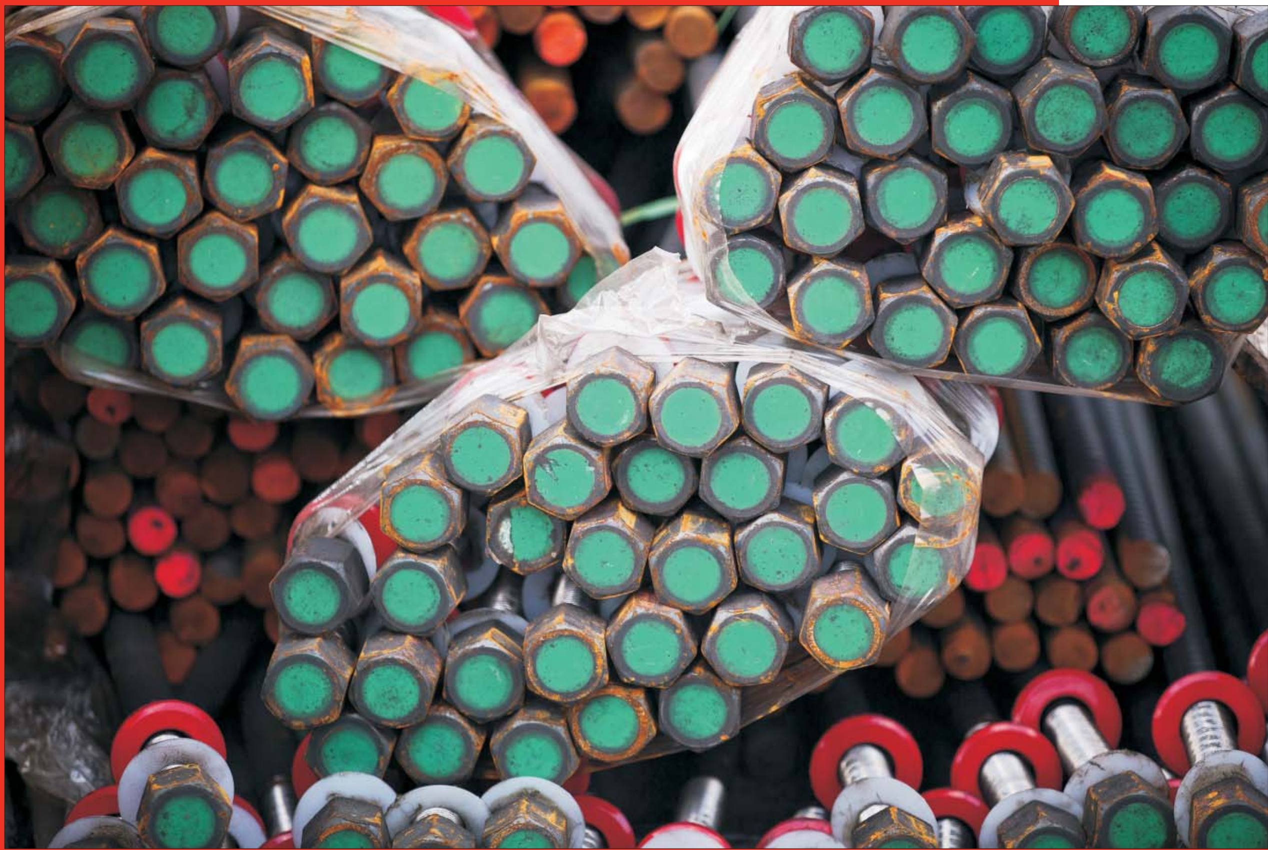

Tasman Extension Project

Environmental Impact Statement

APPENDIX D

GEOMORPHOLOGY ASSESSMENT

Resource Strategies

DONALDSON COAL

Part of Gloucester Coal

Tasman Extension Project Stream Risk and Impact Assessment: Fluvial Geomorphology

Dr Christopher J Gippel

For

Evans & Peck, Resource Strategies,

Donaldson Coal

March 2012

FLUVIAL SYSTEMS

GEOMORPHOLOGY • CATCHMENT HYDROLOGY
RIVER REHABILITATION • ENVIRONMENTAL FLOWS

Tasman Extension Project Stream Risk and Impact Assessment: Fluvial Geomorphology

Evans & Peck, Resource Strategies, Donaldson Coal

by Dr Christopher J Gippel

Fluvial Systems Pty Ltd

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Table of Contents

1 Introduction

1.1 Background

Donaldson Coal Pty Limited's (Donaldson Coal's) existing approved operations are located within the Newcastle Coalfield and include:

- Tasman Underground Mine;
- Donaldson Open Cut Mine; and
- Abel Underground Mine.

Donaldson Coal has proposed an extension of underground mining operations at the existing Tasman Underground Mine (the Tasman Extension Project [the Project]).

As part of the Environmental Impact Statement (EIS) for the Project, and in accordance with the Director-General's Requirements, Fluvial Systems Pty Ltd was engaged to characterise geomorphological character of streams in the Project area, and assess the potential impacts to geomorphological character from the Project. The findings of the assessment are summarised in this report.

The findings of this report have drawn on the information detailed in the *Subsidence Assessment* prepared by Ditton Geotechnical Services (2012) (Appendix A to the EIS), and have contributed to the *Surface Water Assessment* prepared by Evans and Peck (2012) (Appendix C to the EIS).

1.2 Scope of this report

The key tasks of this report are to:

- Identify significant natural stream features that might be at risk from subsidence impacts that could be expected from the proposal
- Assess potential subsidence-related impacts and consequences on natural stream features
- Recommend, if necessary, actions designed to mitigate risks to stream geomorphology associated with subsidence
- Prescribe an appropriate monitoring regime to detect impact of the proposal to stream geomorphology, and to measure the effectiveness of mitigation actions

This report characterizes the fluvial geomorphological features within the extent of the Proposed West Borehole Seam Workings (herein referred to as the Project area). Potential impacts of the proposal were assessed on the basis of subsidence predictions by Ditton Geotechnical Services (2012).

2 Methodology

2.1 General approach

Characterisation of the fluvial geomorphology of the Project area was approached at two measurement scales:

1. Geomorphic stream type (lengths of stream at the reach-scale, usually 1,000s and 100s of metres, consistent in terms of connectivity with the surrounding valley, bed material, and channel form)
2. Geomorphic feature (characteristic physical features of streams at the cross-section- and reach-scale, usually 100s and 10s of metres)

An approach, based on standard methods, was devised to classify streams of the Project area according to geomorphic type, and to measure the geomorphic features of the streams at the cross-section and reach-scale. This report provides sufficient technical information such that the methodology could be repeated in the Project area at a later time by a third party. Also, the primary and secondary data from the work are provided here in sufficient detail to allow a comparison of future geomorphological character with benchmark (current) geomorphological character.

Characterisation of the fluvial geomophological features of the Project area was based on a combination of field survey and desktop analysis of existing data. The field survey was undertaken by Dr Christopher Gippel of Fluvial Systems Pty Ltd over the period 4th to 9th April 2011.

2.2 Definition of the study area

The primary Project area was interpreted as the perimeter of the proposed mine workings (panels), as this is the area that is under the direct influence of mining, and most impacted by subsidence. The limit of subsidence was considered to correspond with the modelled extent of 2 mm subsidence, as determined by Ditton Geotechnical Services (2012). The boundary for the Project area was determined as the perimeter of the panels or expanded to the 2 mm subsidence contour if it was outside the extent of the panels (Figure 1).

There are historical and current workings around Mt Sugarloaf in the shallower Fassifern seam, in the vicinity of the proposed Project. These workings have limited coincidence with streams in the Project area (Figure 1).

As well as the proposed West Borehole Seam workings Project area, the study area also included the catchment within which the Project area was situated (Figure 1). This was included because understanding the fluvial geomorphology of a stream requires a catchment perspective. In other words, the geomorphological characteristics and behavior of a stream in its lower reaches are partly a reflection of processes in the headwaters.

The principle for extending the area under consideration beyond the proposed West Borehole Seam workings Project area was to follow any streamline upstream to one of:

- the head of the stream, or
- where the stream channel became indistinct,

and downstream to one of:

- where the stream joined another stream,
- where the stream met a major artificial boundary such as a road, or

- where the marginal benefit of additional data would be small because the stream was unlikely to change its character for a reasonable distance downstream.

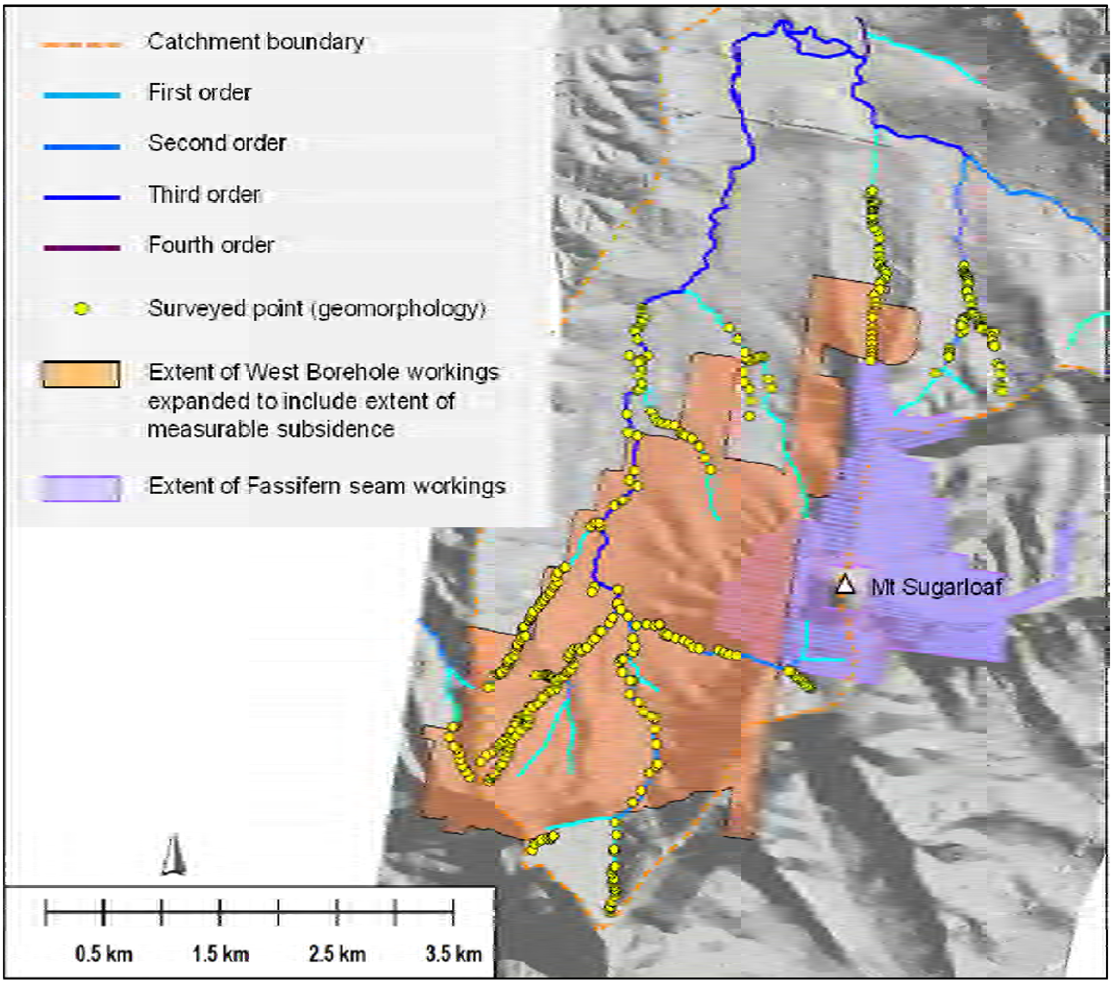

Figure 1. Streams (blue lines on 1:25,000 topographic sheet) within Surveyors Creek catchment in the study area classified by Strahler stream order. Locations of the 385 points included in the fluvial geomorphology field survey are indicated. Also shown is the extent of the proposed West Borehole Seam workings, expanded to include the extent of measurable subsidence (if outside boundary of mine workings). The extent of current and past workings in the shallower Fassifern seam is also indicated.

2.3 Definition of the stream network

The stream network was defined as those streams marked with a blue line on the 1:25,000 Topographic Map Series, covered here by Wallsend 9232-S and Beresfield 9232-3N sheets. The digital streamline layer (Land and Property Information, NSW Government) was different to the blue line network on the printed topographic sheets. The digital layer comprised more streamlines, and most of the streamlines did not join to another. The field survey revealed that both the digital and printed layers had deficiencies in representing streamlines. This problem was resolved by using field data to correct (where this was necessary, and where data were available) the streamlines represented on the 1:25,000 topographic sheets. Some additional small drainage lines were observed on aerial images, and on the ground, that were not marked on the 1:25,000 topographic sheets. These drainage lines were not included in the stream network.

The streams in the Project area drain in a general northerly direction from upper Surveyors Creek, which joins Wallis Creek to the north of the Project area. Wallis Creek joins the Hunter River at Maitland. A short length of Wallis Creek headwater stream also lies within the Project area. This creek flows west into Wallis Creek.

The streamlines were assigned names according to the convention that the east-west aligned arm of Surveyors Creek to the north of the Project area was given the name Surveyors Creek 1 (S1), while the south-north aligned arm running through and to the west of the Project area was given the name Surveyors Creek 2 (S2). None of the tributaries are named on maps, so they were assigned names according to the convention that a tributary joining directly to Surveyors Creek 1 or Surveyors Creek 2 was assigned a unique letter from the alphabet, and then any tributary joining directly to that tributary was given a second unique letter from the alphabet. The headwater stream flowing west of Surveyors Creek into Wallis Creek was named Wallis Creek 1 (W1) (Figure 2).

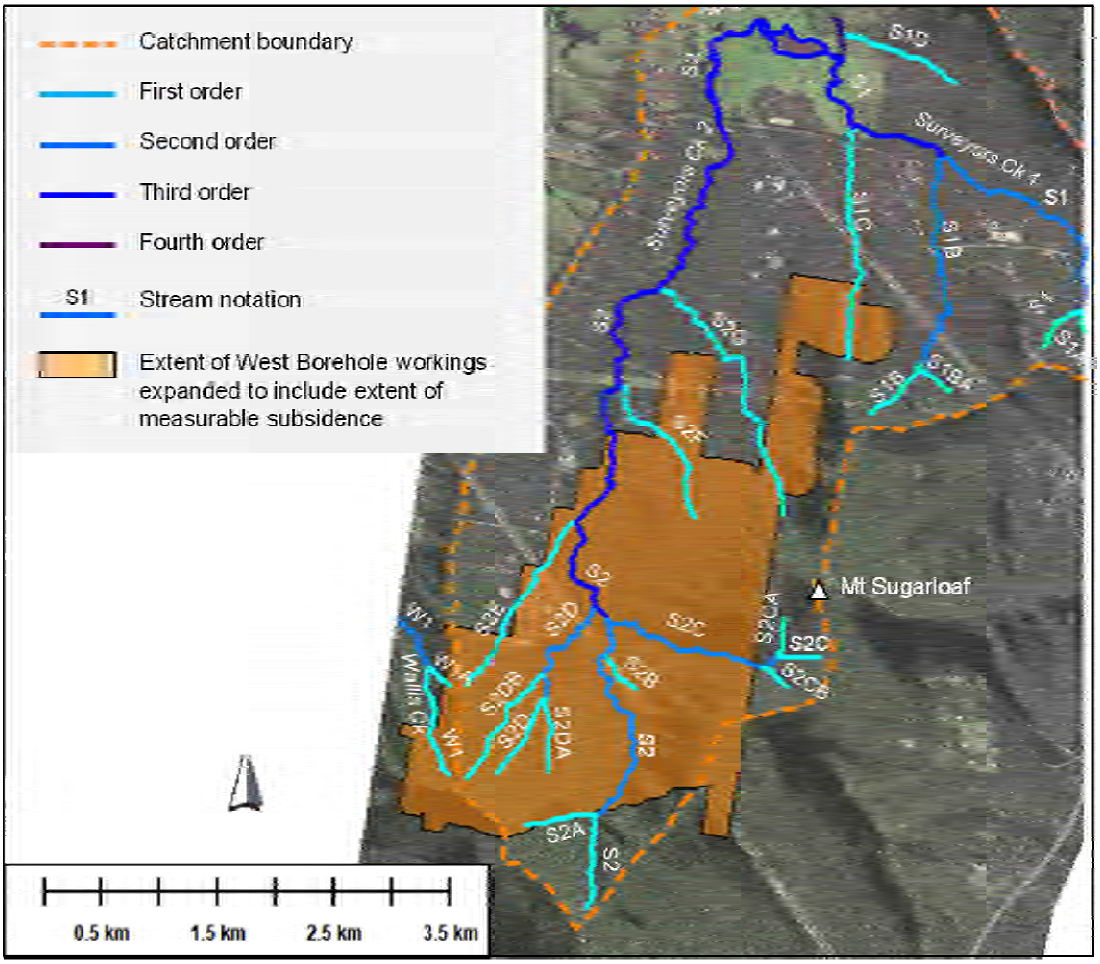

Figure 2. The naming convention used in this report for streams in the study area. Streams classified by Strahler stream order.

