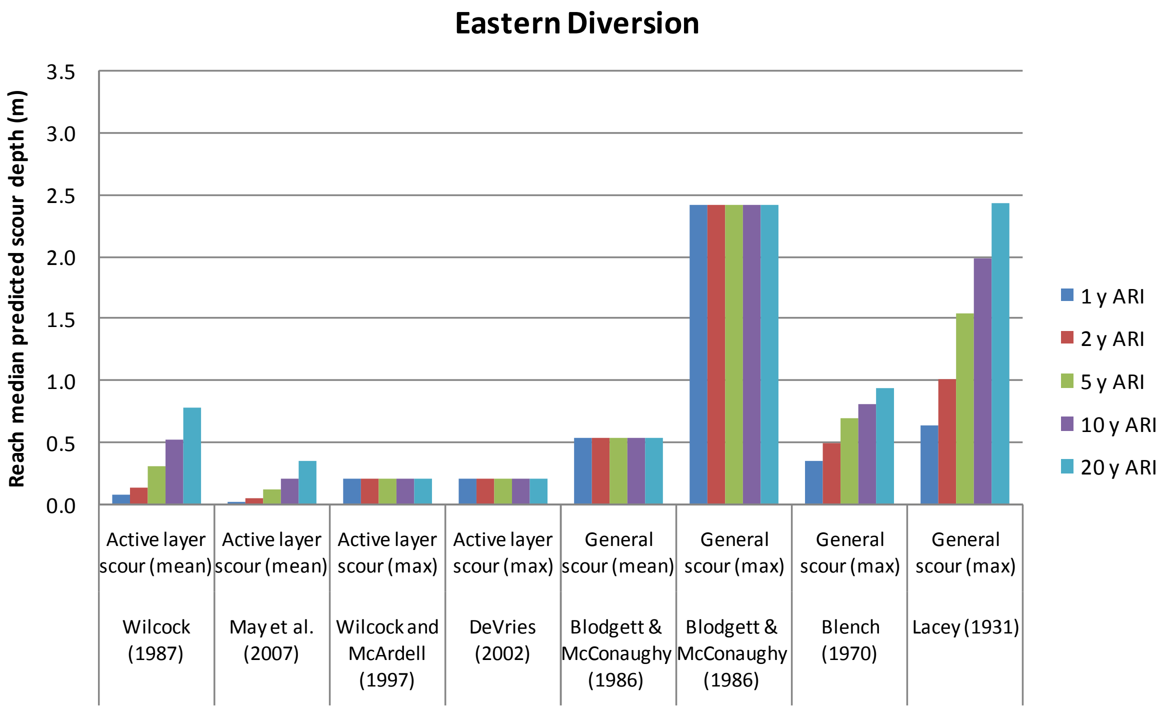


Figure 4.5:
Calculated reach median values of a range of active layer and general scour predictions for the proposed Eastern Diversion.

