2022

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Andrew Hunter

Phil Flentje

Alan Moon

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The Princes Highway along Bulli Pass is a narrow, heavily trafficked two lane section of the Princes Highway that traverses steep slopes on a grade of 9H:1V on the Illawarra Escarpment, about 11 km north of Wollongong, and 75 km south of Sydney in New South Wales (NSW), Australia. It is an important arterial road for the northern suburbs of Wollongong, connecting Mt Ousley Road (M1 Princes Motorway) at the crest of the escarpment to the suburb of Thirroul on the coastal plain at the base of the escarpment. Bulli Pass has a long history of landslide and rockfall events, some of which were reported as early as 1890. One of the most significant of these events occurred on 17 August 1998 during a 1 in 100 year rainfall event. The 1998 landslide event comprised approximately 38 debris flows and slides and numerous rockfalls which partially inundated a number of cars and trapped about 15 cars on the pass. More recently, in early 2015, a small rockfall penetrated the windscreen of a car travelling up the pass.

Transport for New South Wales (TfNSW) commissioned an investigation into slope instability hazards affecting the road in late 2011. This was followed in 2015 by a Risk Mitigation Options study and the detailed design of risk mitigation works in 2016. This paper provides an overview of the methods used to investigate hazards and assess risk at the site over a five year period. This has included research into the landslide history, geomorphological mapping, acquisition and review of airborne laser scanning (ALS) data, review of rainfall data and the development of a landslide volume frequency model. The development of this model allowed hazards to be readily communicated and risks to be assessed. The actual design and construction of the Shallow Landslide Barriers and the Debris Flow Barriers that followed on from these assessments will be discussed in a subsequent companion paper.

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BULLI PASS LANDSLIDE RISK MANAGEMENT PART 1 - HAZARD ASSESSMENT

Andrew Hunter[1]**, Phil Flentje**[2] **and Alan Moon**[3]
[1]GHD, Sydney; [2]University of Wollongong ; [3]Engineering Geologist, Adelaide

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ABSTRACT

The Princes Highway along Bulli Pass is a narrow, heavily trafficked two lane section of the Princes Highway that traverses steep slopes on a grade of 9H:1V on the Illawarra Escarpment, about 11 km north of Wollongong, and 75 km south of Sydney in New South Wales (NSW), Australia. It is an important arterial road for the northern suburbs of Wollongong, connecting Mt Ousley Road (M1 Princes Motorway) at the crest of the escarpment to the suburb of Thirroul on the coastal plain at the base of the escarpment. Bulli Pass has a long history of landslide and rockfall events, some of which were reported as early as 1890. One of the most significant of these events occurred on 17 August 1998 during a 1 in 100 year rainfall event. The 1998 landslide event comprised approximately 38 debris flows and slides and numerous rockfalls which partially inundated a number of cars and trapped about 15 cars on the pass. More recently, in early 2015, a small rockfall penetrated the windscreen of a car travelling up the pass.

Transport for New South Wales (TfNSW) commissioned an investigation into slope instability hazards affecting the road in late 2011. This was followed in 2015 by a Risk Mitigation Options study and the detailed design of risk mitigation works in 2016. This paper provides an overview of the methods used to investigate hazards and assess risk at the site over a five year period. This has included research into the landslide history, geomorphological mapping, acquisition and review of airborne laser scanning (ALS) data, review of rainfall data and the development of a landslide volume frequency model. The development of this model allowed hazards to be readily communicated and risks to be assessed. The actual design and construction of the Shallow Landslide Barriers and the Debris Flow Barriers that followed on from these assessments will be discussed in a subsequent companion paper.

1 INTRODUCTION

Bulli Pass is a narrow, heavily trafficked two-lane section of the Princes Highway that traverses steep slopes on the Illawarra Escarpment about 11km north of Wollongong and about 75km south of Sydney (Figure 1). More than 12,000 vehicles use the road each day. It is an important arterial road for the northern suburbs of Wollongong, connecting the M1 Princes Motorway at the crest of the escarpment with the coastal suburb of Thirroul at the foot of the escarpment. The escarpment is covered in dense littoral temperate rainforest as seen in Figure 2, 3 and 4. This paper deals with the forested slopes above the upper 1.1 km section of the pass from the hairpin bend (about 180 m below the top of the escarpment) to the intersection with the M1 Motorway at the top of the escarpment.