2.4 Field survey

The objective of the field survey was to obtain sufficient information to enable characterisation of stream type, and stream geomorphic features. Stream type classification relies partly on attributes that can only be measured in the field, and partly on attributes that can be measured from maps and a digital elevation model (DEM). In Surveyors Creek, the dense vegetation cover, and the relatively small size of the geomorphic features, meant that stream attributes could not be measured from aerial photographs or other remotely sensed imagery, so they have to be measured in the field.

Some stream reaches were located in very steep headwater areas, and the vegetation in some of the lowland stream reaches was difficult to penetrate. These difficulties meant that a few reaches could not be accessed.

The approach to field survey was to walk along the streamline until a noteworthy feature was encountered. In most instances this constituted a knickpoint, a pool, or a change in stream form or bed material. In the absence of noteworthy features, basic observations of channel dimensions, bed material and large woody debris were made at random points about 20 to 100 metres apart (depending on stream size and heterogeneity).

As well as measuring and recording data on a standard field sheet, geo-referenced photographs were taken at each observation point. In total, data were collected at 385 sites (Figure 1). These field-based observations were supported by topographic data obtained from the DEM.

2.5 Digital data

Digital aerial photography data, and digital elevation data in the form of 2 m contours, were supplied by Donaldson Coal. The contour data were converted to an elevation grid (DEM) using Global Mapper™ software. The software automatically selects the optimum grid size to suit the input data, which in this case was 2.475 metres.

2.6 Stream order

Stream order was assigned according to the Strahler system, whereby a headwater stream is order 1, and the order increases by 1 when a stream of a given order meets one of the same order.

2.7 Stream gradient and length

Global Mapper™ software was used to generate from the DEM data the distribution of topography of the catchment (elevation and slope), length and gradient of stream lines, and elevation of surveyed points. These variables were measured at the unit of stream link, which is either a first order stream in its entirety, or the length of stream between two tributaries.

Although ground-thruthed, the mapped streamlines were a simplification of the actual planform, in that they did not necessarily fully characterize the detail of the alignments, particularly in highly sinuous reaches. This leads to under-estimation of stream length, and therefore over-estimation of stream gradient.

2.8 Geomorphic type

The Strahler order of a stream depends on the definition of the stream network (which is dependent on mapping scale, and methodology of the cartographer). Streams of the same order can have entirely different characteristics, even within the same local area. For example, first-order streams draining from the tops of mountains are very different to short first-order streams joining the main stream in a lowland situation. For the purpose of interpreting geomorphic character and predicting sensitivity of streams to subsidence, a classification based on topographic and reach-scale geomorphic characteristics is more useful than a stream order classification. Thus, the primary stream classification developed for this report was based on geomorphic type. Delineation of stream types and type boundaries was based on field observations supported by topographic data obtained from the DEM.

2.8.1 Section- and reach-scale features

Cross section and reach-scale geomorphic features were the fundamental unit of field observation and measurement. When a feature was observed, its location was recorded using hand-held GPS. The dimensions of the feature were measured, and at the same time, the density of large woody debris and the bed material size were recorded. The following features were observed in the Project area:

- Continuous defined channel (bed and banks present)
- Indistinct channel (flow path but no clear bed and banks)
- Incised gully (channel deeper than expected for a stable stream)
- Pool (could be wet or dry)
- Hydraulic control (shallow area that controls flow level)
- Cascade/waterfall (length of steeply-sloping rock or boulder in headwaters)
- Knickpoint (vertical drop in channel bed, can be in headwaters in rock or boulder, or in fine grained sediments in lower valley setting)
- Head of creek (upstream extent of a headwater channel)
- Channel junction (where two streams meet)
- Track crossing (where a track passes directly over or through the stream)
- Ponded water presence

The dimensions of some features were measured using a tape measure or range finder. For knickpoints, their depth (height from base to top) was measured. For pools, their length, maximum width and maximum depth were measured. These dimensions were with respect to their potential full level, as defined by the elevation of the downstream hydraulic control, so did not necessarily relate to the level of water in the pool on the day of the survey.

Basic channel dimensions of width and depth were measured relative to the bankfull morphological surface. Bankfull level was defined on the basis of channel form, vegetation and lichen limits. In incised streams, two sets of width and depth measurements were made, one that characterised the inset bankfull channel, and that characterized the entire incised channel form.

Large woody debris (LWD) loading was counted over a 20 metre stream length, centred on the observation point. Here LWD was defined as dead wood within the bankfull channel longer than 1.0 m and thicker than 0.1 m. The wood density per 20 m of channel was assigned to one of 5 classes: 0 = none, 1 = 1-5 pieces, 2 = 6-10 pieces, 3 = 11-20 pieces, and 4 = more than 20 pieces.

Bed material size was placed within one of six classes:

- Exposed solid rock
- Boulder (>256 mm)
- Cobble (64 - 256 mm)

- Gravel (2 – 64 mm)
- Sand (0.06 – 2 mm)
- Cohesive (mostly silt and clay)

The primary observation for bed material was the dominant size class. However, in some locations the bed material was evenly mixed across a number of size classes, or was multi-modal. In these instances, up to three bed material sizes were noted as present, in descending order of dominance.

2.8.2 Stream type classification

The geomorphic stream type classification used here borrowed from, and is consistent with, the River Styles® framework (Brierley and Fryirs, 2000; Brierley and Fryirs, 2005; Brierley and Fryirs, 2006; Fryirs and Brierley, 2006). The River Styles® classification is based on valley setting, level of floodplain development, bed materials and reach-scale physical features within the stream. The River Styles® framework was designed to cover all Australian stream types, and can be applied at a large scale, where a range of different styles would be expected. Most of the styles apply to partly confined and unconfined (i.e. alluvial/lowland) valley settings where streams are relatively large and feature many distinctive units such as levees, pools and riffles, bars, islands, benches, cutoff channels, backswamps, wetlands and floodplains. The streams in Surveyors Creek catchment are relatively small-scale and generally lack these features. The River Styles® framework would probably recognise only three stream types in Surveyors Creek (Headwater, Valley Fill and Chain-of-Ponds). For this characterisation of streams in Surveyors Creek catchment it was considered desirable to include a higher level of detail in the stream type classification.

In the Project area, the classified streams were all within confined valley settings, and therefore exhibited no proper floodplain development. However, the streams differed in terms of bed particle size, channel form and channel continuity. The type-classification comprised two main groups: (i) confined valley streams in bedrock and with coarse-grained bed material, and (ii) streams formed on valley fill with fine-grained bed material (Figure 3). The confined coarse-grained group gave rise to the Headwater type (Figure 3). The fine-grained streams fell into six types depending on continuity, relative depth, and whether or not a flat sand-bed was present (Figure 3). The other type was Unclassified, which was applied to any stream where there was insufficient information on which to place the stream into a type, or it was not necessary to do so because the stream fell outside the area of main interest (Figure 3). These types are specific to the Project area, and are a sub-set of the many geomorphic stream types found in Australia.

The stream network in Surveyors Creek 2 exhibited evidence of incision. Incised streams were regarded as a modified form of the natural un-incised type. Incision is the result of some form of perturbation to the stream baselevel, the catchment hydrology, or the stream resistance (type and cover of vegetation and large woody debris). The age and cause of the incision process in the streams of the Project area could not be determined, so it is not known whether the incision is part of a natural cycle, caused by human disturbance, or accelerated by human disturbance. For the valley fill streams, the heads of the incised reaches (knickpoints) were clearly active, so the process is ongoing. The catchment is largely forested and undisturbed, with no evidence of wildfires for two decades. Forestry has been practiced in the area in the past but its impact on the streams is unknown. Incision is more likely to have been initiated from disturbance to the downstream end of the streams. Downstream of the Project area the catchment of Surveyors Creek is cleared or partially-cleared and there are many tracks present. Disturbance of valley fill vegetation cover is one possible mechanism for initiation of incision.

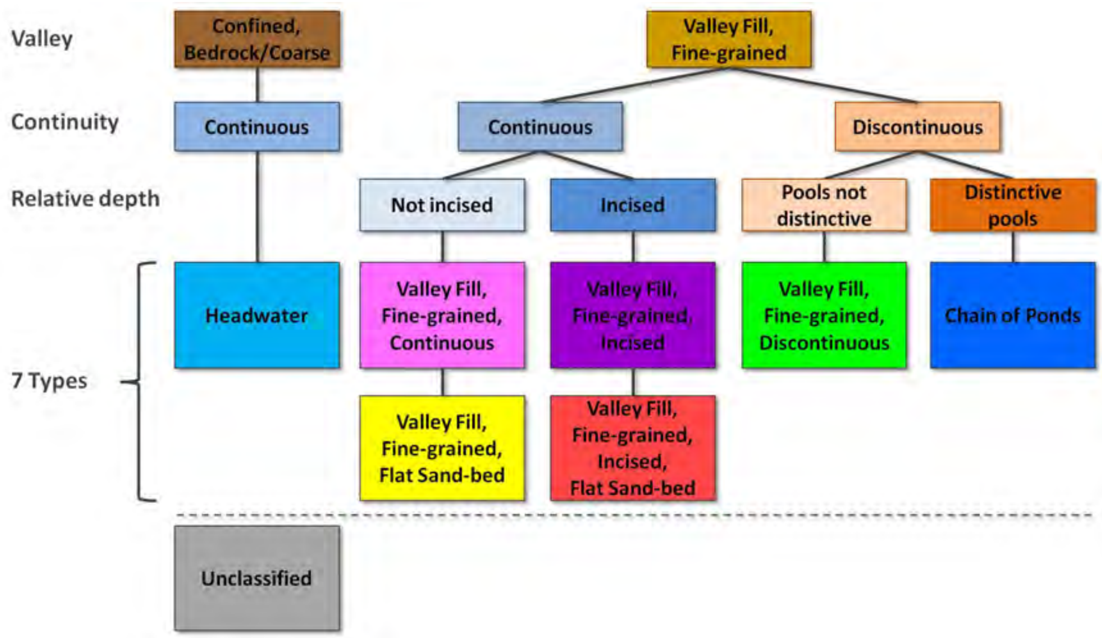

Figure 3. The seven geomorphic stream types (plus Unclassified type) identified in the Surveyors Creek catchment study area.

2.9 Impact assessment

Subsidence associated with the proposed West Borehole Seam Workings Project area was predicted by Ditton Geotechnical Services (2012). The modelling involved assessment of subsidence effects on the surface and subsurface features with and without Subsidence Control Zones (SCZs) present. This assessment of the geomorphological impacts is concerned only with the scenario of SCZs present, which is the scenario that includes mitigation actions, as this is what would be implemented for the Project.

Ditton Geotechnical Services (2012) provided long profiles of selected streams in the Project area for the pre-mining (existing) and the post-mining (with SCZs present) scenarios. The assessment of impacts of subsidence on fluvial geomorphological form and process was undertaken using a semi-quantitative risk analysis approach, whereby risk is the product of fragility and recovery potential. Recovery potential is partially dependent on geomorphic condition.

Brierley et al (2011) used the term "**fragility**", defined as the ease of adjustment of bed material, channel geometry, and channel planform when subjected to degradation or certain threatening activities (Cook and Schneider, 2006). Fragility also includes the concept of resilience. In a fragile stream with low resilience, a significant adjustment may result in a change to a different type of river, if a certain threshold (level of disturbance) is exceeded (Brierley et al., 2011).

Categories of fragility were defined by Cook and Schneider (2006) (Table 1).

Outhet and Cook (2004) (see Cook and Schneider, 2006) defined "**geomorphic condition**" in terms of three categories (Table 2).

Table 1.
Categories of stream geomorphic fragility defined by Cook and Schneider (2006).

Fragility	Description
Low fragility:	Resilient ('unbreakable'). Minimal or no adjustment potential. Only minor changes occur such as bedform alteration and the likelihood of river change is minimal, regardless of the level of damaging impact.
Medium fragility:	Local adjustment potential. The reach may adjust over short sections within the vicinity of the threatening process. Major changes to river character can occur, but only when a high threshold of damaging impact is exceeded. For example, a catastrophic flood, sediment slug or clearing of all vegetation from bed, banks and floodplain may be required to induce change.
High fragility:	Significant adjustment potential and sensitive to change. The reach may be dramatically altered or degraded over long sections. Major character changes can occur when a low threshold of damaging impact is exceeded (e.g. clearing of bank toe vegetation alone).

Table 2.
Categories of stream geomorphic condition defined by Outhet and Cook (2004).

Geomorphic condition	Description (simplified from the original)
Good condition	Natural and intact; self-adjusting and fast recovery from natural disturbance; intact vegetation
Moderate condition	Localised degradation; geomorphic units modified, such as unexpected grainsize; patchy vegetation cover
Poor condition	Accelerated rates of erosion; high volumes of sediment with low diversity of form; vegetation absent

"**Recovery potential**" is a measure of the capacity of a reach to return to good condition or to a realistic rehabilitated condition, given the limiting factors (or threats) impacting on the reach (e.g. riparian vegetation condition such as weed succession, land use such as livestock grazing and trampling impacts, presence of infrastructure such as dams and the rate/degree of physical pressures acting on the reach) (Brierley et al., 2011). Categories of recovery potential were defined by Cook and Schneider (2006) (Table 3). These categories do not suit assessment of the risk associated with a particular future threat (i.e. subsidence). For this study, the threat level was quantified as a function of geomorphic condition (Table 2) and the **relative subsidence** (Table 4). In this scheme, the threat is less for reaches in good condition, which have higher natural recovery potential.

Relative subsidence was defined herein terms of the changes to the stream slope due to subsidence. If slope increased less than 5% then it was regarded as an insignificant threat. Also, post-mining stream slopes were only regarded as a threat if they were steep relative to the distribution of slopes in the existing streams. The threshold slope that defined a risk was set at the 90^{th} percentile slope value in the existing streams, specific to each stream type. For instances where post-mining slopes exceeded the 90^{th} percentile slope value in the existing streams, the relative subsidence was considered to be higher the greater was the percentage increase in slope due to subsidence. Subsidence threat levels were assigned to four categories (Table 4).

Table 3.
Categories of recovery potential defined by defined by Cook and Schneider (2006).

Recovery potential	Geomorphic condition	Threat criteria (only those relevant to streams in the Project area)
Conservation	Good	No disturbance
Strategic recovery	Variable	Local headcuts present; riparian vegetation locally disturbed; large woody debris locally disturbed; excess sediment from upstream gully; potential to impact adjacent fragile reach; short reach within longer reach of high conservation value; poorly represented or unique type
Rapid recovery potential	Moderate	Well connected to upstream reaches in good condition that supply large woody debris, sediment and seed
High recovery potential	Moderate	Poorly connected to upstream reaches in good condition that supply large woody debris, sediment and seed
Moderate recovery potential	Moderate to poor	Little large woody debris, sediment and seed supply; can only recover faster if upstream reaches recover
Low recovery potential	Poor	No large woody debris, sediment and seed supply; on the verge of shifting to a different river type

Table 4.
Four categories of subsidence threat level used for this study.