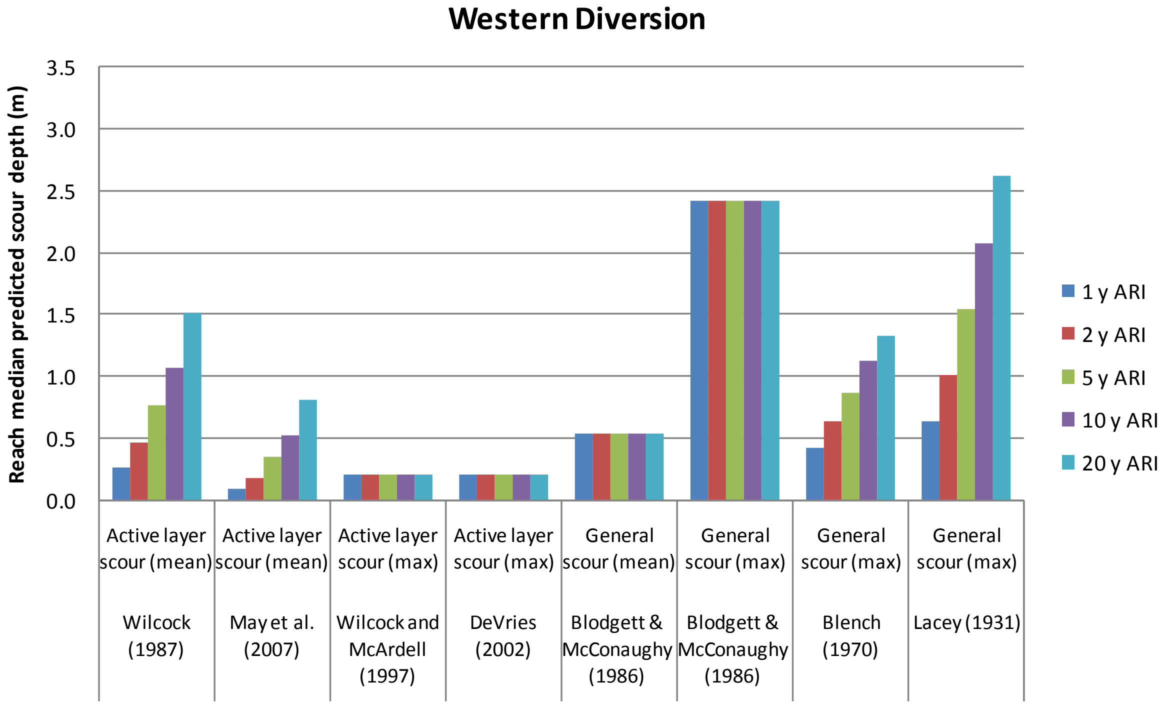


Figure 4.6: Calculated reach median values of a range of active layer and general scour predictions for the proposed Western Diversion.

4.3 Existing Channel and Terrace

Fluvial geomorphological processes in the existing channel under the scenario with the diversions in place were not modelled. This was not considered necessary, because the sections of existing channel that are diverted will not experience high flow rates – all flows <5 year ARI and the majority of higher flows will pass down the diversion channels. The major morphological change will be due to subsidence.

The sections of existing channel that are diverted will become relatively inert from a fluvial geomorphology perspective. The lack of frequent flood events will mean that the bed material will become stabilised and the channel overgrown. When a flood event >5 year ARI occurs in Bowmans Creek and a proportion of the flows overflow into the existing channel, the flow rates within the section of existing channel will be low, and velocities and shear stresses will also be relatively low. Bed sediment mobilisation is not likely, and there will be no sediment transport through the reach due to the block banks preventing entry and exit of bed material.

In summary, in terms of hydrology, hydraulics and fluvial geomorphology, the sections of existing channel that are diverted will undergo a major change of character, and the natural stream processes will not operate like they do in the existing creek.

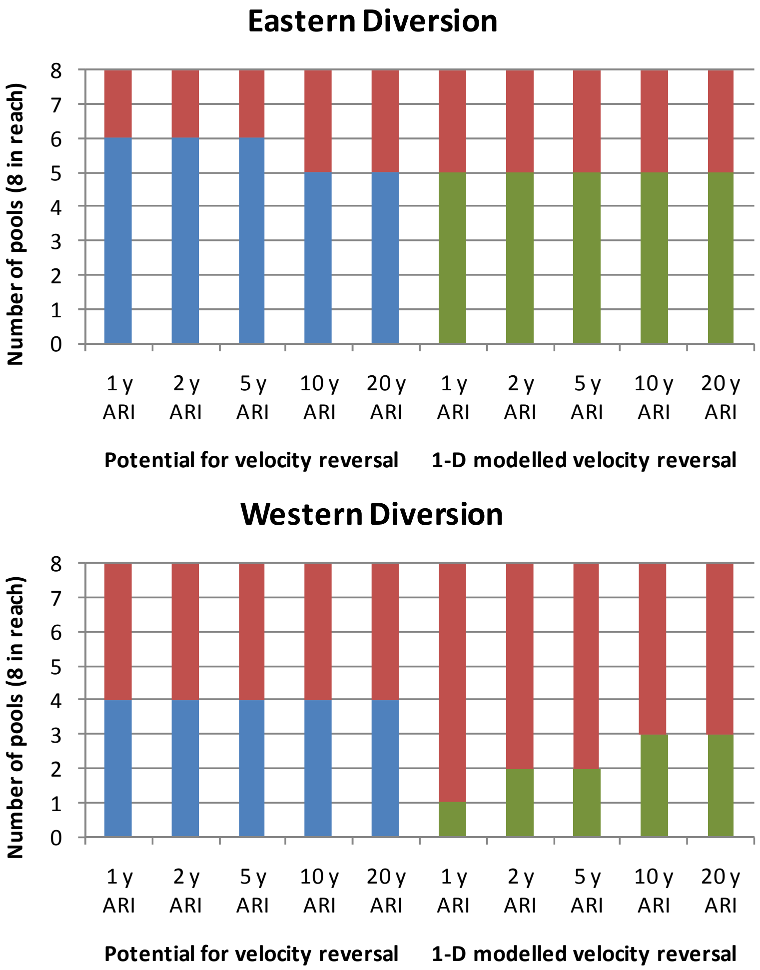


Figure 4.7:
Predicted number of pools with potential for velocity reversal [relationship of Caamaño et al. (2009)] and number of pools showing velocity reversal in 1-D model for the proposed Eastern and Western Diversion channels.