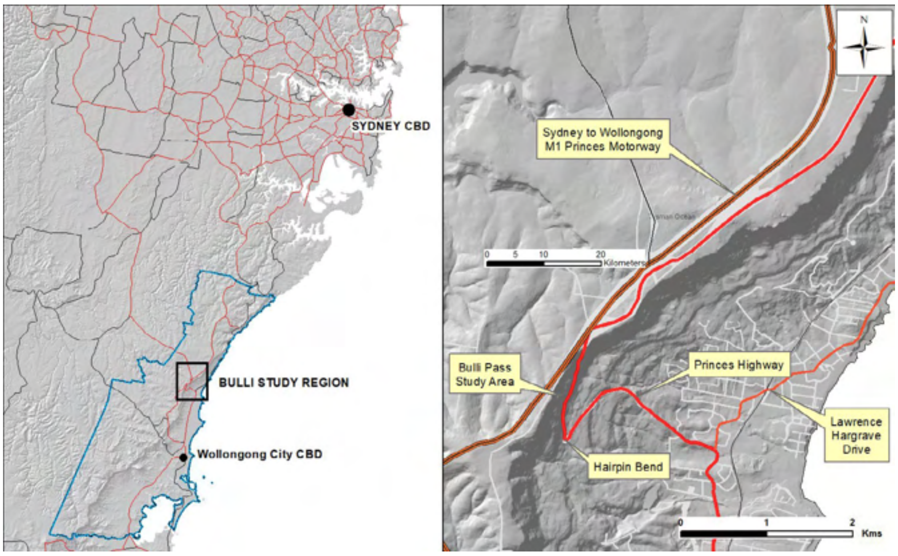


Figure 1: Location plan of Bulli Pass with respect to the M1 Princes Motorway and Sydney

Figure 2: Oblique March 2009 aerial view of Bulli Pass section of the Illawarra Escarpment looking south. The hairpin bend is just left of centre

The first track cut down the escarpment by pioneers in the vicinity of Bulli Pass was in 1815 and by 1828 a route was found to enable bullock drays to descend the escarpment. The current route of the pass was constructed in 1867, however at this time the road was only a single lane wide. Wheeled vehicles (i.e. horse drawn carriages) began using the road in 1863 and bitumen was laid on the road surface in 1926. Figure 3 is a 1907 image and shows narrow carriage wheel marks in the gravel pavement.

Figure 3: Looking north up Bulli Pass from the hairpin, 1907 (National Museum of Australia)

Landslide terminology used in this paper generally follows the scheme proposed by Cruden & Varnes (1996). Rock falls and debris flows have been reported at the site since the late 1800s, with the most notable of these events being initiated by a severe rainfall event on 17 August 1998 that caused widespread landslides and flash flooding in Wollongong and surrounding suburbs (Flentje, Chowdhury and Tobin, 2000). This paper presents the outcome of the investigation carried out by three engineering geologists, all with extensive backgrounds in landslide risk assessment, to assess landslide hazards at the site and in particular, the development of a landslide volume frequency model.

2 GEOLOGY AND GEOMORPHOLOGY

The geological sequence underlying Bulli Pass comprises the lower part of the Hawkesbury Sandstone and the upper formations of the Narrabeen Group (Figure 5) with the strata dipping gently to the southwest at up to 7°, however generally the strata dips at less than 2°. The escarpment geomorphology, strongly influenced by the underlying geology, reflects varying competencies of the underlying Permian/Triassic sedimentary units. The Hawkesbury Sandstone caps the escarpment, forming cliffs up to 20 m high, however it is either very thin or absent over the northern part of the site. The Bulgo Sandstone underlies the majority of the slopes at the site and can be subdivided into three distinct facies with each of these facies occupying approximately one third of its thickness; the basal pebbly facies, the middle volcanic facies and the upper shaly facies.

Figure 4: Oblique drone view from south of the hairpin looking north up the pass road and the subject forested slopes above

Two distinct geotechnical domains (GD1 to the north and GD2 to the south) have been identified at the site based on the geomorphology, as shown in Figures 5 and 6. As discussed below, the nature of landslide hazards in each domain is different. The boundary between the two domains is a ridge that crosses the escarpment slopes diagonally from west-southwest to east-northeast. This ridge line is reflective of the catchment boundary between the dominant Slacky Creek to the south and Hewitts Creek to the north. Slacky Creek has dissected the escarpment and draws from a larger catchment which extends to the west of the escarpment, whilst Hewitts Creek's catchment is limited to the escarpment slopes. This ridge dividing these two domains has steep south to southeast facing slopes on its southern side and the ridge coalesces with the upper escarpment at its upslope western end.