		Geomorphic condition		
		Good	Moderate	Poor
Relative subsidence	$S_A \leq P_{90}S_B$ or $S_R \leq 1.05$	Insignificant	Insignificant	Insignificant
	$S_A > P_{90}S_B$ and $1.05 < S_R \leq 1.25$	Low	Moderate	High
	$S_A > P_{90}S_B$ and $1.25 < S_R \leq 1.50$	Moderate	High	High
	$S_A > P_{90}S_B$ and $S_R > 1.50$	High	High	High

where,

$$S_R = \frac{S_A}{S_B}$$

S_B = slope before mining,

S_A = slope after mining,

$P_{90}S_B$ = 90^{th} percentile of slope before mining for stream type

The likelihood of change, or risk to the integrity of stream geomorphic form and process, was a function of geomorphic fragility (consequence) multiplied by the subsidence threat level (likelihood) (Table 5).

Table 5.
Four categories of geomorphic risk used for this study.

		Subsidence threat level			
		High	Moderate	Low	Insignificant
Vulnerability (fragility)	High	High	High	Moderate	Insignificant
	Medium	High	Moderate	Low	Insignificant
	Low	Low	Low	Low	Insignificant

3 Results

This section is illustrated with selected photographs. The latitude and longitude of each photograph is provided in their individual captions. Their locations are also depicted on a key map (Figure 4).

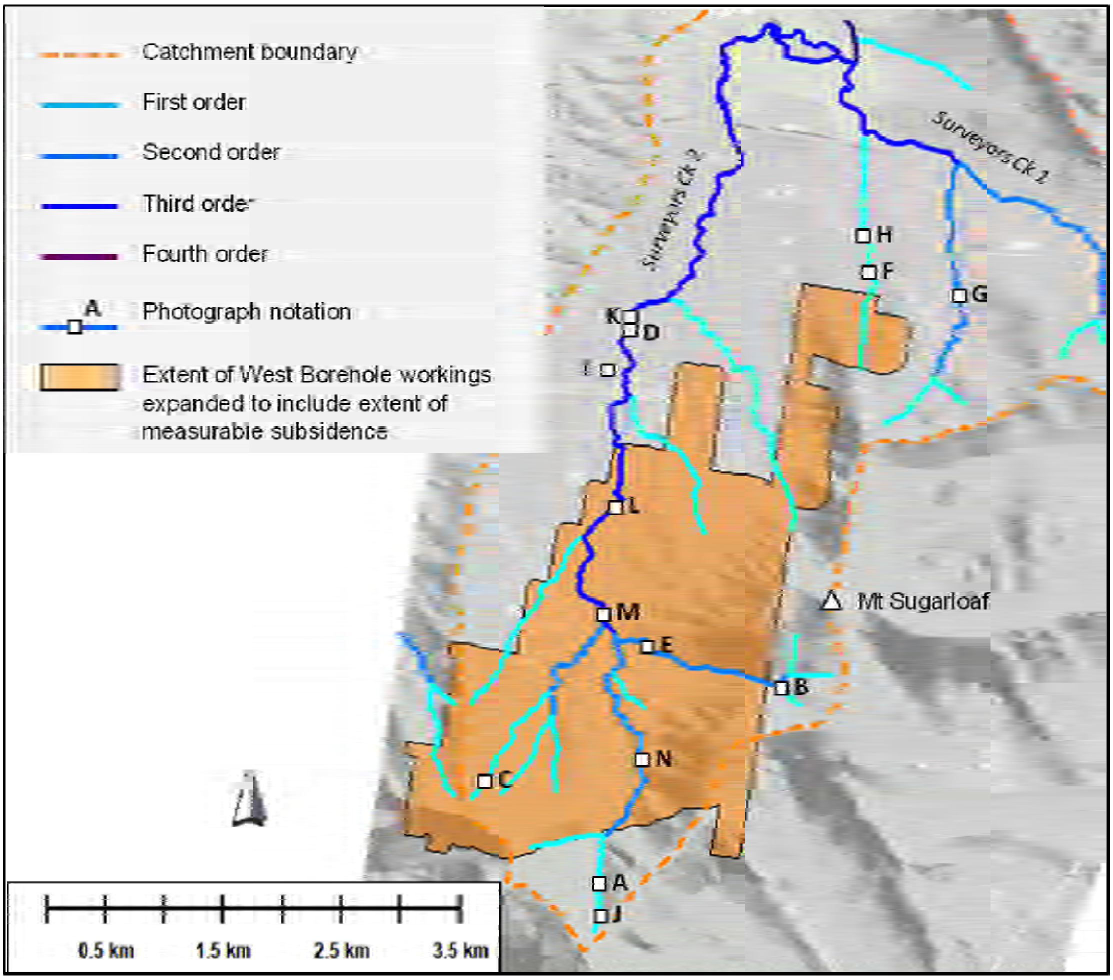

Figure 4. Location of photographs used in this report.

3.1 Topography

The panels of the proposed mine cover an area with elevation in the range 40 to 370 m AHD (Figure 5). Valley slopes range from near flat to near vertical (Figure 6). A steep cliff line runs along the southeastern section of the Project area, with two vertical faces of 25 m observed on stream lines (Figure 6, Figure 7 and Figure 8). Some first-order streams are in low elevation, low slope areas, and some are in high elevation, high gradient areas.

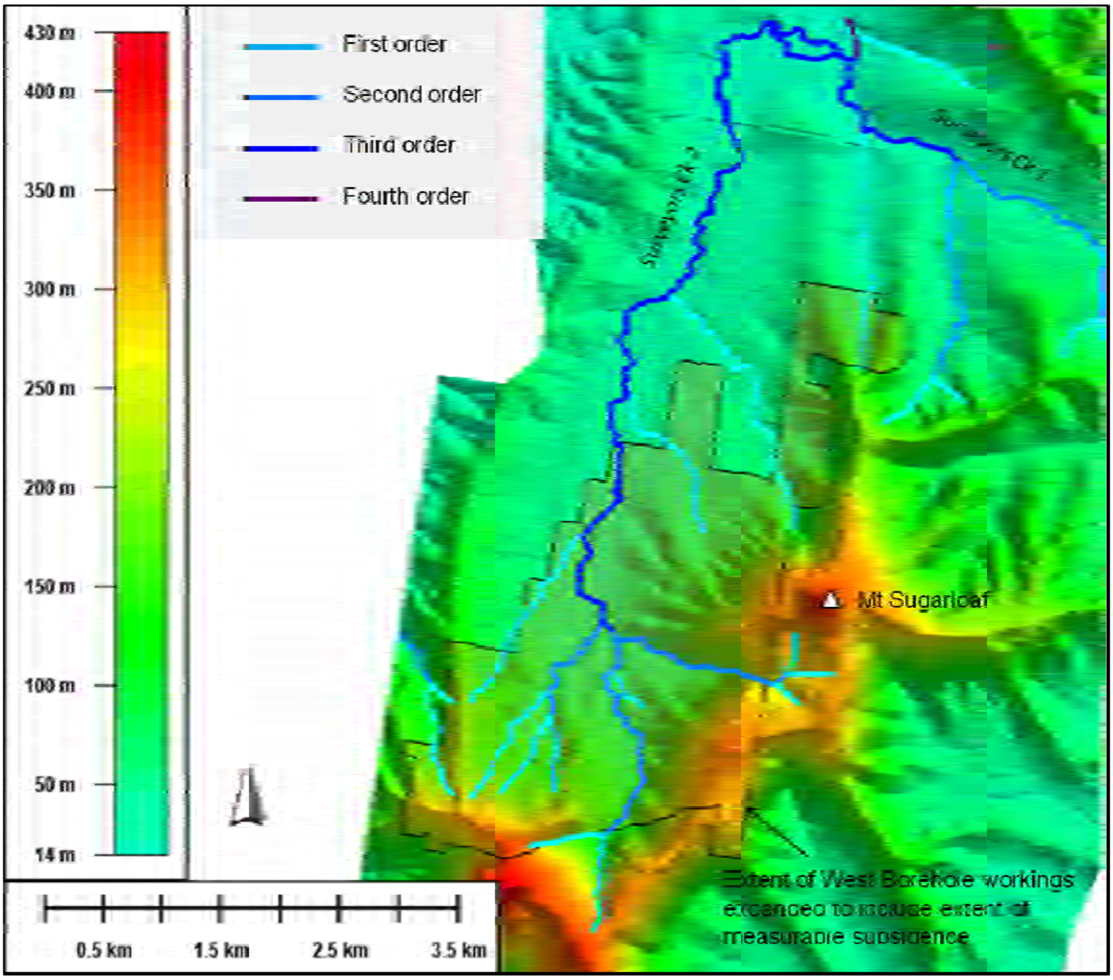

Figure 5. Topography of the study area showing the stream network in relation to elevation in m AHD. Map is hill-shaded.

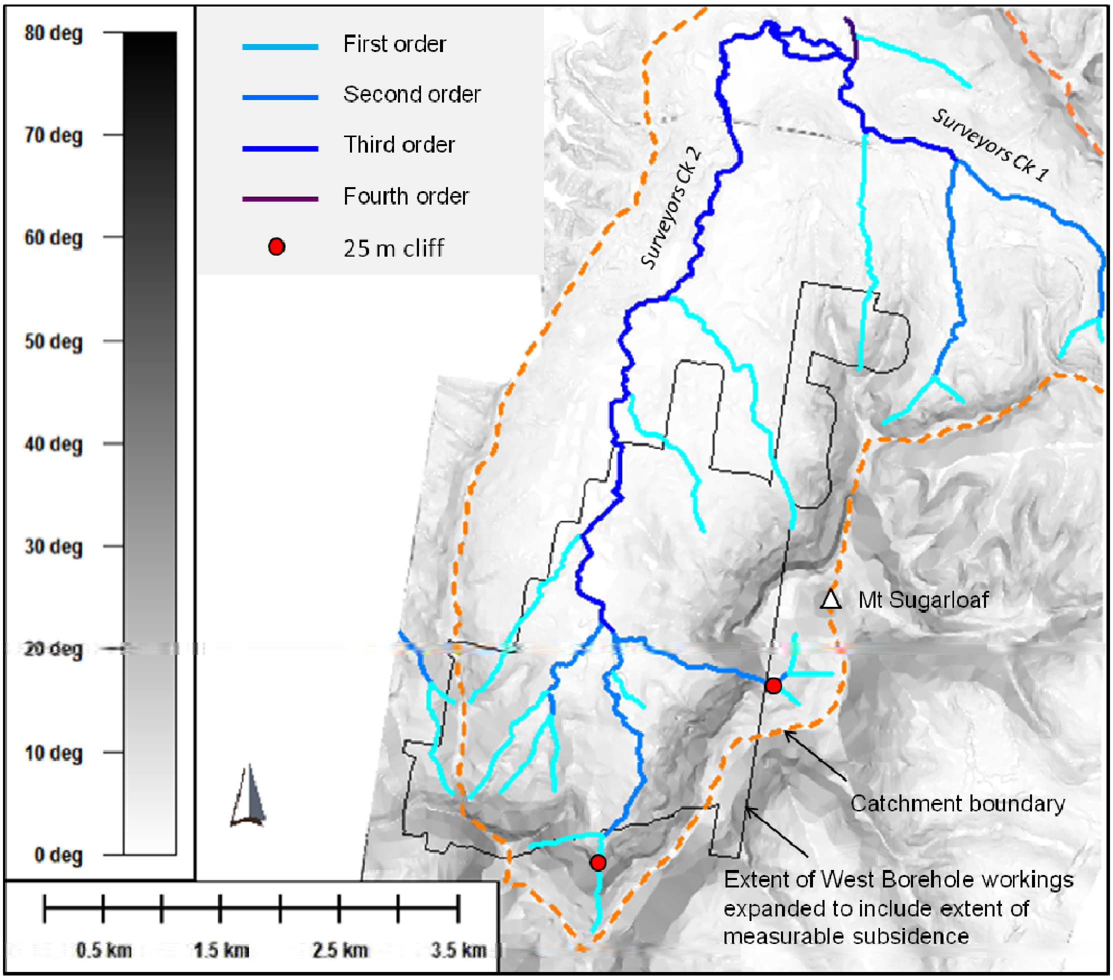

Figure 6. Topography of the study area showing the stream network in relation to slope in degrees.

Figure 7. Headwater stream type, S 2 (first-order), 151° 31' 2.03"E , 32° 54' 40.10"S. Cliff with a drop of 25 m. Photo location A (looking downstream).

Figure 8. Headwater stream type, S 2 C B (first-order), 151° 32' 0.18"E, 32° 53' 50.63"S. Cliff with a drop of 25 m. Photo location B (looking downstream).

3.2 Stream order

In the part of the Surveyors Creek catchment (plus a small area of upper Wallis Creek) investigated here, 33 unique reaches were classified by stream order (Figure 2). These comprised 20 first-order streams, 6 second-order streams, 2 third-order streams and 1 fourth-order stream.

The area within the proposed West Borehole Seam Project area contained 14.2 km of stream length, compared to 37.9 km of the wider catchment (Figure 9). Of the stream lengths within the mine area, only 2.08 km was third-order (Figure 9).

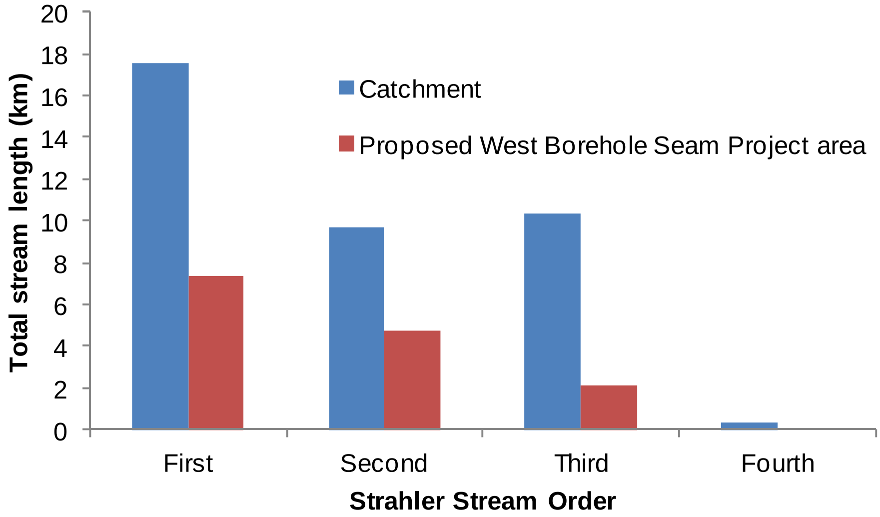

Figure 9. Total length of streams classified by Strahler stream order, for the Surveyors Creek 1 and 2 catchments (plus a small area of upper Wallis Creek catchment), and the area within the proposed West Borehole Seam Workings.

3.3 Stream geomorphic type

The stream geomorphic type classification (Figure 10) did not match the Strahler stream order classification. The area within the proposed West Borehole Seam Project area contained a similar proportion of the different stream types as was found in the catchment (Figure 11). The main difference was for the Unclassified type, which was relatively more common in the wider catchment (because it was not necessary to classify these stream lengths).

The Headwater stream type was limited to steep areas, with Valley Fill types beginning at the foothills (Figure 10). Chain-of-ponds type was characteristic of the two north flowing tributaries of Surveyors Creek 1 (Figure 10).

While lengths of un-incised, continuous and discontinuous valley fill stream types were present, most of the Valley Fill stream lengths in Surveyors Creek 2 were Incised, Flat Sand-bed type or Flat Sand-bed type (not incised). This is suggestive of some form of disturbance (natural and/or human induced). The field observations suggested that while the streams were well vegetated and relatively stable, the incision and erosion processes remain active.