4.4 Implications of Natural Incision Trajectory for Diversions

As established in this report, Bowmans Creek remains on a trajectory of incision and widening. The rate of channel change appears to be relatively slow, as catastrophic changes did not occur in association with the major flood event of June 2007.

The diversion channels have been designed to have similar levels of stability as the existing creek. Thus, the diversion channels can be expected to change in morphology at the same rate as the existing creek.

4.5 Probability of Avulsion

In the foreseeable future, Bowmans Creek would be highly unlikely to adopt an alternative alignment to that of the proposed diversion channels. While the channel will continue to move within the defined diversion macro-channel corridor, and the side slopes of that macro-channel may occasionally erode as the channel widens its corridor, the chance of an avulsion under high flood conditions is remote.

Avulsions typically occur on highly sinuous and low gradient streams, perched on an active (frequently flooded) floodplain. Bowmans Creek is incised into a terrace and contains most of the flow during high flood events, so there is little spare energy available to cut a new course through the terrace.

In the future there might be a "line of weakness" on the terrace, following the boundary between the part of the terrace that suffered little or no subsidence and areas that suffered significant subsidence. The subsided areas would be partially filled to create a free draining landscape on the terrace (an existing condition of consent). The filled area would presumably be rehabilitated to have a similar vegetative cover as the rest of the terrace surface, so the weakness would arise from the potential for flow concentration. While a small channel could erode in this area, it would not become an alternative major flow path for Bowmans Creek.

5 MITIGATION MEASURES

As the analog (carbon copy) approach was taken to design of the geomorphic aspects of the proposed diversion channels, there are few issues of concern for the geomorphic integrity of the stream channels. The proposed diversion channels will function in a similar way to the existing channel, although there will be some key differences:

1. The proposed Eastern diversion is significantly shorter and steeper than the reach of the existing creek that it is intended to replace. This has consequences for the stability of the diversion channel at the downstream end.

   Mitigation measure: A grade control structure will be constructed to prevent scour of the channel bed.

2. The proposed diversion channels will have more large wood structures than the existing channel, and these will create more local scour pools than are in the existing channel. There is a risk of deep scour holes forming to the proposed full depth of the bed material (600 mm).

   Mitigation measure: A locally thicker bed layer will be provided in the areas where local scour pools are predicted to occur.

3. The diversion channels will be similarly active as the existing channel, which means that the channels will undergo change in shape and location through time. Some sections of the diversion channels will possibly be subject to higher rates of banks and bed scour, due to the inclusion of tighter bends and steeper overall gradient in the diversion channels compared to the existing channels.

   Mitigation measures: (i) Rates of change will be slowed on the outside banks of bends by using rock beaching; (ii) The positions of riffle will be stabilised using rock bars; (iii) Other surfaces will be protected using jute matting (or similar) in combination with natural vegetation cover; (iv) The diversion will be staged, so that events with high scour potential do not enter the diversion until the plants have become established (full ground coverage).

The matter of how to best construct the suggested grade control structure on the downstream end of the Eastern diversion is best dealt with by engineering design specialists, but some broad recommendations can be made. Various types of grade control (or drop) structure are used in streams, but for Bowmans Creek a section of roughened channel is recommended. This is a steep section of channel that has been engineered and constructed to provide sufficient roughness and hydraulic diversity to enable fish passage despite its steepness. A roughened channel provides grade control at a gradient steeper than the rest of the diversion channel. The bed material is of a size large enough that it is a fixed semi-rigid structure. Individual rocks would be expected to adjust their position and location, but there should be minimal degradation of the structure over time. The roughened channel design would use channel dimensions, slope, and material to create depths, velocities, low turbulence, and a hydraulic profile suitable for fish passage. The life-span of the structure will depend on its design. If it is designed to withstand the 100 year event, then it will be stable until an event larger than this occurs. If the grade control structure is ever damaged, a re-assessment of the hydraulic conditions in Bowmans Creek (including the diversion) will be required, as conditions may have altered sufficiently that a re-design is necessary.