The escarpment slopes in GD1 are more subdued, comprising steep concave and convex colluvial slopes. The most apparent difference is the general absence of the Hawkesbury Sandstone cliff line. Rock cuts in Bulgo Sandstone up to about 15 m high are located adjacent to the climbing lane. The colluvium slopes, typically only 2 to 3m metres thick, immediately above the rock cuts are generally experiencing retrogressing slide type failures. GD1 also contains numerous well defined, active, yet intermittent gullies, some of which originate at the escarpment crest and are incised into bedrock. Many of the gullies were truncated by the original construction of the road side cuttings such that they are now 'hanging' above road level.

GD2 is more typical of the broader Illawarra Escarpment, comprising prominent Hawkesbury Sandstone cliffs with steep rocky talus drape over thick colluvium mantled slopes below. Terraces and gentle slopes have formed intermediate slopes on less competent geological units of the Bulgo Sandstone. Unlike GD1, there are no rock cuts, with steep colluvial slopes with some shallow battered cuts located directly adjacent to the road. In addition, there is a general absence of well-defined gullies across GD2.

3 INVESTIGATION METHODS

All project data compiled and collected (i.e. geology, LiDAR, assets, mining, boreholes, mapping, modelling etc.) was managed using ArcGIS software. Field mapping (geological and geomorphological) was the most important

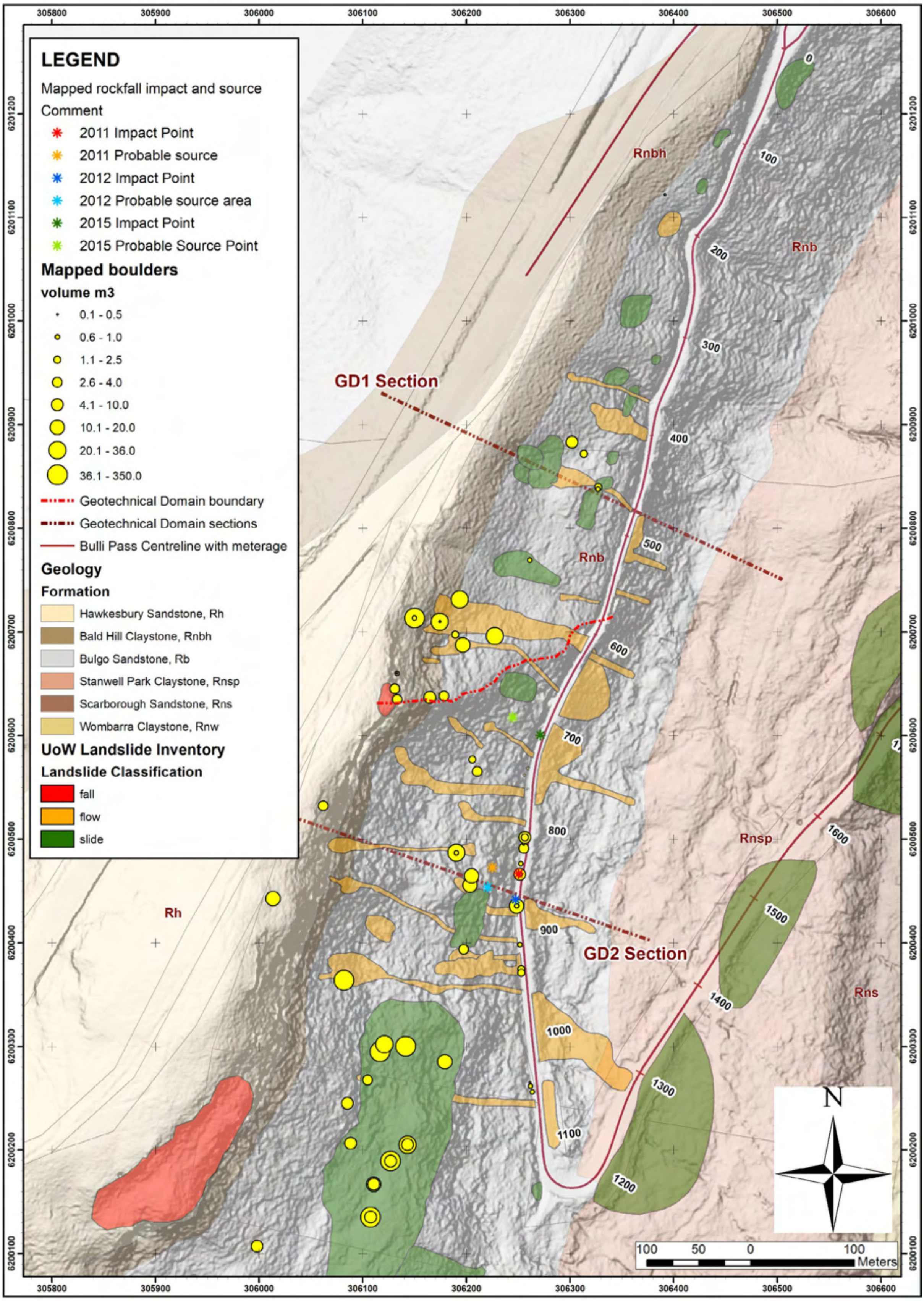


Figure 5: Site map highlighting the road location meterage, geology, landslides, known rockfall impact and source points, boreholes, culverts, geotechnical domains and the two domain type Sections