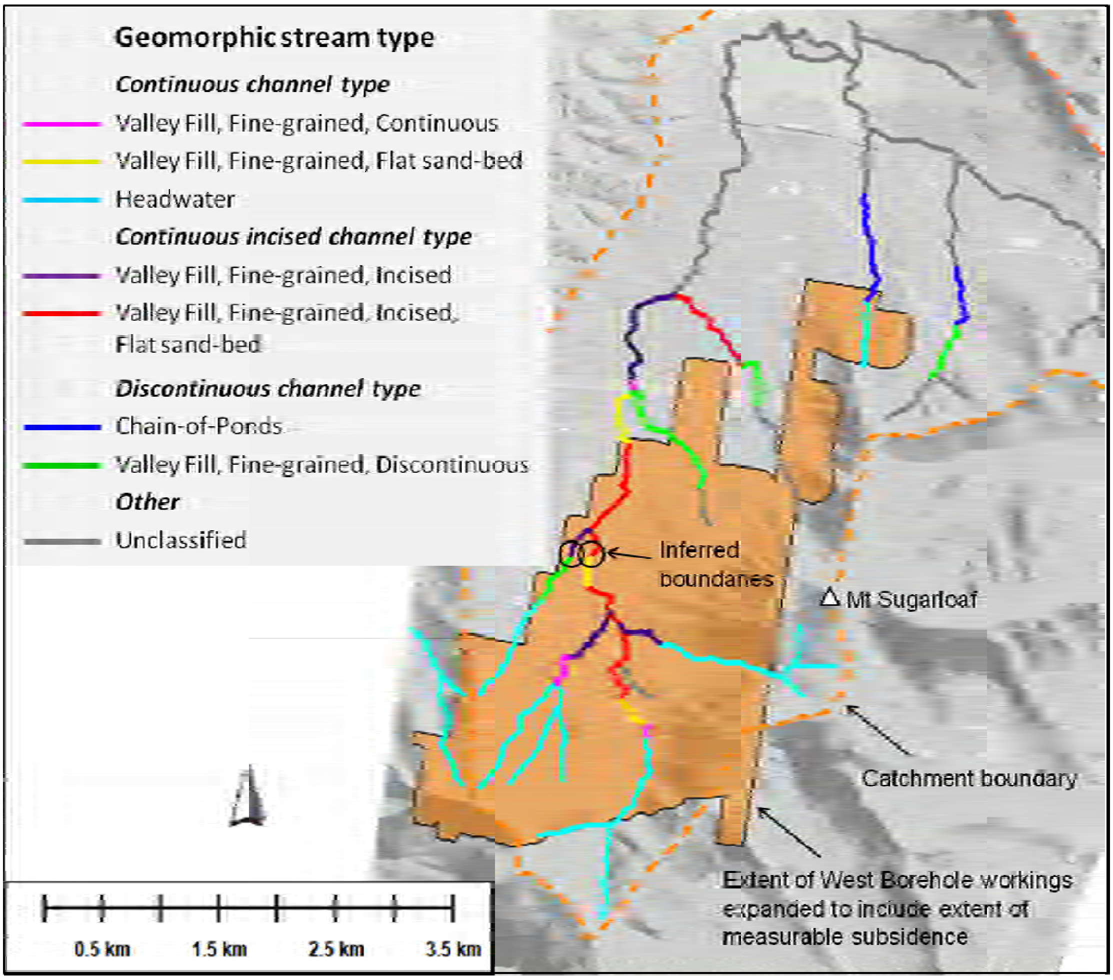

Figure 10. Stream network of the study area classified by geomorphic type. At two locations within the proposed West Borehole Seam workings Project area the stream type boundaries were inferred, because access to the channel was unavailable in the area.

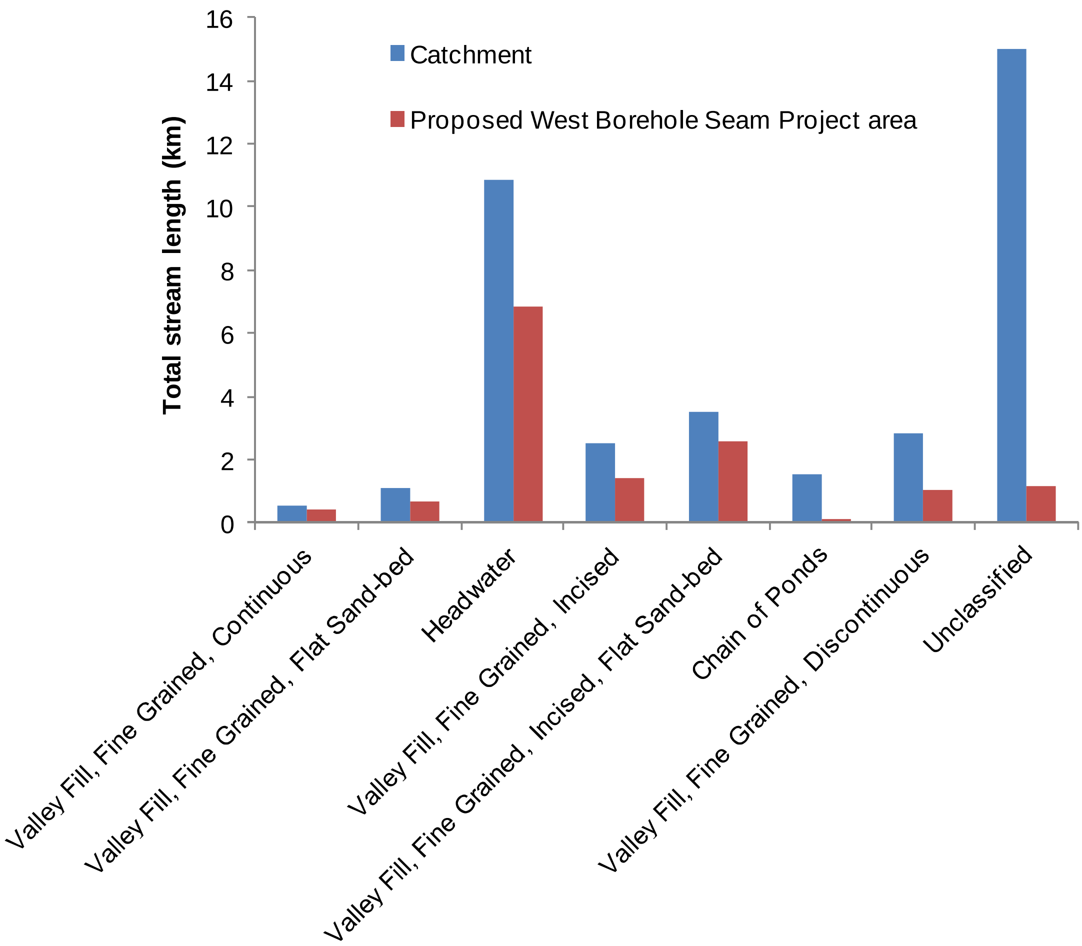

Figure 11. Total length of streams classified by stream geomorphic type, for the Surveyors Creek 1 and 2 catchments (plus a small area of upper Wallis Creek catchment), and the area within the proposed West Borehole Seam Workings.

3.4 Stream gradient

When classified by stream order, the gradients of the stream lengths were highly variable, although as expected, first order streams were much steeper than higher order streams (Table 6). When sorted by geomorphic type, the Headwater streams were significantly different from the valley fill types in terms of gradient (Figure 12 and Figure 13). In the wider catchment, Headwater streams had average reach mean gradients of 130 m/km (Figure 13). In both the wider catchment and the proposed West Borehole Seam Project area, the valley fill types had similar gradients, with average reach mean gradients of approximately 10 – 30 m/km (Figure 12).

Table 6.
All classified streams within Surveyors Creek 1 and 2 catchments (plus a small area of upper Wallis Creek catchment). Length and gradient characteristics of stream reaches classified by Strahler stream order.

Name	Order	Length (m)	Stream gradient			
			Mean (degrees)	90th percentile (degrees)	Mean (m/km)	90th percentile (m/km)
Surveyors Creek 1	1	482	3.92	8.73	69.3	153.5
Surveyors Creek 1	2	2111	0.60	2.87	10.5	50.2
Surveyors Creek 1	3	1680	0.41	1.75	7.1	30.6
Surveyors Creek 1	4	376	0.23	1.54	4.0	26.9
Surveyors Creek 1 A	1	175	1.27	6.67	22.3	117.0
Surveyors Creek 1 B	1	624	6.36	14.14	112.7	251.9
Surveyors Creek 1 B	2	1993	0.82	2.43	14.4	42.4
Surveyors Creek 1 B A	1	340	3.67	10.04	64.6	177.0
Surveyors Creek 1 C	1	2149	2.90	6.40	51.9	112.1
Surveyors Creek 1 D	1	1101	1.45	4.39	25.4	76.8
Surveyors Creek 2	1	861	13.81	29.00	256.3	557.5
Surveyors Creek 2	2	2179	1.43	6.75	25.1	118.4
Surveyors Creek 2	3	8652	0.33	1.41	5.9	24.5
Surveyors Creek 2 A	1	633	16.92	32.54	317.5	644.6
Surveyors Creek 2 B	1	414	1.69	5.94	29.7	104.0
Surveyors Creek 2 C	1	363	6.76	10.70	118.9	189.0
Surveyors Creek 2 C	2	1758	4.28	13.12	77.1	233.1
Surveyors Creek 2 C A	1	343	7.94	11.86	139.9	210.1
Surveyors Creek 2 C B	1	228	8.72	14.85	154.5	265.3
Surveyors Creek 2 D	1	789	6.76	12.26	119.3	217.3
Surveyors Creek 2 D	2	1173	0.80	3.83	14.1	66.9
Surveyors Creek 2 D A	1	645	6.38	14.23	113.1	253.6
Surveyors Creek 2 D B	1	1187	7.27	14.92	129.3	266.5
Surveyors Creek 2 E	1	1844	2.54	7.22	45.3	126.6
Surveyors Creek 2 F	1	1521	1.42	3.40	24.7	59.4
Surveyors Creek 2 G	1	2540	1.41	3.69	24.9	64.5
Wallis Creek 1	1	1010	5.76	12.86	101.7	228.3
Wallis Creek 1	2	504	5.49	8.75	96.3	154.0
Wallis Creek 1 A	1	249	11.07	18.04	197.1	325.9

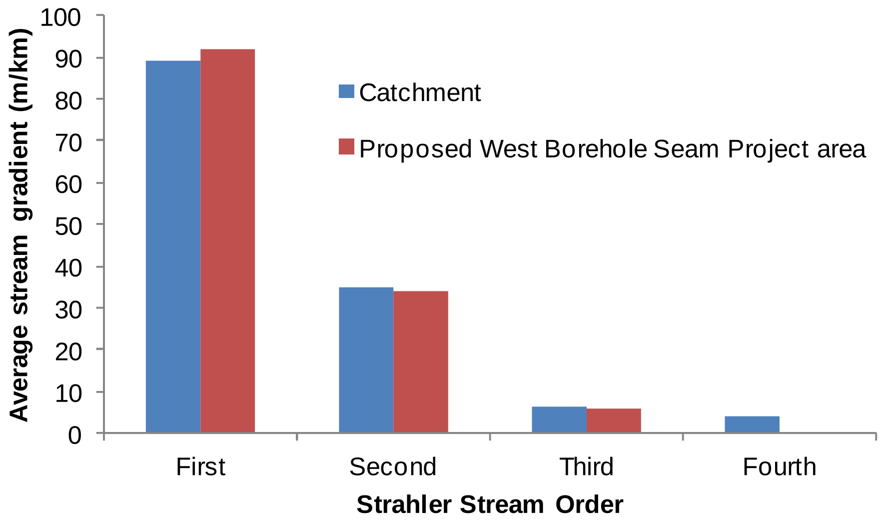

Figure 12. Mean gradients of streams, classified by Strahler stream order, for the Surveyors Creek 1 and 2 catchments (plus a small area of upper Wallis Creek catchment), and the area within the proposed West Borehole Seam Workings.

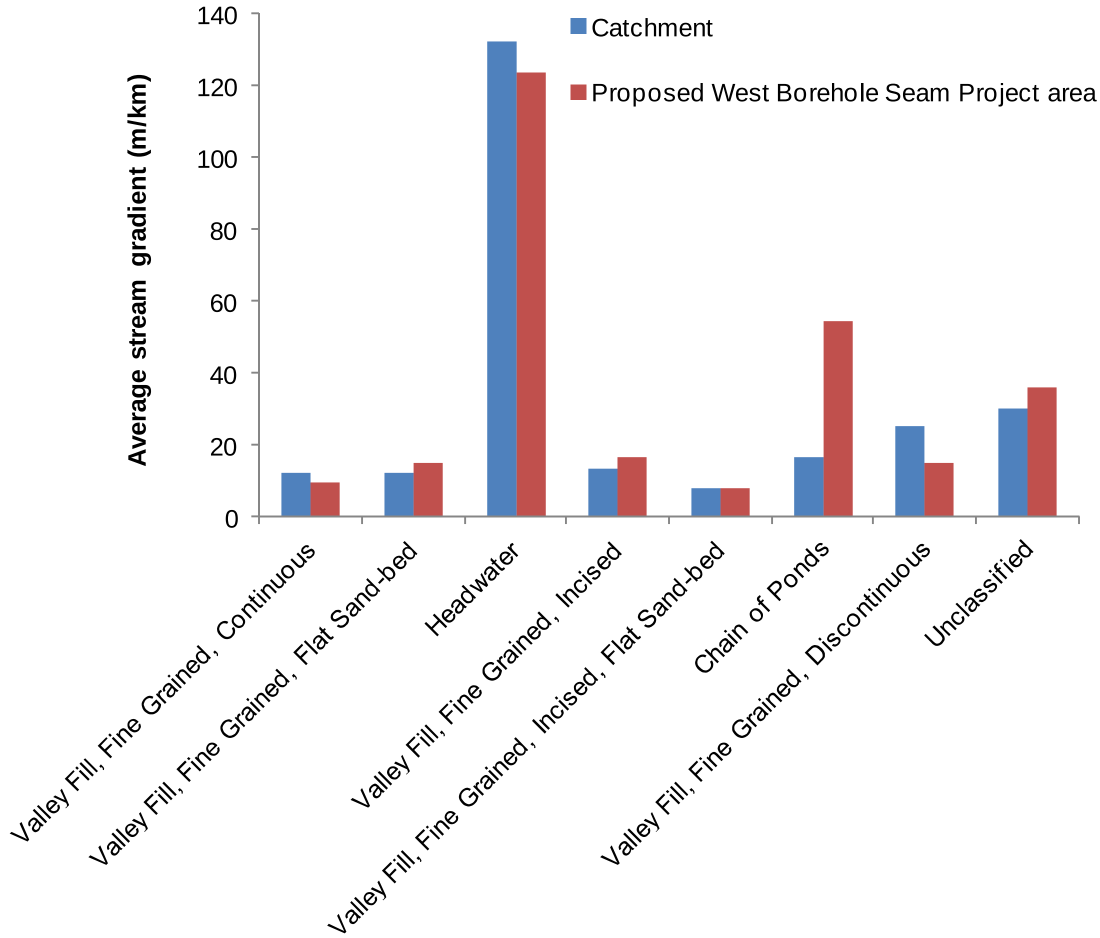

Figure 13. Mean gradients of streams, classified by stream geomorphic type, for the Surveyors Creek 1 and 2 catchments (plus a small area of upper Wallis Creek catchment), and the area within the proposed West Borehole Seam Workings.

3.5 Stream geomorphic features

3.5.1 Channel dimensions

3.5.1.1 Wider catchment area

There was not a strong pattern to bankfull channel dimensions with respect to stream order or stream geomorphic type (Figure 14). The measured dimensions relate only to observations where a channel was present, so the discontinuous channel types also had sections of no discernible width or depth.

Cases of incision were observed on three geomorphic stream types (Figure 15). The incised channels were much wider and deeper than the bankfull channels, and they had considerably lower width/depth ratios (Figure 15).

3.5.1.2 Proposed West Borehole Seam Project area

The channels within the proposed West Borehole Seam Project area had dimensions similar to those in the wider catchment area (Figure 16 and Figure 17).

3.5.2 Incision

The width/depth ratio (Figure 14, Figure 15, Figure 16 and Figure 17) is a key indicator of incised channel form. In the streams of the proposed West Borehole Seam Project area, the incised channel form had a width/depth ratio generally in the range 2 – 6 and always less than 12, which was coincidentally similar to that of the Headwater type (Figure 18). The width/depth ratio of un-incised Valley Fill stream types covered a much broader range (Figure 18).