6 SUGGESTED MONITORING PROGRAM

The objectives of monitoring the geomorphology of the diversion channels would be:

1. To determine if the stability of the diversion channels remains within the range of stability observed on the undiverted Bowmans Creek channel.
2. To determine if the variability of channel forms and character of channel forms in the diversion channels remains within the range observed on the undiverted Bowmans Creek channel.
3. To determine if the bed material particle size distribution in the diversion channels remains within the range observed on the undiverted Bowmans Creek channel.

These objectives can be met through the following monitoring program:

1. Establish 10 cross-sections on each of the Western and Eastern diversions
2. Every five years, or following every event greater in magnitude than the 5 yr ARI event (152 m^3/s peak flow):
   - Sample bed material at the 10 cross-sections on the diversion channels using a valid procedure documented in standard geomorphology texts or quality published literature.
   - Carry out the same procedure at the established cross-sections on the existing channel.
   - Report the bed material particle size distribution data.
   - Statistically compare the data from the diversion channels with that from the existing channel.
   - A deviation in the particle size range observed in the diversion channels of greater than 20 percent outside the particle size range observed in the existing channel will trigger an investigation of the cause.
3. Every five years, or following every event greater in magnitude than the 5 yr ARI event (152 m^3/s peak flow):
   - Survey the channel topography in detail at the 10 cross-sections on the diversion channels.
   - Carry out the same procedure at the established cross-sections on the existing channel.
   - Report the channel change at each section (width at a range of elevations, elevation of thalweg, and bank slope).
   - Statistically compare the data from the diversion channels with that from the existing channel.

- A deviation in the morphology indices observed in the diversion channels of greater than 20 percent outside the range observed in the existing channel will trigger an investigation of the cause.

4. Every five years, or following every event greater in magnitude than the 5 yr ARI event (152 m^3/s peak flow):
   - Survey in detail the thalweg profile through the full length of the diversion channels.
   - Carry out the same procedure at the established long profiles on the existing channel.
   - Report the channel change (deviation about the profile, and measures of the shape of the profile that characterise pool-riffle morphology).
   - Statistically compare the data from the diversion channels with that from the existing channel.
   - A deviation in the morphology indices observed in the diversion channels of greater than 20 percent outside the range observed in the existing channel will trigger an investigation of the cause.

Actions in the form of engineering works on the diversion channel, or the existing channel, must be preceded by an investigation that clearly establishes a need for the works. The investigation will require consideration of engineering, fluvial geomorphology and ecology perspectives.

7 CONCLUSION

Bowmans Creek remains on a trajectory of incision and widening, which probably began up to 60 years ago. The rate of incision has been slowed by exposure of a number of bedrock outcrops. Bed material in the channel is predicted to be mobile during flood events of while the grass covered bars, benches and banks are mostly stable.

The physical form of the two diversion channels was designed such that they would be (as close a possible) carbon copies of the sections of the existing channels that they would replace. The rationale for adopting this approach was that the diverted sections of Bowmans Creek should behave similarly to the existing sections that they would replace. Provision of near identical morphology and sediment transport processes would also mean minimal change to the availability of hydraulic habitat for biota.

Analysis of the hydraulics of the proposed channels suggested that they would have similar levels of geomorphic stability as the existing channel. The bed material in the existing channel is predicted to be unstable for flood events of >1 year ARI, which simply means that the bed material has potential to move (the potential for catastrophic channel change is not implied here). The condition of bed instability should not be interpreted as harmful to stream ecology, as occasional bed instability is necessary for proper ecosystem functioning. In a health stream, mobilisation of bed material would be expected to be associated with flows that occur on average every 1 to 3 years, and the modelling suggested that this was the case for Bowmans Creek.

There was one predicted point of significantly higher bed instability on the crest and downstream side of the riffle at the lower end of the eastern diversion, near where it would enter the existing channel. It is proposed that this area be reinforced with a rock grade control structure to prevent excessive scour. The pool-riffle sequence was designed to be a copy of that in the existing channel, but for the Eastern diversion channel some sections of the sequence had to be shortened or removed (due to the diversion channel being shorter than the section of existing channel that it is intended to replace). The designed pool-riffle sequence should remain relatively stable in terms of location and depth variation, as modelling suggests that at least some of the pools have the capacity to be self-sustaining (through velocity reversal effects at times of high flow).