investigation activity and accurately locating the field observations across the steep and densely forested hillslopes was essential. A sub-1 m accuracy level Trimble GNSS GeoExplorer 6000 was used extensively to record the location of the walked routes and pertinent observations. The collected Trimble data was post-processed using the NSW Government CORSNet network of permanent Global Navigation Satellite System (GNSS) tracking stations to enhance the accuracy of satellite positioning. The Trimble software workflow readily facilitated the integration of data within ArcGIS, and field observations were integrated daily and either paper based or digital map output provided most mornings to help with field mapping. A summary of the observations is shown in Figure 6. Figure 7 shows a larger scale section of GD1 showing several GNSS position lines highlighting routes traversed together with some of the point, polyline and polygon observations recorded, together with final interpreted landslide outlines, over the geological boundaries on the 2015 high resolution ALS hillshade model. The tracklogs confirm that approximately 75 km was traversed during the field mapping, and some of these are shown in Figure 7.

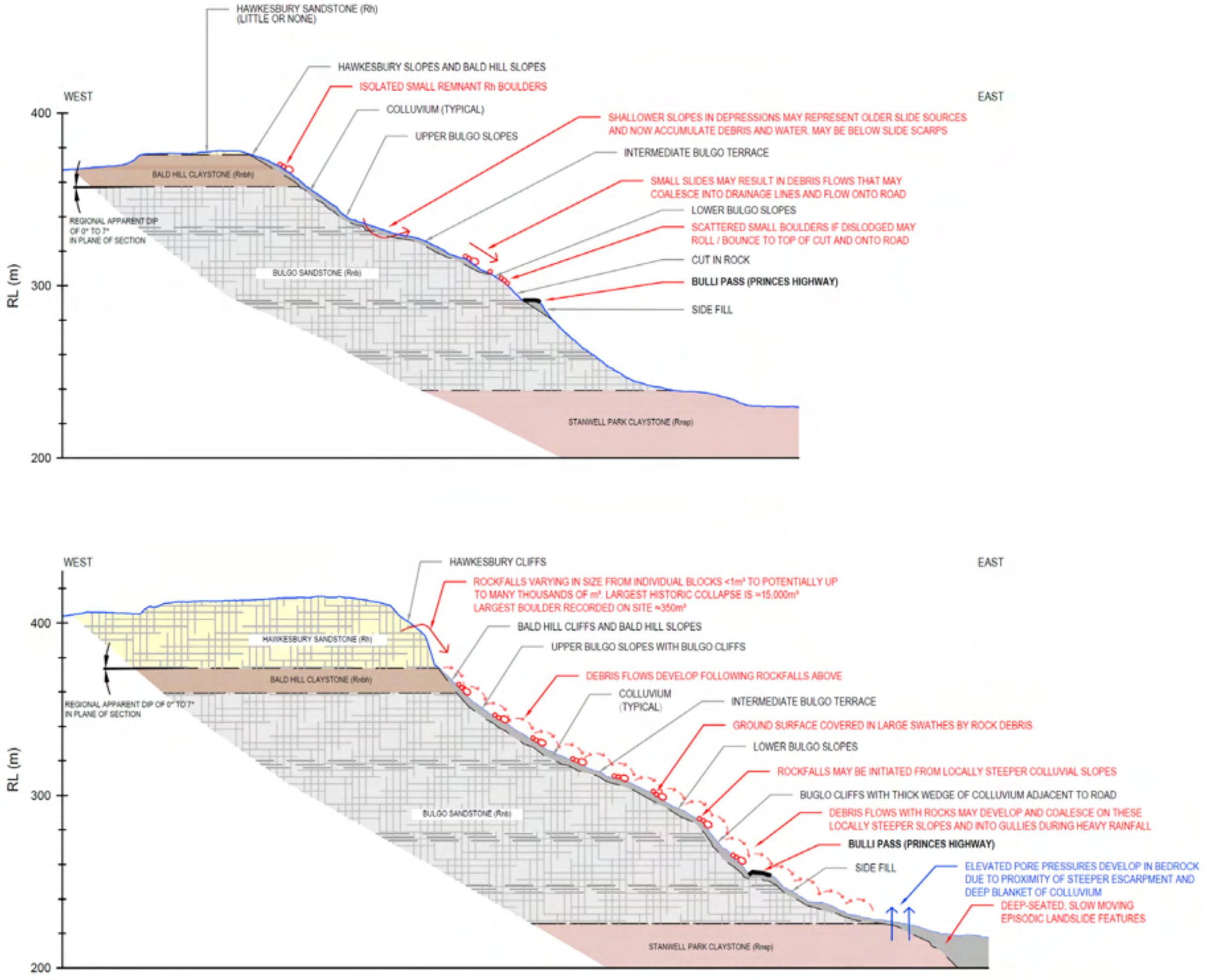


Figure 6: Cross sections (natural scale) at Bulli Pass showing GD1 (top) and GD2 (bottom). Black text refers to geology/geomorphology, red text refers to processes.

The essential starting point of this investigation was assessing the available GIS terrain data (contours or airborne laser scan data). As summarised in the following section, airborne laser scan data was the fundamental tool used as the basis for the GIS and field assessment work.

The University of Wollongong Landslide Research Team, lead by the second author, develops and manages a Landslide Inventory on behalf of industry partners Wollongong City Council, Sydney Trains and the Roads and Maritime Services. This inventory includes landslides on the subject site upslope of the hairpin bend on Bulli Pass. The relevant landslide