Much of Surveyors Creek 2 stream network in valley fill was incised (Figure 10). The incision has worked its way up the main stem, and also into most tributaries. Surveyors Creek 2 was not surveyed downstream of the junction of S2 G, but the aerial photograph suggests that the stream is incised down to George Booth Drive. Downstream of this road, the stream emerges onto a cleared area with a reservoir (Figure 10), where it appears to lose its defined channel form. This is likely a depositional zone for the sand transported by Surveyors Creek 2.

3.5.3 Knickpoints

Knickpoints were common in the streams of the Project area. The knickpoints were of two different types, being (i) those in hard rock and boulder beds associated with headwater streams (mostly first and second order streams), and (ii) those in fine-grained bed sediments associated with valley fill stream types (Figure 10, Figure 19). In headwater streams, knickpoints were structurally (geologically) controlled, being associated with more resistant bedrock outcrops (Figure 20). These stable knickpoints are expected features in headwater streams.

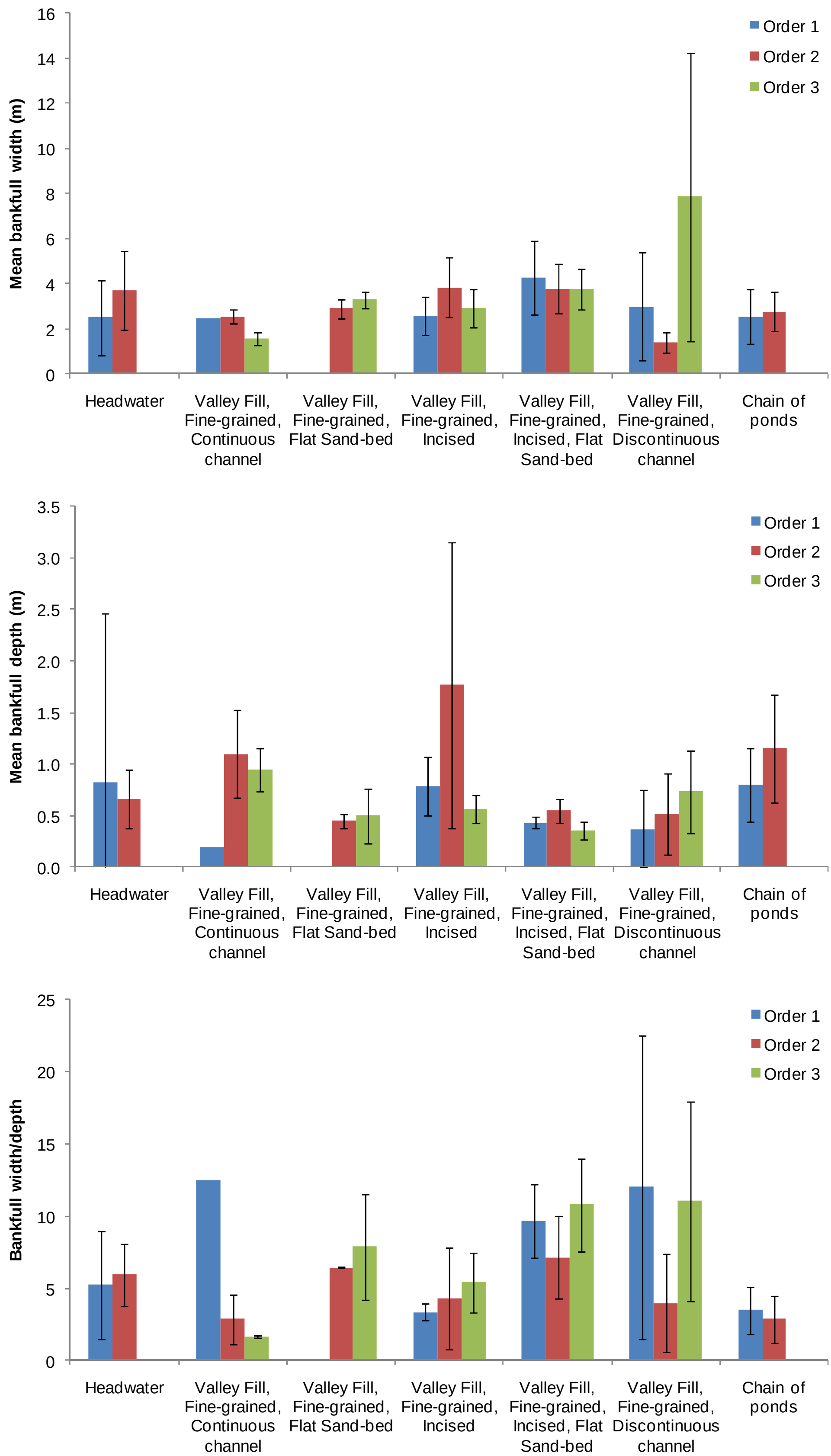

Figure 14. All classified streams in Surveyors Creek 1 and 2 catchments (plus a small area of upper Wallis Creek catchment). Mean (and standard deviation) of channel bankfull dimensions, grouped by stream order and geomorphic type.

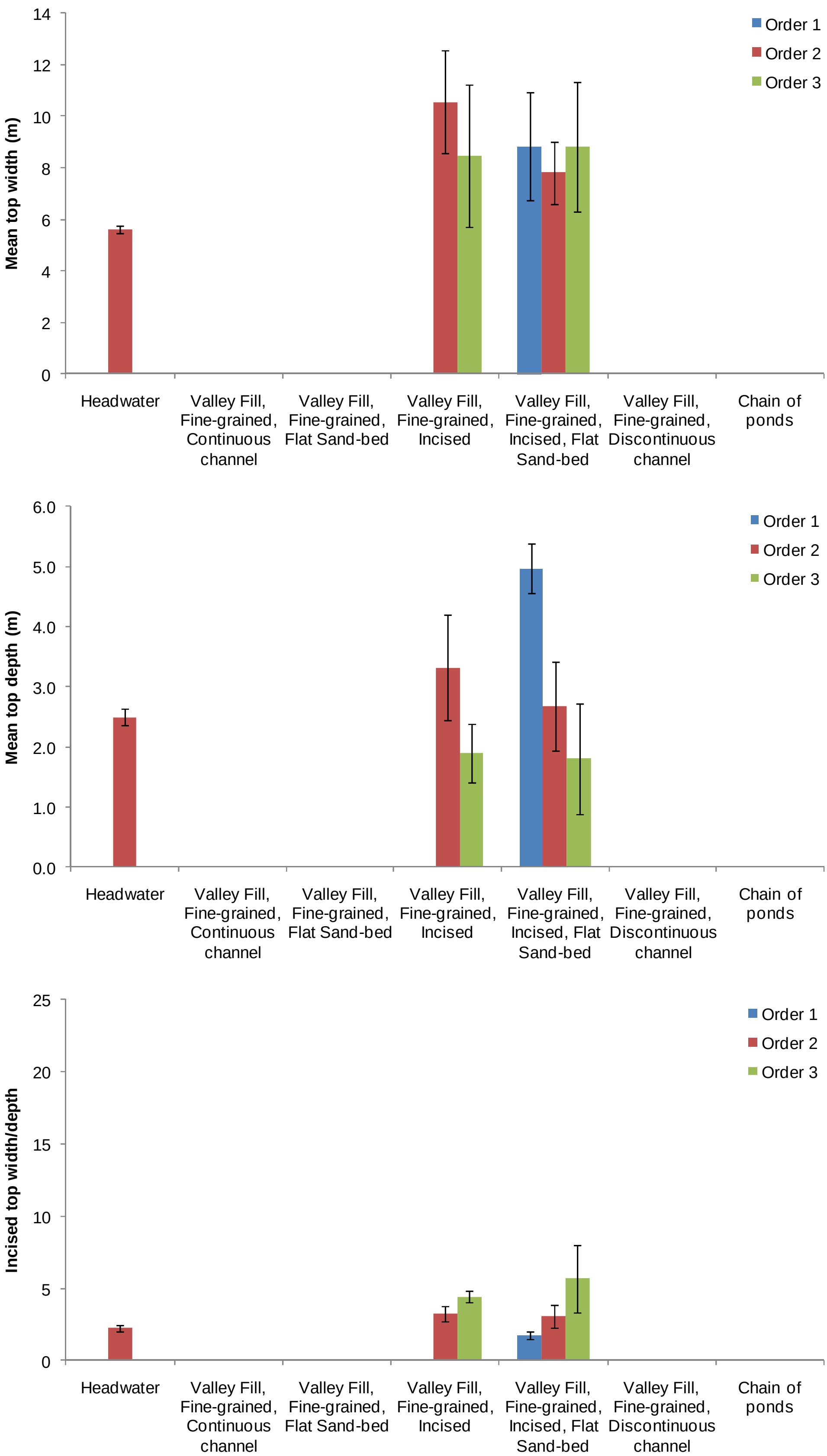

Figure 15. All classified streams in Surveyors Creek 1 and 2 catchments (plus a small area of upper Wallis Creek catchment). Mean (and standard deviation) of incised channel dimensions, grouped by stream order and geomorphic type.

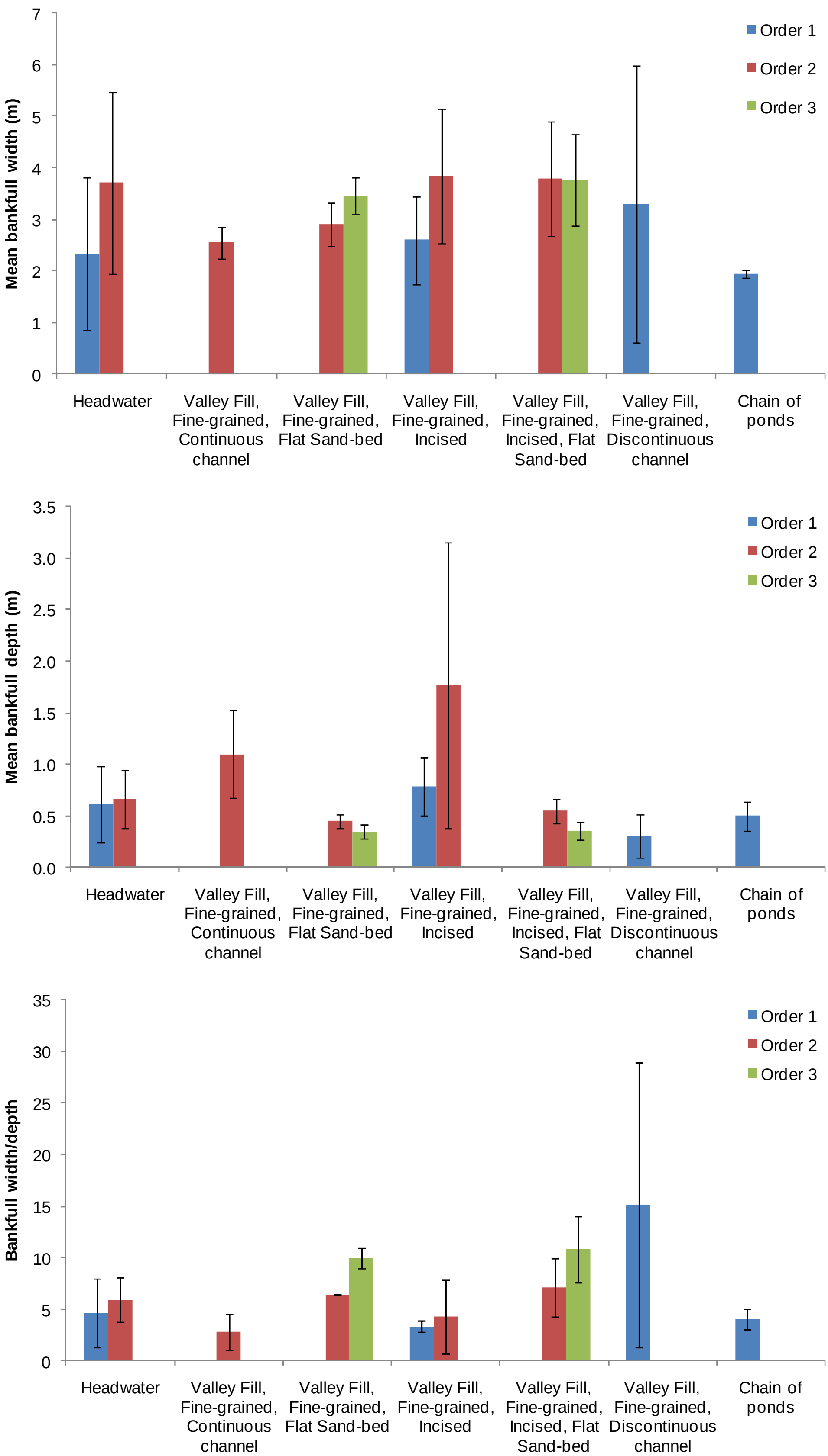

Figure 16. Streams within the area of the proposed West Borehole Seam Project area. Mean (and standard deviation) of channel bankfull dimensions, grouped by stream order and geomorphic type.

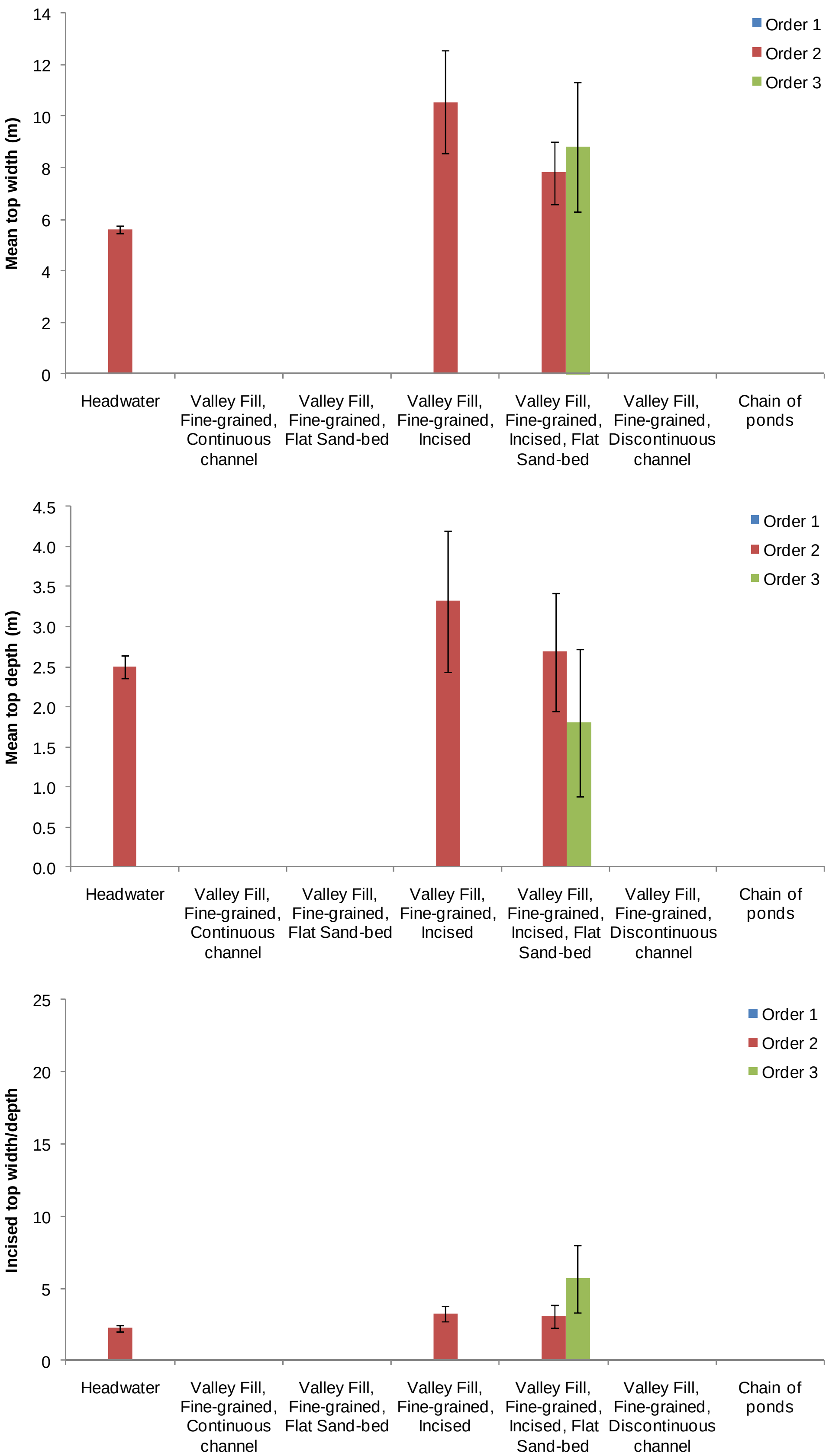

Figure 17. Streams within the area of the proposed West Borehole Seam Project area. Mean (and standard deviation) of incised channel dimensions, grouped by stream order and geomorphic type.