The channel design incorporates elements that will reduce the risk of excessive geomorphic instability. These include one rock grade control structure on the downstream end of the Eastern diversion, rock bars to stabilise the locations of riffles and prevent upstream migrating incision, rock beaching on the outside of meander bends, soft treatments (such as jute matting) on bare surfaces to provide temporary stability until vegetation becomes fully established, and a thicker channel bed sediment layer where local scour holes are expected to form in the vicinity of large woody debris structures.

A monitoring program was recommended to determine the relative stability, the bed material size, and the channel forms of the diversion channels compared to the existing channel.

8 REFERENCES

Abbe, T.B., and Montgomery, D.R. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. *Regulated Rivers: Research & Management* **12**: 201-221.

Andrews, E.D. 1983. Entrainment of gravel from naturally sorted riverbed material. *Bulletin of the Geological Society of America* **94**: 1225–1231.

Benda, L., Poff, N.L., Miller, D., Dunne, T., Reeves, G., Pess, G., and Pollock, M. 2004. The network dynamics hypothesis how river networks structure riverine habitats. *BioScience* **54**(5): 413-427.

Blench T. 1970. Regime theory design of canals with sand beds. *Journal of Irrigation and Drainage Division, ASCE* **96**(IR2): 205–213.

Blodgett, J.C, and McConaughy, C.E. 1986. *Rock Riprap Design for Protection of Stream Channels Near Highway Structures, Volume 2* – Evaluation of Riprap Design Procedures. U.S. Geological Survey, Water-Resources Investigations Report 86-4127, Sacramento, CA.

Brierley, G. and Fryirs, K. 209. Don't Fight the Site: Three Geomorphic Considerations in Catchment-Scale River Rehabilitation Planning. *Environmental Management* **43**: 1201–1218.

Brookes, A. 1996. River Channel Change. In: Petts, G. and Calow, P. (editors) *River Flows and Channel Forms*, Blackwell Science, pp. 221-242.

Buffington, J.M., and Montgomery, D.R. 1997. A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. *Water Resources Research* **33**: 1993–2029.

Chang, H.H. 1988. *Fluvial Processes in River Engineering*. John Wiley and Sons, New York.

Cook, N., and Schneider, G. 2006. *River Styles® in the Hunter Catchment*. NSW Department of Natural Resources, Newcastle.

Caamaño, D., Goodwin, P., Buffington, J.M., Liou, J.C.P. and Daley-Laursen, S. Unifying Criterion for the Velocity Reversal Hypothesis in Gravel-Bed Rivers. *Journal of Hydraulic Engineering* **135**(1): 66-70.

DeVries, P. 2002. Bedload Layer Thickness and Disturbance Depth in Gravel Bed Streams. *Journal of Hydraulic Engineering* **128**(11): 983-991.

DIPNR (Department of Infrastructure, Planning and Natural Resources) 2005. *Stream/Aquifer Guidelines - Management of stream/aquifer systems in coal mining developments, Hunter Region*. Version 1. Department of Infrastructure, Planning and Natural Resources, April.

DNR (Department of Natural Resources) 2006. PINEENA Version 9. New South Wales Surface Water Data Archive. Department of Natural Resources. NSW Government. Available on DVD, using HYDSYS Time Series Management software.

ERM (Environmental Resources Management) 2006. *Bowmans Creek Geomorphology, Pre Mining Assessment*. Environmental Resources Management, Thornton. Ashton Coal Operations Limited, October.

Erskine, W. and Bell, F.C. Rainfall, floods and river channel changes in the Upper Hunter. *Australian Geographic Studies* **20**: 183-196.

Erskine, W.D. 1986. *River metaphorphosis and environmental change in the Hunter Valley, New South Wales*. Unpublished PhD thesis, University of NSW.

Erskine, W.D. and Warner, R.F. 1988. Geomorphic effects of alternating flood- and drought-dominated regimes on NSW coastal rivers. In Warner, R.F. (Ed.), *Fluvial Geomorphology of Australia*, Academic Press, Marrickville, pp. 223-244.

Fischenich, C.J. 2001. *Stability Thresholds for Stream Restoration Materials*. EMRRP Technical Notes Collection (ERDC TNEMRRP-SR-29), U.S. Army Engineer Research and Development Center, Vicksburg, MS.URL: http://el.erdc.usace.army.mil/elpubs/pdf/sr29.pdf (accessed 27 May 2005).