sites from this inventory were included as the starting point of the desktop study work assembling data on the landslide hazards affecting the road. A considerable effort was then applied to revising the mapping of the August 1998 landslides which at the time (1998) were grouped into one large landslide affected area, with a note suggesting the area included approximately 30 smaller debris flows and rockfalls. Oblique aerial photographs of the pass taken in 1998, and field observations were used to complete this process. Numerous other sources of information were explored to supplement and append to the history of landsliding that has impacted the road. These sources included several earlier consultants reports and newspaper articles sourced through Trove (a free online multi-sourced database hosted by the National Library of Australia in partnership with National and State libraries across Australasia). The research on the August 1998 landslides is summarised in Section 6. Overall, the area contains 64 known landslides comprising 4 recent rock falls, 33 debris flows and 27 slide type failures and more than half of these features have been identified and or detailed during the course of this study. This work has enabled the development of the landslide frequency model as discussed in Section 7.

A comprehensive review of aerial photographs was also carried out. A wide range of vertical and oblique photos from 1938 to 2011 were examined. These included black and white small scale vertical photographs, close up hand held oblique photographs, large scale colour vertical aerial photographs and GIS based digital orthorectified images. These were very useful for identifying and constraining ages of various landslide features and identifying rocky debris on the slopes.

As the project developed and progressed into the design phase, much of the analysis and design work was also documented, collated and even in parts undertaken with the aid of the ArcGIS software. Some of this modelling work will be discussed in the companion paper.