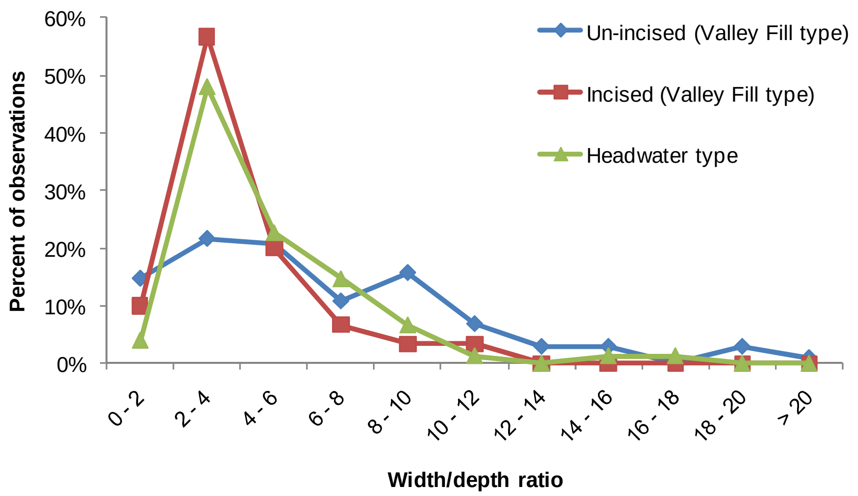

Figure 18. Distribution of width/depth ratios observed for incised and un-incised channel forms of Valley fill stream types and Headwater stream type in the proposed West Borehole Seam Project area.

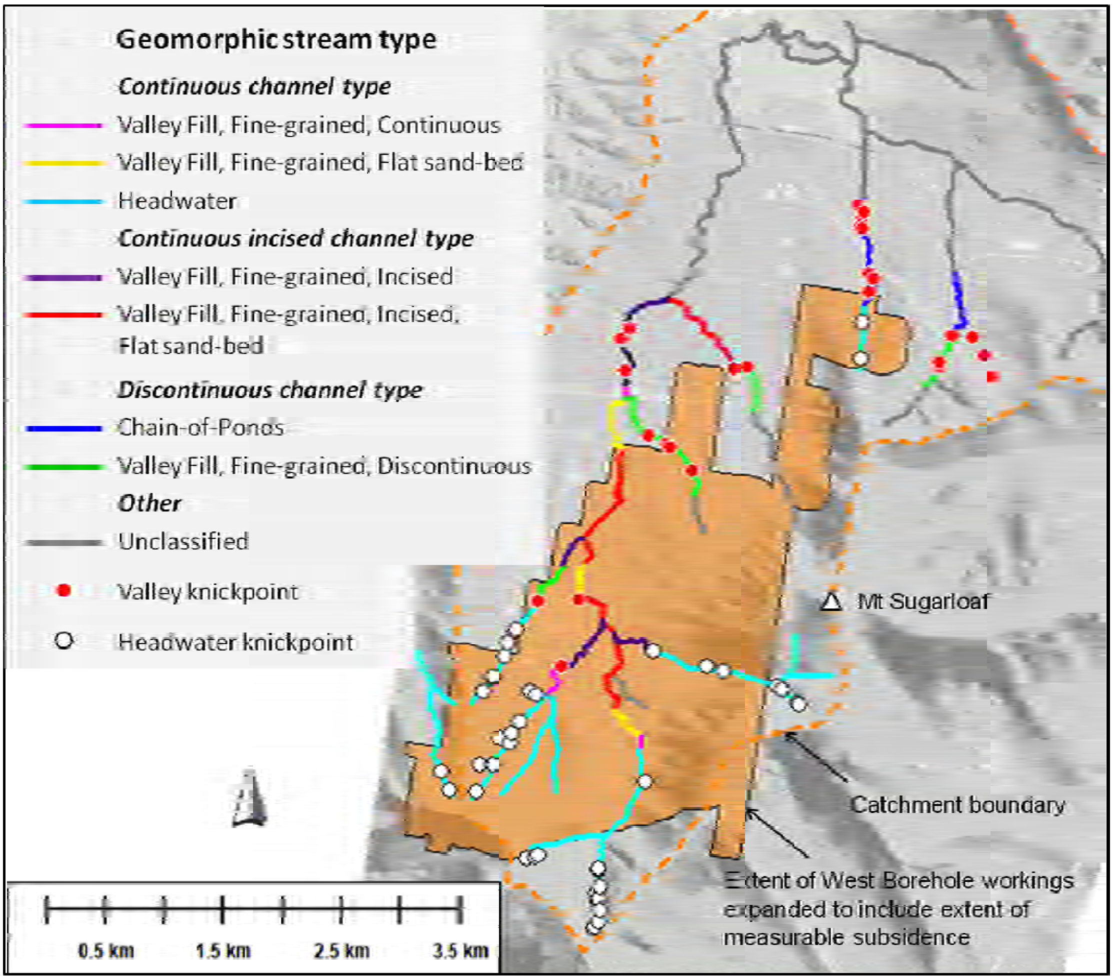

Figure 19. Knickpoints observed in the channel network of the Project area relative to Stream order.

Figure 20. Headwater stream type, S2 D B (first-order), 151° 30' 22.39"E, 32° 54' 18.87"S. Typical headwater knickpoint (1.7 m drop) in bedrock and boulder bed. Photo location C (looking downstream).

Lower gradient streams in valley fill settings were naturally of continuous or discontinuous forms. Such streams are dynamic, and might go through cycles of cut and fill in response to perturbations in the natural climate and hydrology. Incision migrates in the upstream direction, with the upstream extent of the incision marked by a knickpoint, which is also known as a head-cut. An example of this was observed on stream S2 in the third-order section (Figure 21). Here the incision was actively migrating upstream, as evidenced by freshly exposed bed material and fallen trees and shrubs where the banks had collapsed.

Incised channel form was expected immediately downstream of a valley fill knickpoint. Over time, the incised channel downstream of the migrating knickpoint might infill with sediment scoured from upstream. This process can lead to discontinuous recovery from incision, such that at the same time, part of a stream length is degrading, and part of it is aggrading.

The transition from one geomorphic stream type to another was often marked by a knickpoint (Figure 19). An example of this was observed on stream S2 C in the second-order section, when the stream transitioned from Headwater type to Valley Fill, Fine-grained, Incised stream type (Figure 22). Here the stream had incised through the unconsolidated valley fill deposits until it met resistance from an outcrop of shale.

Knickpoints were much deeper in headwater streams compared to valley fill stream types (Figure 23). In valley fill streams, knickpoints were generally less than 1 metre high. (Figure 23).

Figure 21. Valley Fill, Fine-grained, Incised stream type, S2 (third-order), 151° 31' 14.25"E, 32° 52' 12.12"S. Typical Valley Fill stream type knickpoint (1.5 m drop) in sand and cohesive bed. Photo location D (looking upstream).

Figure 22. Headwater stream type, S2 C (second-order), 151° 31' 20.70" E, 32° 53' 40.54"S. Knickpoint (1.9 m drop) in bedrock marking the transition between Headwater type and Valley Fill, Fine-grained, Incised stream type. Photo location E (looking upstream).

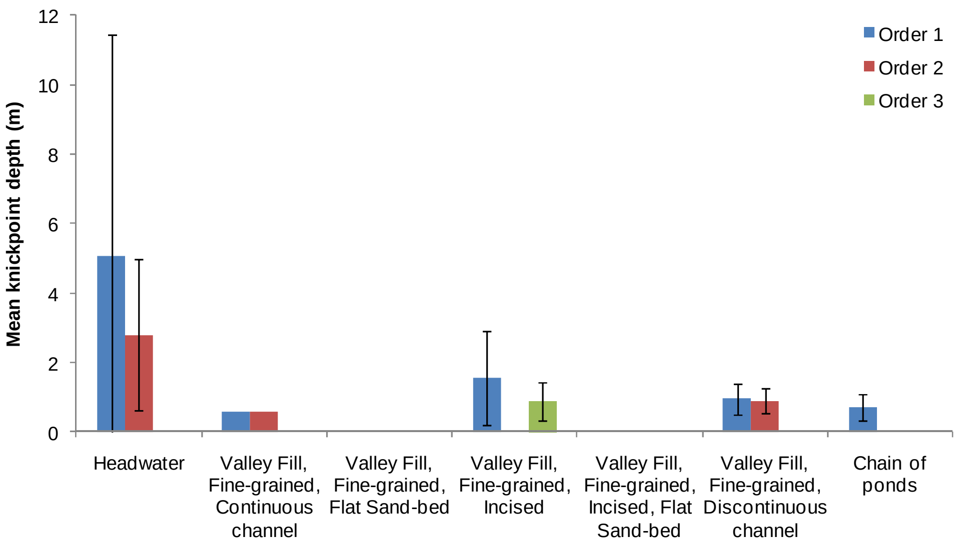

Figure 23. All classified streams in Surveyors Creek 1 and 2 catchments (plus a small area of upper Wallis Creek catchment). Mean (and standard deviation) of depth of knickpoints, grouped by stream order and geomorphic type. No standard deviation indicates 1 or 2 cases only.

Figure 24. Chain-of-ponds stream type, S1 C (first-order), 151° 32' 32.26" E, 32° 52' 2.91"S. Vertical face on upstream end of pool, denoted as a knickpoint transition to a vegetated hydraulic control. Photo location F (looking downstream).

Figure 25. Chain-of-ponds stream type, S1 B (first-order), 151° 33' 1.09" E, 32° 52' 1.56"S. Vegetated, stable hydraulic control between pools. Photo location G (looking downstream).

3.5.4 Hydraulic controls

Hydraulic controls were noted only in the Chain-of-ponds setting, where they represented high points separating the pools, often being vegetated. Two streams had Chain-of-ponds type: S1 C and S1 B (Figure 10). Of these streams, only S1 C had knickpoints (Figure 19). In stream S1 C, the upstream ends of most pools appeared to be actively incising into the valley fill (Figure 24), while in S1 B the pools tended to grade into the high ground between pools (Figure 25).

3.5.5 Pools

The majority of the significant pools in the Project area were associated with the Chain-of-ponds stream type (Figure 26). These pools were elongated, and of varying depth and width (Figure 27). Most pools were dry or nearly dry on the day of the survey (4 - 9 April 2011), but a few were full of water (Figure 28). Large pools were uncommon in the headwater streams, largely because of their high gradient. The largest pool in the Project area was to the side of the Surveyors Creek 2 main stem (Figure 29).

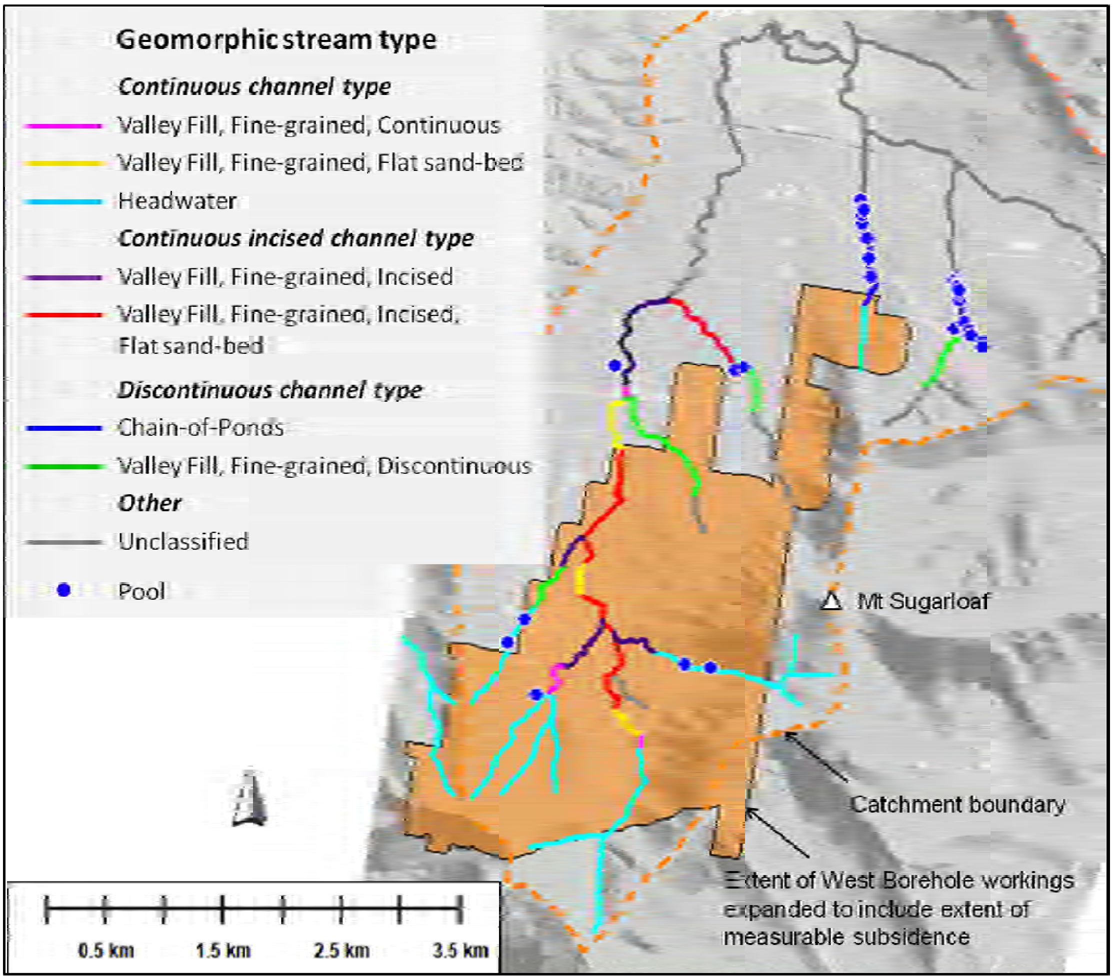

Figure 26. Significant pools observed in the channel network of the Project area relative to geomorphic type.