FISRWG (Federal Interagency Stream Restoration Working Group) 1998. *Analysis of corridor condition. Chapter 7 in Stream Corridor Restoration: Principles, Processes and Practices*. National Technical Information Service, U.S. Department of Commerce, Springfield, VA.

Florsheim, J.L., Mount, J.F. and Chin, A. 2008. *Bank erosion as a desirable attribute of rivers*. BioScience 58(6): 519-529.

Folk, R.L. and Ward, W.C. 1957. Brazos River Bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology* **27**(1): 3-26.

Gippel, C.J. 1995. Environmental hydraulics of large woody debris in streams and rivers. *Journal of Environmental Engineering* **121**(5): 338–95.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., Gippel, C.J. and Nathan, R.J. 2004. *Stream Hydrology: An Introduction for Ecologists*. Second Edition, John Wiley & Sons, Chichester.

Hancock, F. 2001. Mining in river corridors – Hunter Valley management requirements. In *Proceedings of the MSTS 5th Triennial Conference, Coal Mine Subsidence 2001, Current Practice and Issues*, Maitland, 26 to 28 August. Mine Subsidence Technological Society, The Institution of Engineers, Australia, pp. 17-24. URL: http://www.mstsociety.org/members/papers/2001/2001_Paper%2017.pdf (accessed 24 September 2009).

Hicks, D.M. and Mason, P.D. 1991. *Roughness Characteristics of New Zealand Rivers*. Water Resources Survey, Department of Scientific and Industrial Research, Marine and Freshwater, Wellington, New Zealand.

Holling, C.S. 1973. Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics* **4**: 1-23.

Institution of Engineers Australia 1987. *Australian Rainfall and Runoff - a Guide to Flood Estimation*. D.H. Pilgrim (ed.), Institution of Engineers, Australia, Barton, ACT.

Karr, J.R. and Freemark, K.E. 1985. Disturbance and vertebrates: an integrative perspective. In Pickett, S.T.A. and White, P.S. (eds) *The Ecology of Disturbance and Patch Dynamics*. Academic Press, Orlando, pp. 153–172.

Keller, E. A. 1971. Areal sorting of bed-load material: The hypothesis of velocity reversal. *Geol. Soc. Am. Bull*. **82**: 753–756.

Kemp, J., Harper, D.M. and Crosa, G.A. 1999. Use of 'functional habitats ' to link ecology with morphology and hydrology in river rehabilitation. *Aquatic Conservation: Marine and Freshwater Ecosystems* **9**: 159-178.

Komar, P.D. 1987. Selective gravel entrainment and the empirical evaluation of flow competence. *Sedimentology* **34**:1165–1176.

Kuczera, G. and Franks, S. 2006. Book IV – Estimation of peak discharges. Draft for review. *Australian Rainfall & Runoff – a Guide to Flow Estimation* (4th Edition). National Committee on Water Engineering, Institution of Engineers, Australia, Barton, ACT. URL: http://www.ncwe.org.au/arr/detail_toc.html (accessed 3 October 2009).

Lacey, G. 1931. Regime diagrams for the design of canals and distributaries. *Technical Paper No. 1*, United Provinces, P.W.D. Irrigation Branch.

Lake, P.S. 1995. Of floods and droughts: river and stream ecosystems of Australia. In Cushing, C.E., Cummins, K.W. and Minshall, G.W. (eds) *River and Stream Ecosystems*. Elsevier, Oxford, pp. 659–694.

Lake, P.S. 2000. Disturbance, patchiness, and diversity in streams. *Journal of the North American Benthological Society* **19**: 573–592.

Leopold, L 1970. *An improved method for size distribution of stream bed gravel*. Water Resources Research 6(5): 1357-1366.

Lester, R.E. and Boulton, A.J. 2008. Rehabilitating Agricultural Streams in Australia with Wood: A Review. *Environmental Management* **42**: 310-326.

Levin, S.A. and Paine, R.T. 1974. Disturbance, patch formation and community structure. *Proceedings of the National Academy of Sciences* **71**: 2744–2747.

Lisle, T.E. 2005. Bed mobility: a key linkage between channel condition and lotic ecosystems. *Eos. Trans. AGU* **86**(18), Jt. Assem. Suppl., Abstract B44B-01. URL: http://www.agu.org/meetings/sm05/sm05-sessions/sm05_B44B.html (accessed 17th November 2007).