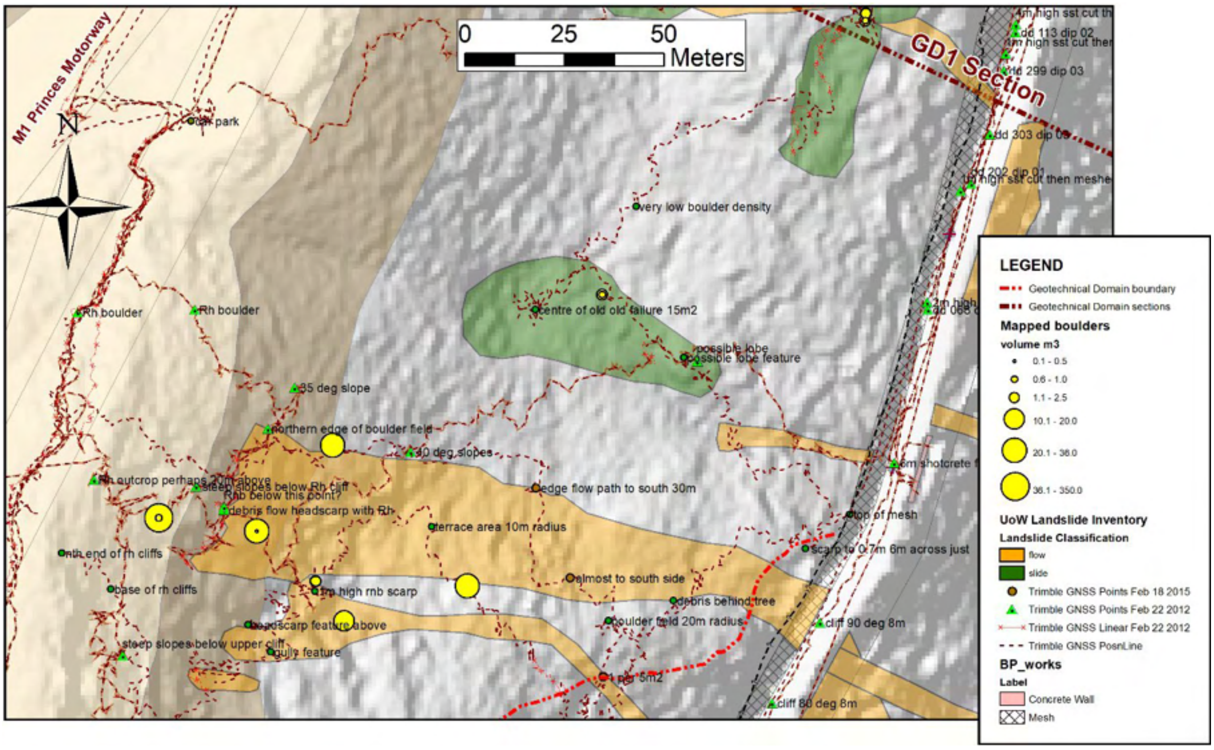


Figure 7: This figure highlights many of the observed point, line and polygon landslide features together with the recorded GNSS Position Lines south of the GD1 Section line extending to the ridge feature which forms the boundary between GD1 and GD2, displayed over the textured ALS/LiDAR hillshade surface within ArcGIS.

4 AIRBORNE LASER SCAN (LIDAR) DATA

An initial desktop study determined that Airborne Laser Scan (LiDAR) data coverage was not available for the site (Figure 8, A). However subsequently the data supplier identified that data coverage was available (Figure 8, B) but of poor quality. The available data was supplied at no cost and a new survey was commissioned by TfNSW. The 2011 data allowed the team to make some initial sections and aided map preparation for early reconnaissance mapping. New ALS data (Figure 8, C) was provided in 2012 and whilst a marked improvement on the 2011 data, it was lower accuracy than required for the detail hydro-geological assessments and the ultimate design of the selected barrier solution. In early 2015, a new ALS commission was specified by the team, calling for a sampling rate of 10 points per square metre. The 2012 ALS data provided 1.4 million points across the 200 hectare collection area, with an average spacing of 0.7 points per square metre. However, this data set, on some areas of the densely forested slopes above the road, had one ground return point per approximately 90 square metres. The 2015 data (Figure 8, D) provided 3.8 million points across the 200 hectare site, with an average of 1.9 points per square metre, and maintained a good average in densely forested areas of approximately 0.6 square metres per point.