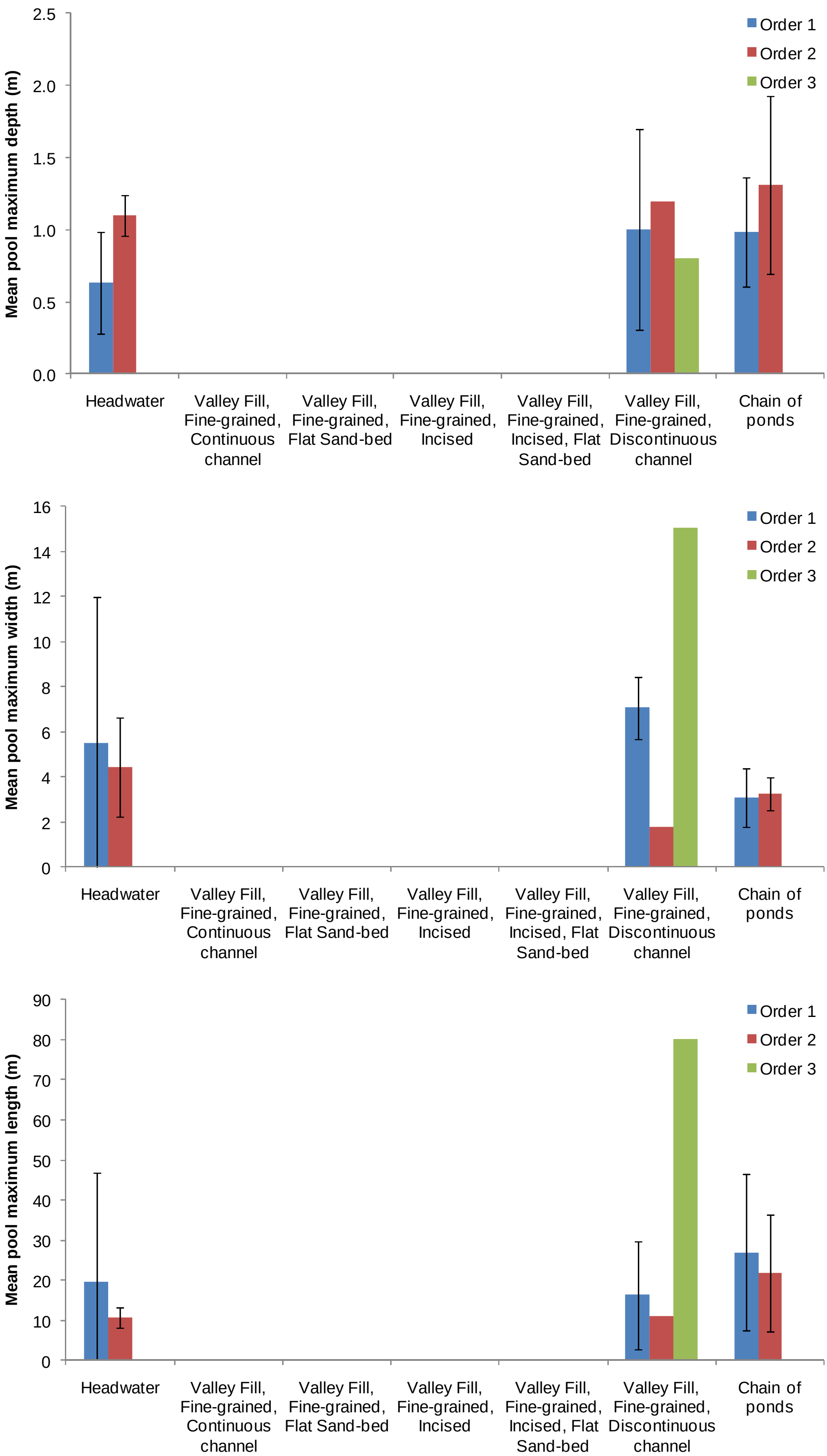

Figure 27. All classified streams in Surveyors Creek 1 and 2 catchments (plus a small area of upper Wallis Creek catchment). Mean (and standard deviation) of maximum depth, width and length of pools, grouped by stream order and geomorphic type. No standard deviation indicates 1 or 2 cases only.

Figure 28. Chain-of-ponds stream type, S1 C (first-order), 151° 32' 29.950"E, 32° 51' 44.25"S. Example of a pool containing water on the day of survey (4 April 2011). Photo location H (looking downstream).

Figure 29. The largest pool observed in the Project area, S2 (third-order), 151° 31' 10.89"E, 32° 52' 18.49"S. This pool was located adjacent to the main channel. Photo location I (looking upstream).

3.5.6 Water (on day of survey)

Rain fell on most days of the week of the survey, so ponded water was found in some of the pools, and some headwater streams had minor flow (Figure 30). The flow in the headwater streams was turbid, most likely as a result of water washing off unsealed tracks on the ridge crest.

Figure 30. Minor flow (note turbid water) in headwater stream on 7 April 2011, S2 (first-order), 151° 30' 59.64"E, 32° 54' 57.10"S. Photo location J (looking downstream).

3.5.7 Exposed bedrock

Exposed bedrock was common in the beds of the headwater streams (Figure 31). There was only one observed outcrop of bedrock in the valley fill streams, located on Surveyors Creek 2 main stem (Figure 32). This site was close to the most downstream extent of the survey. In this reach, the stream channel was mildly incised, with three active knickpoints present (Figure 19). Although the stream bed appeared to be actively degrading in this area, bedrock outcrops, such as the one observed here, will act as a local control on the rate of bed lowering.

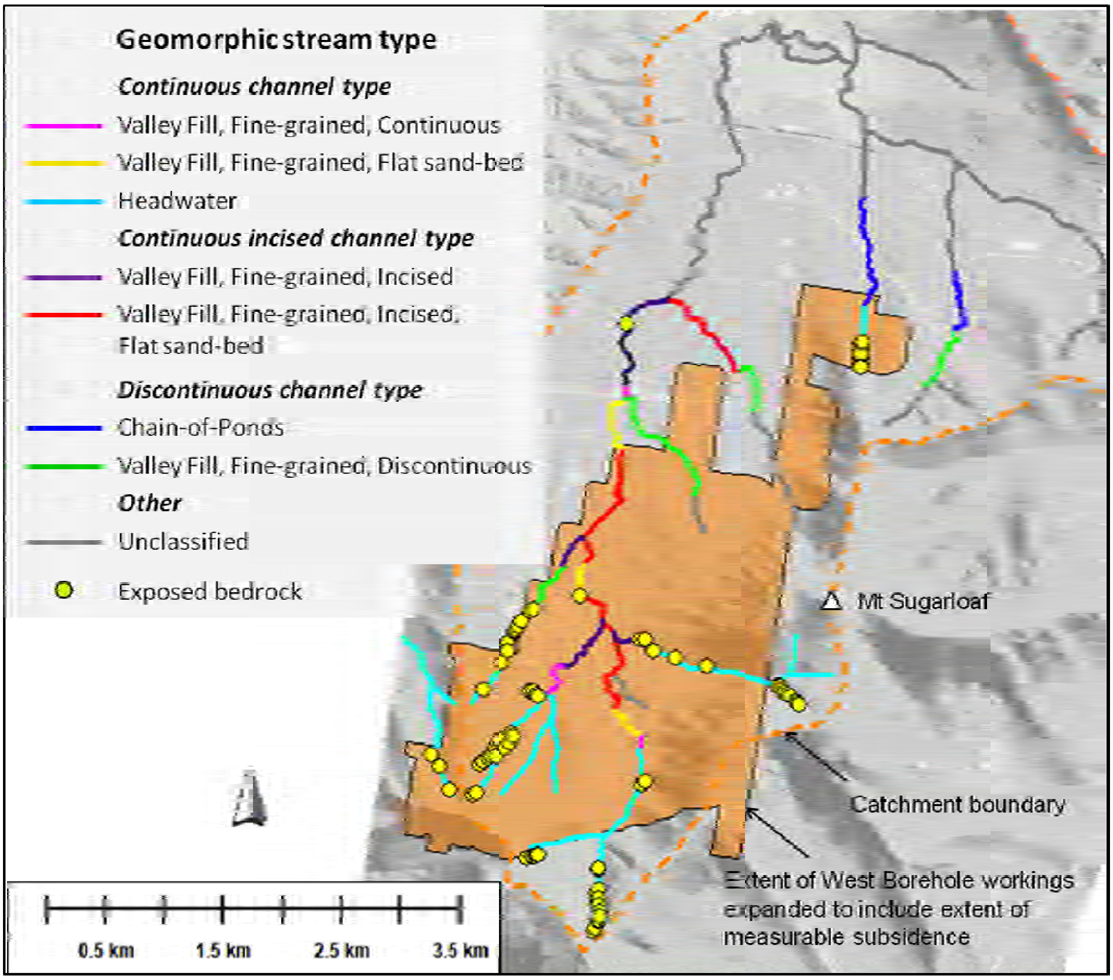

Figure 31. Bedrock outcrops observed in the bed of channel network of the Project area, relative to geomorphic type.

Figure 32. Unusual bedrock outcrop in the bed of S2 (third-order), 151° 31' 13.47"E, 32° 52' 10.76"S. Photo location K (looking downstream).

3.5.8 Bed material

The geology of the Project area comprises a resistant layer of Triassic Narrabeen Group (Clifton Sub-Group) (tuff, claystone, sandstone, conglomerate, coal) forming the high ridges, and slightly older Late Permian Newcastle Coal Measures (conglomerate, sandstone, tuff, shale, coal) over the foothills. A distinctive cliff line (Figure 6) is formed along the edge of the Triassic material. The headwater streams had large-sized bed material comprising exposed bedrock, boulders and cobbles. This material represented either in-situ bedrock or weathered material transported under the influence of gravity, assisted by fluvial action in major storm events. The bedrock contains sand, so it was expected to find sand in the bed material of the streams.

Most of the lower reaches of Surveyors Creek 2 contained a distinctive flat sand-bed (Figure 33). The channel was rectangular in shape, with the bed being relatively featureless. In southeast Australia, streams of this type are usually associated with a previous phase of catchment disturbance (vegetation clearing and subsequent gullying) that created an over-supply of sediment which the streams were not fully competent to transport. This is not the case for the catchment in the Project area, which is fully forested. Although forestry has been practiced in the catchment in the past, the headwaters are too steep and inaccessible to ever have been cleared.

The valley fill contains large stores of sandy material (Figure 34), sourced from weathered bedrock, that is released as bedload when channels migrate across the fill or incise into it. The relatively large volume of sand in the bed of Surveyors Creek 2, plus evidence of incision, suggests that the stream is relatively active, with most of the sand probably sourced from eroding channel walls.

Figure 33. Flat sand-bed stream type, S2 (third-order), 151° 31' 3.61"E, 32° 53' 4.17"S. Photo location L (looking downstream).

Figure 34. Channel incised into fine-grained valley fill (sand-rich) with flat sand-bed, S2 (third-order), 151° 31' 13.47"E, 32° 52' 10.76"S. Photo location M (looking downstream).

Sand was the dominant bed material in the lower reaches of the streams in the proposed West Borehole Seam Project area, and coarse material dominated the bed material of the headwater streams. However, some of the headwater stream reaches were observed to contain considerable quantities of sand in their beds. In this setting, the coarser bed material is embedded within the overlying sand layer (Figure 35). The source of this material is the soils on the drier rocky ridge crests and sandy soils on the steep headwater slopes. This sand works its way downstream and adds to the material making up the flat sand-beds of the valley fill streams.

Figure 35. Headwater stream type, S2 (second order), 151° 31' 16.11"E, 32° 54' 11.75"S. Coarse boulder and cobble bed material is embedded in sand. Photo location N (looking downstream).

3.6 Summary of geomorphic characteristics of reaches within proposed West Borehole Seam workings area

Summary data concerning the key geomorphic features of the streams that fall within the boundary of potential influence from subsidence due to the proposed West Borehole Seam Workings are provided in three tables (Table 7, Table 8 and Table 9).

Table 7.
Streams within the area of the proposed mine West Borehole Seam Project area. Length and gradient characteristics of stream reaches.

Reach	Order	Length (m)	Stream gradient			
			Mean (degrees)	90th percentile (degrees)	Mean (m/km)	90th percentile (m/km)
Surveyors Creek 1 C	1	651	5.37	12.96	95.1	230.1
Surveyors Creek 2	2	2094	1.40	6.63	24.6	116.3
Surveyors Creek 2	3	2077	0.35	1.65	6.1	28.8
Surveyors Creek 2 A	1	283	19.95	34.06	383.8	684.5
Surveyors Creek 2 B	1	414	1.69	5.94	29.7	104.0
Surveyors Creek 2 C	2	1493	4.63	17.87	84.3	322.7
Surveyors Creek 2 D	1	789	6.76	12.26	119.3	217.3
Surveyors Creek 2 D	2	1173	0.80	3.83	14.1	66.9
Surveyors Creek 2 D A	1	645	6.38	14.23	113.1	253.6
Surveyors Creek 2 D B	1	1187	7.27	14.92	129.3	266.5
Surveyors Creek 2 E	1	1545	2.59	8.53	46.2	150.0
Surveyors Creek 2 F	1	913	1.69	3.57	29.4	62.4
Surveyors Creek 2 G	1	418	3.02	8.73	53.2	153.5
Wallis Creek 1	1	462	8.46	14.12	149.8	251.6
Wallis Creek 1 A	1	64	15.13	19.19	271.4	346.5

Table 8.
Streams within the area of the proposed West Borehole Seam Project area. Dimensions and geomorphic features. S = Surveyors Creek; W = Wallis Creek; $\bar{X}$ = mean; σ = standard deviation; P_{50} = median; P_{75} = 75th percentile; P_{25} = 25th percentile; N = number of observations; ND = no data; - = not applicable.

Reach	Order	Bankfull width (m)		Bankfull depth (m)		Top width (m)		Top depth (m)		Bankfull width/depth		Incised top width/depth		LWD load class (0 - 4)		Knickpoint height (m)			Pool	Rock on bed
		$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	P_{50}	$\frac{(P_{75}-P_{25})}{2}$	N	$\bar{X}$	σ	N	N
S 1 C	1	2.5	0.9	1.22	0.76	-	-	-	-	2.8	1.8	-	-	1	1	3	1.7	0.6	0	1
S 2	2	3.6	1.2	0.59	0.18	7.7	1.3	2.78	0.75	6.2	2.4	2.9	0.7	2	2	1	2.1	-	0	2
S 2	3	3.7	0.8	0.36	0.08	8.8	2.5	1.81	0.92	10.7	3.0	5.7	2.3	2	1.5	0	-	-	0	0
S 2 A	1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
S 2 B	1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
S 2 C	2	3.5	1.6	0.54	0.28	9.1	2.7	2.96	0.84	7.2	2.3	3.1	0.7	1	1.5	3	3.0	2.6	2	2
S 2 D	1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
S 2 D	2	3.5	1.4	1.87	1.08	-	-	-	-	2.3	1.3	-	-	1	0.8	1	0.6	-	0	0
S 2 D A	1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
S 2 D B	1	2.4	0.6	0.50	0.18	-	-	-	-	5.5	3.0	-	-	1	1.5	5	1.5	0.6	0	2
S 2 E	1	2.7	2.6	0.48	0.24	-	-	-	-	7.3	9.2	-	-	1	1.5	7	1.1	0.4	2	6
S 2 F	1	1.8	0.3	0.27	0.29	-	-	-	-	12.7	8.7	-	-	4	4	3	0.7	0.2	0	0
S 2 G	1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
W 1	1	2.0	0.6	0.55	0.19	-	-	-	-	3.9	1.5	-	-	1	1	2	0.5	-	0	2
W 1 A	1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

Table 9.
Streams within the area of the proposed West Borehole Seam Project area. Geomorphic stream types present in reaches. H = Headwater; CP = Chain-of-ponds; VF = Valley Fill; FG = Fine-grained; I = Incised; C = Continuous channel; D = Discontinuous channel; FSB = Flat Sand-bed; U = Unclassified.

Reach	Order	Stream types
Surveyors Creek 1 C	1	CP H
Surveyors Creek 2	2	VF/FG/FSB VF/FG/I/FSB VF/FG/C H
Surveyors Creek 2	3	VF/FG/FSB VF/FG/I/FSB
Surveyors Creek 2 A	1	H
Surveyors Creek 2 B	1	U
Surveyors Creek 2 C	2	VF/FG/I H
Surveyors Creek 2 D	1	H
Surveyors Creek 2 D	2	VF/FG/I VF/FG/C H
Surveyors Creek 2 D A	1	H
Surveyors Creek 2 D B	1	H
Surveyors Creek 2 E	1	VF/FG/I VF/FG/D H
Surveyors Creek 2 F	1	VF/FG/D U
Surveyors Creek 2 G	1	U
Wallis Creek 1	1	H
Wallis Creek 1 A	1	H

4 Risk of Subsidence Impacts

The risks of subsidence impacts to geomorphic character (i.e. form and process) of streams in the Project area were assessed using a risk assessment method, with the risk to geomorphic character considered to be dependent on the following:

- Geomorphic fragility of the stream, which is a function of both the potential for changes to the stream due to threatening processes, and the resilience of the stream to threatening processes.
- The existing geomorphic condition of the streams in the Project area.
- Relative subsidence (i.e. the change in bedslope due to subsidence, relative to the existing bedslope of a particular stream, as well as the distributions of bedslopes for the various stream types within the Project area).