Liu, H.K., Chang, F.M. and Skinner, M.M. 1961. Effect of bridge construction on scour and backwater. Department of Civil Engineering, Colorado State University, *Report No. CER60-HKL22.*

Lorang, M.S. and Hauer, F.R. 2003. Flow competence and streambed stability: an evaluation of technique and application. *J. N. Am. Benthol. Soc.* **22**(4):475–491.

Marsh, N., A. Western, R. Grayson, I. Rutherfurd, and B. L. Finlayson. 2001. Enhancing instream habitat with large woody debris: a flume experiment. In I. Rutherfurd, F. Sheldon, G. Brierley, and C. Kenyon (eds) *Third Australian Stream Management Conference*. Cooperative Research Centre for Catchment Hydrology, Brisbane, Australia, pp. 397-402.

Maunsell Australia 2008. *Bowmans Creek Geomorphology Review, Ashton Coal Project*. Maunsell Australia Pty Ltd, Maitland. Ashton Coal Operations Limited, October.

May, C.L., Pryor, B., Lisle, T.E., and Lang, M.M. 2007. Assessing the risk of redd scour on the Trinity River. Report prepared for the Bureau of Reclamation, Trinity River Restoration

Program, Weaverville, CA. 63p. URL: http://csmres.jmu.edu/geollab/may/web/Research/Reprints/Trinity_Scour_Report.pdf (accessed 25 September 2009).

Miller, M.C., McCave, I.N. and Komar, P.D. 1977. Threshold of sediment motion in unidirectional currents. *Sedimentology* **24**:507–528.

Montgomery, D.R. 2002. Hydro-Geomorphic Variability as an Ecological Template for Aquatic and Riparian Ecosystems. *American Geophysical Union*, *Fall Meeting 2002*, abstract #H62F-05. URL: http://adsabs.harvard.edu/abs/2002AGUFM.H62F..05M (accessed 20 July 2008).

New South Wales, Dept. of Public Works 1990. Lower Hunter Valley flood study: Oakhampton to Green Rocks, Maitland City Council, Maitland.

Parsons Brinkerhoff Pty Ltd 2003. Thornton North Master Plan Volume 2 – Background Report. Maitland City Council, Maitland, November. URL: http://www.maitland.nsw.gov.au/UserFiles/File/PlanningDev/CityStrategy/ThorntonNth/Background%20Report.pdf (accessed 12 June 2009).

Patterson Britton & Partners 2001. *Appendix N*, *Bowmans Creek Diversion Report*. Ashton Mining Project, Camberwell. Proposed Diversion of Bowmans Creek. White Mining Limited. Issue 2, October.

Pemberton, E.L. and Lara, J.M. 1984. *Computing Degradation and Local Scour*. Technical Guideline for Bureau of Reclamation. Bureau of Reclamation Sedimentation and River Hydraulics Section, Denver, CO.

Petts, G.E. and Calow, P. 1996. The nature of rivers. In Petts, G. and Calow, P. (eds) *River Restoration*, Blackwell Science, Oxford, pp. 1-6.

Petts, G.E., Large, A.R.G., Greenwood, M.T. and Bickerton, M.A. 1992. Floodplain assessment for restoration and conservation: linking hydrogeomorphology and ecology. In Carling, P.A. and Petts, G.E. (eds) *Lowland Floodplain Rivers: Geomorphological Perspectives*. John Wiley & Sons Ltd, Chichester, pp. 217-234.

Poff, N.L. 1997. Landscape filters and species traits: towards mechanistic understanding and prediction in stream ecology. *Journal of the North American Benthological Society* **16**: 391-409.

Poff, N.L. and Allan, J.D. 1995. Functional organisation of stream fish assemblages in relation to hydrological variability. *Ecology* **76**: 606–627.

Poff, N.L. and Ward, J.V. 1989. Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. *Canadian Journal of Fisheries and Aquatic Sciences* **46**: 1805-1818.

Poff, N.L., Olden, J.D., Pepin, D.M. and Bledsoe, B.P. 2006. Placing global stream flow variability in geographic and geomorphic contexts. *River Research and Applications* **22**: 149-166.

Prosser, I.P., Rutherfurd, I.D., Olley, J.M., Young, W.J., Wallbrink, P.J. and Moran, C.J. 2001. Large-scale patterns of erosion and sediment transport in river networks, with examples from Australia. *Marine and Freshwater Research* **52**(1): 81-99.

Rahman, A. and Hollerbach, D. 2003. Study of Runoff Coefficients Associated with the Probabilistic Rational Method for Flood Estimation in South-east Australia In *Proc. 28th Intl. Hydrology and*

Water Resources Symp., I.E. Aust., Wollongong, Australia, 10-13 Nov. 2003, Vol. 1, pp. 199-203.