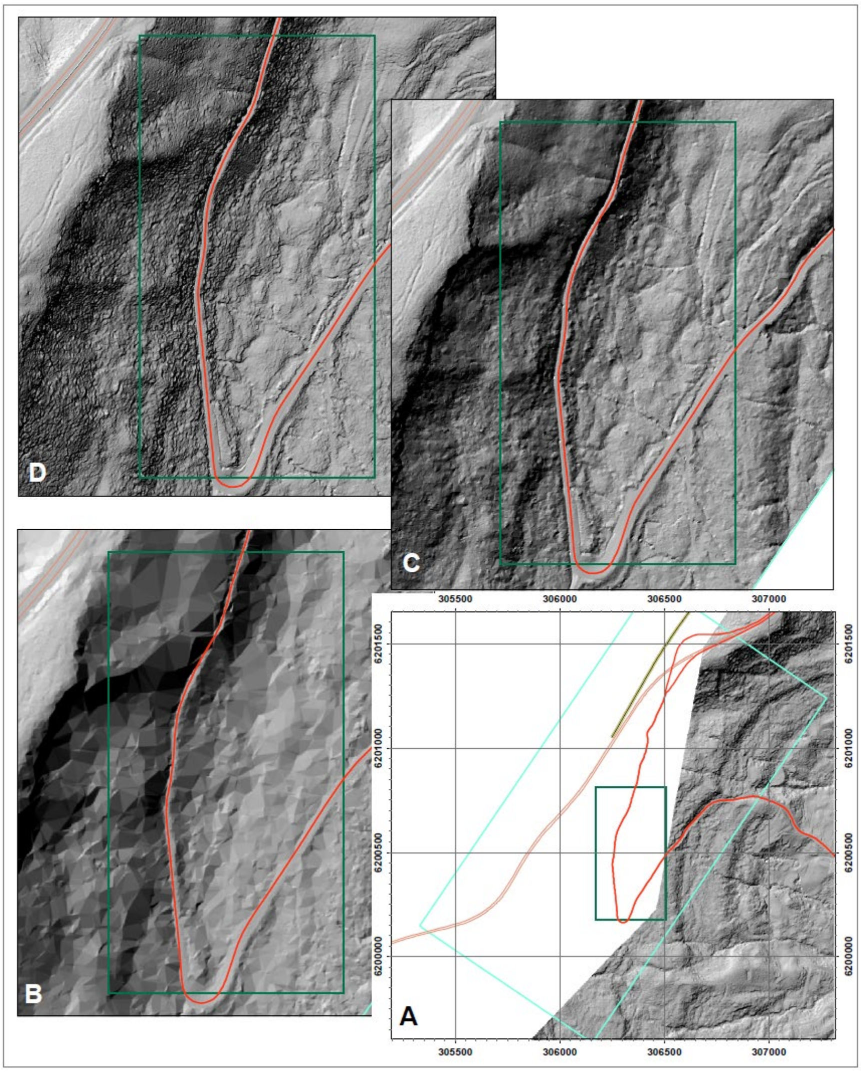


Figure 8: A – pre 2011 ALS coverage of the slopes above Bulli Pass was not available: B – free ALS data below delivery specs for another client: C – first tranch of ALS collected by the TfNSW for this investigation: D – final tranch of ALS data of high resolution to aid hydro and 3D flow modelling and to finalise design of GeoBrugg Barrier.

The project team printed a 3D model of the hillshade terrain by exporting a Virtual Reality Modelling Language (VRML) .wrl file from the ArcScene software and had it printed on a 3D printer. The printed model was approximately 800 mm long, 300 mm deep and 200 mm high and it proved to be a very popular talking point in meetings and was used to clearly demonstrate some of the slopes most pertinent features.

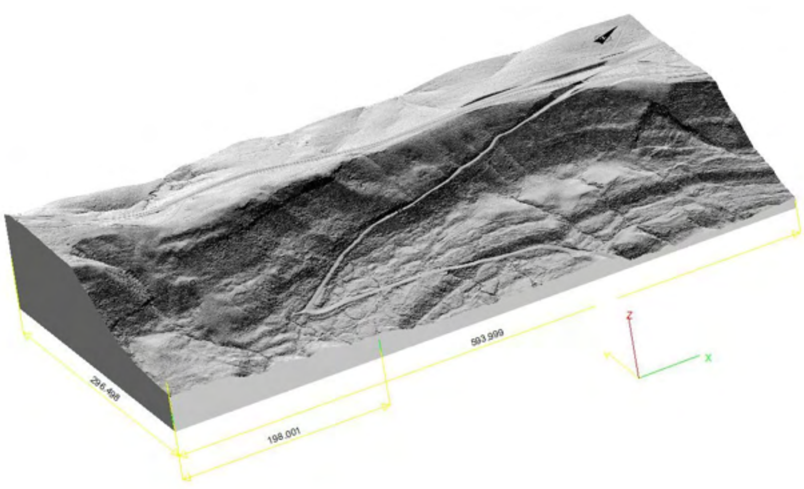


Figure 9: The 3D model with dimensions that was 3D printed

5 UNDERGROUND COAL MINING HISTORY

Underground coal mining has occurred beneath some of the site as part of the Excelsior I, II and B Collieries and both the Bulli and Balgownie seams have been mined. The available mine records extending across the site have been sourced from the Department of Mines and georeferenced as well as can be managed, without any survey, using cadastral reference boundaries with some of the results shown in Figure 10. This work has confirmed the extent of bord and pillar mining operations during the 1920's up to the 1950's and that there have been some areas of secondary pillar extraction as the mining was closing out during the mid-1940's to late 1950's. We acknowledge mining impacts would have occurred at the site however these impacts were not able to be discerned during fieldwork. However, in contrast a large rock wedge failure partly related to mine subsidence is located on the escarpment about 1 km north of the site (Henman & Flentje, in prep.).

Figure 10: Excelsior I, II and B Collieries board and pillar operations in the vicinity of Bulli Pass

6 AUGUST 1998 RAINFALL AND LANDSLIDE EVENT

During late afternoon on 17 August 1998 and during the following days, Bulli Pass was affected by a series of debris flows and rock falls along the full length of the site. The landsliding was initiated by an extreme rainfall event as highlighted in the Figures 11 to 13 below. Figure 11 shows the Australian Water Technologies (AWT) Bulli Pass rainfall pluviometer plot of hourly rainfall (importantly 750 m northeast from the centre of the subject site), clearly highlighting the intense rainfall of the later afternoon and evening of 17 August.