The risk was determined based on a function of likelihood (subsidence threat level, based on geomorphic condition and relative subsidence) and consequence (geomorphic fragility).The methodology for assessing the risk to geomorphic character based on the factors above is provided in Section 2.9.

4.1 Generic subsidence impacts and consequences for geomorphological forms and processes

Subsidence results in both vertical and horizontal displacement. The slope of the surface dictates the vertical displacement with respect to the horizontal, so in general, the higher the slope, the greater is the potential for impact to the morphology of the land surface (Blodgett and Kuipers, 2002). In the extreme case of near vertical surfaces, cliff falls can result (Hebblewhite, 2009).

Subsidence can cause the formation of open cracks, fissures or pits, which, if connected either directly or indirectly to surface water (streams, lakes, ponds), may lead to partial or complete loss of water that is drained to lower strata or mine workings (Blodgett and Kuipers, 2002).

Hebblewhite (2009) reported that while the capacity to predict subsidence effects was well developed, the same could not be said for the capacity to predict the impacts of subsidence. This is partly because of the complexity of the problem (Hebblewhite, 2009).

Direct impacts of conventional subsidence behaviour on watercourses can include:

- lowering of stream embankments;
- change in stream gradient (longitudinal stream profile);
- tilting of the bed so that flow is biased to one side of the watercourse; and
- cracking of the watercourse bed (NSW Department of Planning, 2008).

These impacts can have a number of consequences, including ponding of water and erosion of stream banks (NSW Department of Planning, 2008).

4.2 Threatening processes to geomorphic character of streams of the Project area

The potential impacts associated with subsidence for the Project are described in the subsidence assessment by Ditton Geotechnical Services (2012). It should be noted that the assessment of potential subsidence impacts considered the implementation of the relevant SCZs shown in Figure 10.

Table 10.
Proposed Subsidence Surface Constraints, Performance Measures and Subsidence Control Zones

Surface Feature	Subsidence Performance Measure	Subsidence Control Zone
Cliff Lines	Minor impact resulting in negligible environmental consequence. No additional risk to public safety.	First workings only within 30 m of a cliff line greater than 20 m in length resulting in less than 150 mm subsidence. Partial extraction with stable remnant pillars resulting in less than 300 mm of subsidence for all other cliff lines.
Steep Slopes	Minor impact resulting in negligible environmental consequence. No additional risk to public safety.	Partial extraction with stable remnant pillars resulting in less than 300 mm of subsidence beneath slopes greater than 26.5°.
3rd Order Streams or above	Negligible environmental consequences (that is, negligible diversion of flows and negligible change in the natural drainage behaviour of pools). Negligible connective cracking to underground workings.	First workings only within 26.5° angle of draw resulting in less than 20 mm subsidence at the edge of the bank.
1st and 2nd Order Streams	Not more than minor environmental consequences. Negligible connective cracking to underground workings.	Partial extraction with stable remnant pillars resulting in less than 300 mm of subsidence where the depth of cover to the stream is less than 80 m.
Groundwater Dependent Ecosystems and Hunter Lowlands Redgum Forest on 3rd Order Streams	Negligible environmental consequence.	Partial extraction with stable remnant pillars resulting in less than 300 mm of subsidence.

Notes: Cliff Lines - a continuous rock face with minimum height of 10 m and minimum slope of 2 to1

Steep Slopes - an area of land having gradient between 1 in 3 and 2 in 1

Groundwater Dependent Ecosystems – Coastal Warm Temperate Sub Tropical Rainforest and Alluvial Tall Moist Forest

Minor - Relatively small in quantity, size and degree given the relative context
Negligible - Small and unimportant

Based on potential impacts associated with subsidence for the Project, a number of subsidence-related threatening processes to the geomorphic character of streams in the Project area were identified (Table 11).

Table 11.
List of subsidence-related threatening processes that pose a potential risk to the geomorphological character of streams of the Project area.

Threatening Process	Potential threat level
Cliff fall in upper headwaters	Headwaters are naturally highly variable in form, so geomorphic impact is small. Primarily a geotechnical issue.
Cracking of bedrock sections of stream beds	Leakage through cracks in rock beds can reduce baseflow and drain pools, but this does not directly impact sediment transport or bed stability. Primarily a geotechnical and hydrological issue.
Sinking of sand-bed sections of streams	This stream type will probably be resilient through rapid infilling of subsided areas with sand (high transport rate)
Hydraulic control points that maintain the depth of water in pools could subside	There are few pools within the area proposed for mining, and the most important pools (chain-of-ponds stream type reaches) are mostly downstream of the area affected by subsidence, and therefore at low risk
Reversal of flow direction	The streams have sufficiently high gradient that reversal of flow direction is unlikely
Knickpoint migration upstream of areas of subsided stream bed	**A realistic threat**, particularly in areas immediately downstream of existing knickpoints, and where subsidence increases stream gradient beyond the natural range of variation

Based on the above consideration of the potential subsidence-related threats (Table 11), the main threatening process in the Project area is locally high stream gradients causing formation of knickpoints, or exacerbation of existing knickpoints.

4.3 Risk of geomorphic change due to subsidence, associated with stream type

4.3.1 Geomorphic Fragility

The fragility of the stream types in the Project area were assessed relative to the categories of Cook and Schneider (2006, see Table 1), and in consideration of the threatening processes (and their potential threat level) described in Section 4.2 (Table 12).

4.3.2 Existing Geomorphic Condition

The level of threat to streams from subsidence is lower the closer the stream is to good (natural) condition (because streams in good condition are more robust) (Table 4).

Although some of the stream reaches were incised and flat-sand beds were present in places, there was no evidence that these were unnatural features, as the streams and their catchments were essentially undisturbed (apart from isolated short lengths where the streams crossed high voltage power line easements, narrow lightly used tracks, or roads with properly formed culverts). Thus, all stream reaches were assessed to be in good geomorphic condition, according to the criteria of Outhet and Cook (2004) (described in Table 2).

Table 12.
Classification of geomorphic fragility of stream types in the Project area.

Geomorphic stream type	Geomorphic fragility	Rationale
Continuous channel type		
Valley Fill, Fine Grained, Continuous	High	Potential for knickpoint migration with incision, leading to stream migration or avulsion.
Valley Fill, Fine Grained, Flat Sand-bed	Low	High sediment supply will infill subsidence
Headwater	Low	Naturally highly variable form with pools, steps and high gradients
Continuous incised channel type		
Valley Fill, Fine Grained, Incised	Moderate	Potential for knickpoint migration (active knickpoints present in existing streams). Incised form not conducive to avulsion.
Valley Fill, Fine Grained, Incised, Flat Sand-bed	Low	High sediment supply will infill subsidence. Incised form not conducive to avulsion
Discontinuous channel type		
Chain of Ponds	High	Subsidence likely to create new pools or enlarge existing pools. Potential for knickpoint migration with incision (kickpoints stable in existing streams).
Valley Fill, Fine Grained, Discontinuous	High	Potential for knickpoint migration with incision (active knickpoints present in existing streams).
Other		
Unclassified	Unknown	No information

4.3.3 Relative Subsidence

Subsidence profiles were provided by Ditton Geotechnical Services (2012) for streams S2, S2E, S2D, S2C, and S2F (Figure 2), and these subsidence profiles were determined with SCZs present. The geomorphic risk associated with subsidence could not be assessed for other stream reaches in the Project area, which consisted of short sections of steep headwater streams and one unclassified stream (S2G).

The relative subsidence for these streams was determined over short stream lengths (average 6 m long) with regard to four relative subsidence categories (defined in Table 4). These categories were determined on the basis that a more steeply sloping bed in the upstream direction results in a greater threat to geomorphic character, as the more steeply sloping bed may cause formation of a knickpoint that migrates upstream and scours the bed and banks.

4.3.4 Risk to geomorphic stream form and process

Using the methodology described in Section 2.9 (i.e. determining subsidence threat level [relative subsidence X geomorphic condition] and then determining geomorphic risk [subsidence threat level X geomorphic fragility]), the risk to geomorphic stream form and process was assessed.

Most of the stream lengths were assessed to be insignificant, with a few isolated short lengths of stream being assessed at low, moderate and high risk levels (Figure 36).

The highest risk areas were located on Valley-fill, Fine-grained, Discontinuous stream type on Stream S2F, as these stream sections were identified as having high fragility (due to the potential for knickpoint migration), and high relative subsidence (i.e. high relative upstream slope).

The unassessed streams were steep headwater streams, and one unclassified stream. Based on the similarities with the geomorphic characteristics of the assessed streams, the unassessed streams are likely to have an insignificant risk to geomorphic stream form and process due to subsidence.

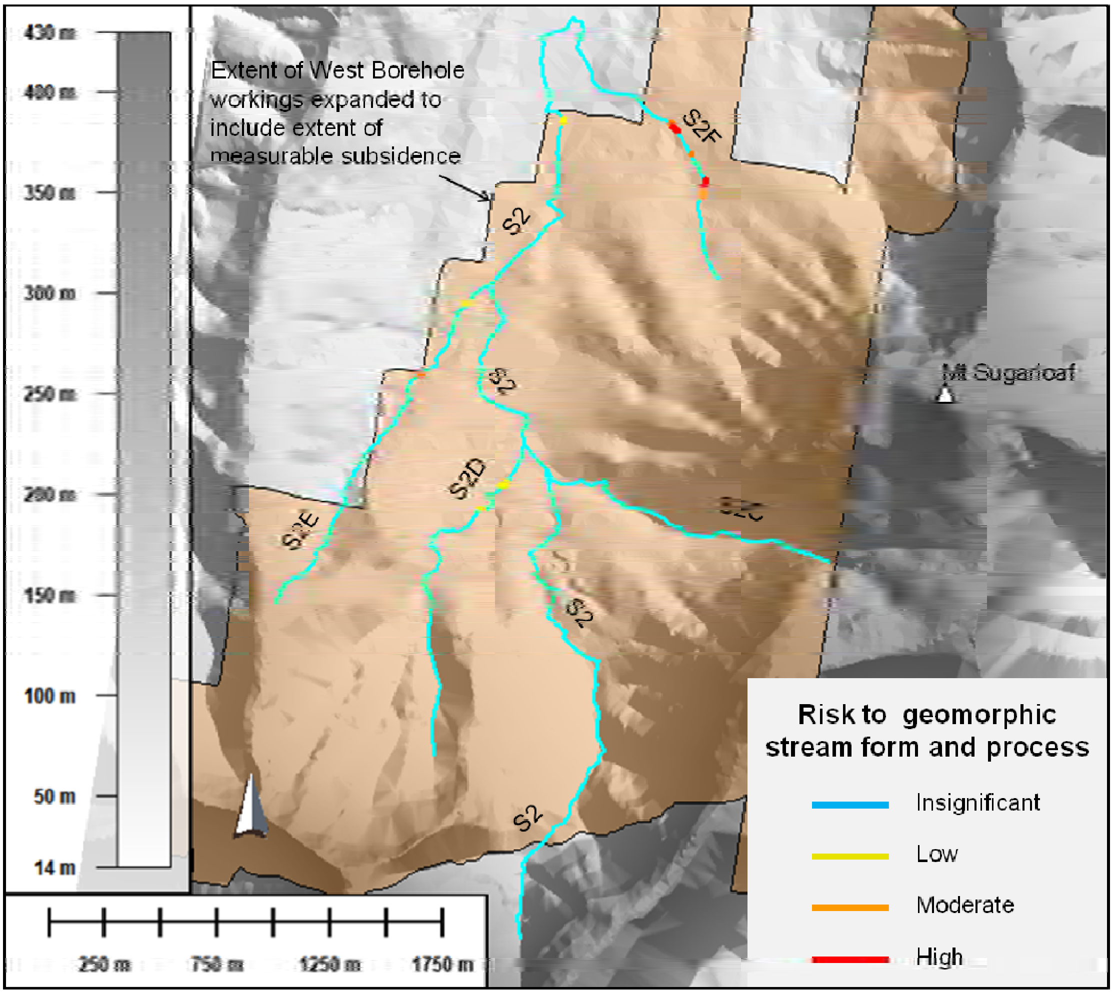

Figure 36. Assessed risk to geomorphic stream form and process under the condition of predicted subsidence with SCZs. Only the streams with subsidence predictions are shown.

5 Conclusion, Monitoring and Mitigation

5.1 Conclusion

This report characterised the fluvial geomorphological features of the streams in the Project area. The report used repeatable methods which were fully described. The data described the benchmark condition from which the future geomorphic condition of the streams can be compared.

The streams comprised a number of geomorphic types, with all being in good geomorphic condition (i.e. essentially natural with intact form and process).

The risks to geomorphic stream form and process associated with the predicted changes due to subsidence were semi-quantitatively assessed. This process was acknowledged to be uncertain. Overall, the majority of the assessed stream lengths had an insignificant risk of geomorphic change due to subsidence. A few short sections were assessed to have higher risk (due to steepening of the bed profile on valley fill stream type).

5.2 Monitoring

The assessment of subsidence by Ditton Geotechnical Services (2012) sets out details of a subsidence monitoring program and management plan. The monitoring program includes regular topographic survey of the thalweg and cross-sections of Surveyors Creek Tributary 2 and a number of key headwater tributaries. Visual inspections and photographic surveys are proposed before, during, and after mining as an adjunct to the topographic survey. This program will provide some of the information required for monitoring of stream geomorphology.

In addition to the above subsidence monitoring, at the locations on the streams identified as having a low/moderate/high risk to geomorphic characteristics (Figure 36), permanent reference points for annual photographic recording should be established. These photographs must be assessed, and then reported on, by a professional geomorphologist.

This report provides data for the baseline geomorphic condition of streams in the Project area. The methodology used in this report to characterise geomorphic condition is repeatable, and as such, the geomorphological survey undertaken for this report should be repeated after mining to identify potential impacts associated with subsidence.

The geomorphic response to subsidence is likely to be slow, so a frequency of five years for catchment-wide re-survey and reporting of stream geomorphological condition is suggested. The headwater streams identified in this report would not need to be included in the monitoring program, as the risk to geomorphic character is expected to be insignificant (Figure 36). However, it is suggested that a sample of 10 headwater sites (i.e. randomly distributed points on headwater streams) are included in the survey to confirm this assumption.

5.3 Mitigation

Mitigation is to eliminate or reduce the frequency, magnitude, or severity of exposure to risks, or to minimise the potential impact of a threat. The key subsidence-related process that threatens the geomorphic condition of streams in the Project area is the development, and upward migration, of knickpoints (see Section 4.2). It is considered inappropriate to attempt to pro-actively manage this threat because, although considerable effort was made to quantify the level of risk and identify the locations most at risk, the risk has an uncertain probability. Thus, it is recommended to address the risk of knickpoint formation through a process of adaptive management. Under this process: (i) regular monitoring would detect if and where the threat occurs, (ii) an assessment would be made to determine the potential consequences of the observed threat, and then, (iii) appropriate control works would be put in place.

The subsidence monitoring described by Ditton Geotechnical Services (2012) would identify development of knickpoints, particularly at the locations on the streams identified in as having a low/moderate/high risk to geomorphic characteristics (see Figure 36).

If significant development of knickpoints is observed, these should be professionally assessed in order to determine the most appropriate control measure. In general, on streams of this size and grade, easily degraded materials that cannot be securely fixed to the bed (e.g. coir logs) are unsuitable. The most commonly used, and reliable, approach to knickpoint control is rock grade control structures. These can be expensive to build, especially if the site has poor access for trucks and heavy equipment. Also, heavy equipment can inadvertently cause damage to the vegetation and bank material in riparian zones. For streams in the Project area, large wood structures could be the most appropriate method of treating knickpoints.

Brooks et al. (2006) noted the difficulty of controlling bed degradation using wood-based strategies alone, but described some examples of this approach being successfully trialed in streams in the Hunter Valley and northern NSW. The most appropriate of these approaches for vulnerable streams in the Project area are log sills.

Log sills are buried, multi-log structures, using logs without rootwads for the cross spanning logs to ensure a snug fit, keyed well into both banks. Geo-fabric is used in the sub-surface portion of the log sill to reduce the risk of undercutting. These structures are generally built as a full channel spanning structure across small sand-bed streams (Brooks et al., 2006, p. 71). The log sills are stabilized using log pins driven vertically into the bed of the stream.

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