Raine, A.W. and Gardiner, J.N. 1995. Rivercare: *Guidelines for Ecologically Sustainable Management of Rivers and Riparian Vegetation*. Land and Water Resources Research and Development Corporation, Canberra.

Reddoch, A.F. 1957. River control work in the non-tidal section of the Hunter River and its tributaries. *Journal of the Institution of Engineers, Australia* **29**: 241-247.

Resh, V.H., Brown, A.V., Covich, A.P., Gurtz, M.E., Li, H.W., Minshall, G.W., Reice, S.R., Sheldon, A.L., Wallace, J.B. and Wissmar, R.C. 1988. The role of disturbance in stream ecology. *Journal of the North American Benthological Society* **7**: 433-455.

Rijal, N and Rahman, A. 2005. Design Flood Estimation in Ungauged Catchments: Quantile Regression Technique And Probabilistic Rational Method Compared. In Zerger, A. and Argent, R.M. (eds) *MODSIM 2005 International Congress on Modelling and Simulation*. Modelling and Simulation Society of Australia and New Zealand, December 2005, pp. 1887-1893. URL: http://www.mssanz.org.au/modsim05/papers/rijal.pdf (accessed 30 June 2009).

Sear, D.A. 1996. The sediment system and channel stability. In Brookes, A. and Shields, F.D. Jr (Eds) *River Channel Restoration-Guiding Principles for Sustainable Projects*. John Wiley & Sons, Chichester, pp. 149-177.

Shields, F.D. Jr, Knight, S.S. and Cooper, C. 2000. Cyclic perturbation of lowland river channels and ecological response. *Regulated Rivers: Research & Management* **16**: 307-325.

Sinclair Knight & Partners Pty Ltd 1981. NSW Coastal Rivers Flood Plain Management Studies - Hunter Valley, N.S.W. Coastal Rivers Flood Plain Management Studies Steering Committee, Department of Public Works, Sydney.

Singleton Shire Council 1984. Singleton Floodplain Management Study. Cameron McNamara Consultants, April.

Skidmore, P.B., Shields, F.D., Doyle, M.W. and Miller, D.E. 2001. Categorization of Approaches to Natural Channel Design. In: *Proceedings of the ASCE Wetlands Engineering and River Restoration Conference*, Reno, NV.

Spink, A., Fryirs, K., Brierley, G. and Lloyd, K. 2007. An interdisciplinary perspective of riverwork projects in the Upper Hunter Catchment, NSW: has river rehabilitation begun? In Wilson, A.L., Dehaan, R.L., Watts, R.J., Page, K.J., Bowmer, K.H., and Curtis, A. 2007. *Proceedings of the 5th Australian Stream Management Conference*. Australian rivers: making a difference. Charles Sturt University, Thurgoona, New South Wales, pp. 378-383.

Townsend CR. 1989. The patch dynamics concept of stream community structure. *Journal of the North American Benthological Society* **8**: 36–50.

Wallerstein, N.P. 2003. Dynamic model for constriction scour caused by large woody debris. *Earth Surface Processes and Landforms* **28**: 49-68.

Ward, J.V. and Stanford, J.A. 1983. The intermediate-disturbance hypothesis: an explanation for biotic diversity patterns in lotic ecosystems. In Fontaine, T.D. III and Bartell, S.M. (eds) *Dynamics of Lotic Ecosystems*. Ann Arbor Science Publishers, Ann Arbor, Michigan, pp. 347-356.

Webb, McKeown & Associates Pty Ltd 1998. Lower Hunter Valley (Oakhampton to Green Rocks), Supplementary Flood Study, City of Maitland, Maitland, October.

Wilcock, P.R. 1997. The components of fractional transport rate. *Water Resour. Res*. **33**: 247–258.

Wilcock, P.R., and McArdell, B.W. 1997. Partial transport of a sand/gravel sediment. *Water Resour. Res*. **33**: 235–245

Wilcock, P.R., Barta, A.F., Shea, C.G., Kondolf, G.M., Matthews, W.V.G., and Pitlick, J. 1996. Observations of flow and sediment entrainment on a large gravel-bed river. *Water Resour. Res*. **32**: 2897–2909.

Yalin, M.S. and Karahan, E. 1979. Inception of sediment transport. *Journal of Hydraulics* **105**: 1433–1443.