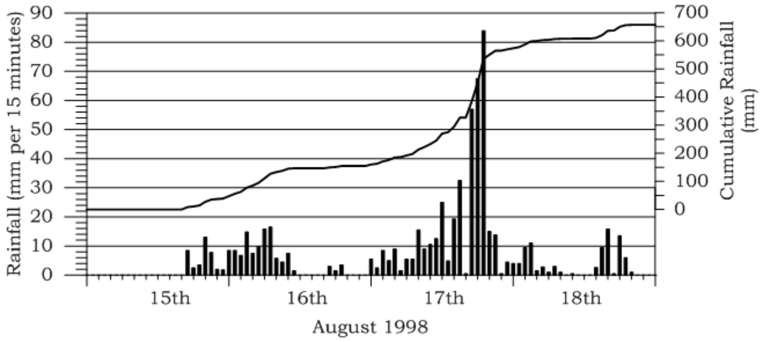


Figure 11: Public Works Bulli Pass hourly rainfall histogram

Figure 12 shows contours of 12 hr cumulative rainfall from midday on 17 August using data from 29 automatic rainfall stations that were operating at that time. This figure shows the clear orographic effect of the escarpment on the on-shore winds from this intense slow-moving east coast trough.

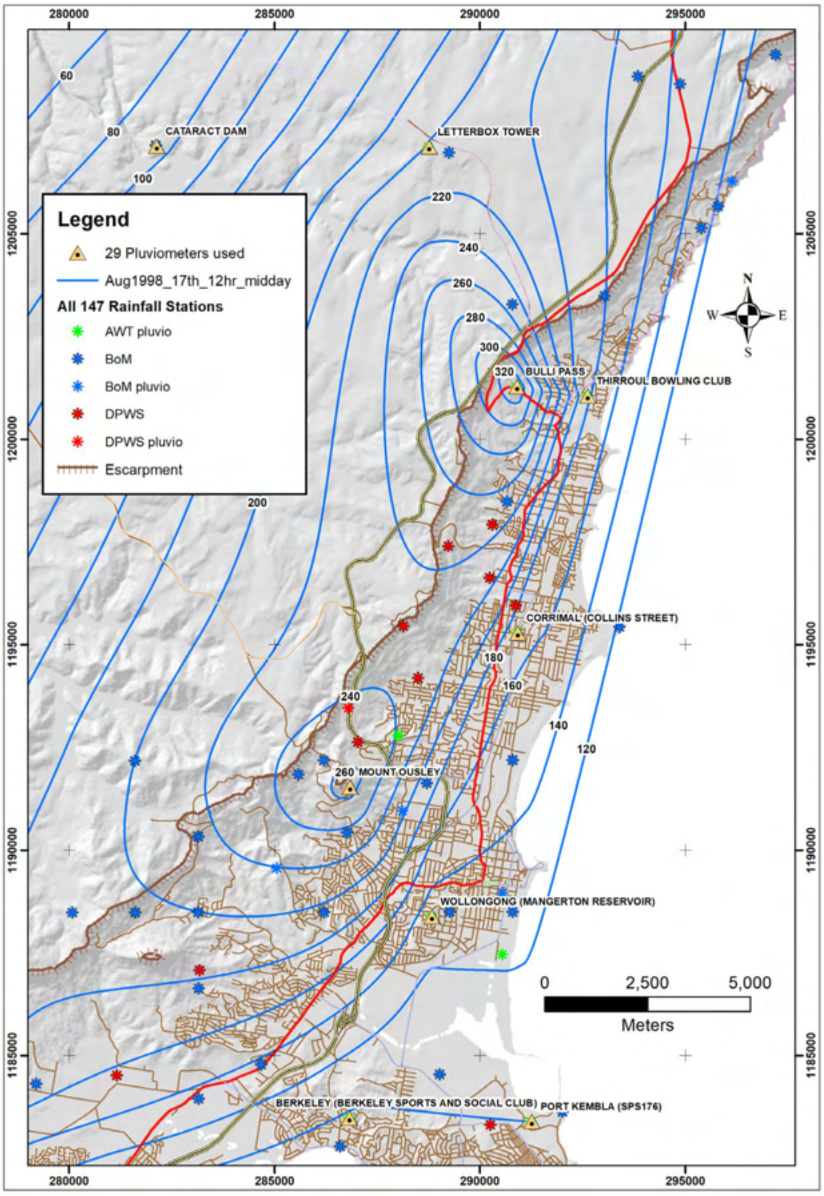


Figure 12: 12 hr rain totals from midday on 17th August 1998. The orographic effect of the rainfall event, and its focus between Bulli and Mt Keira is clear even with only 29 rainfall station values for the period.

The Bureau of Meteorology Intensity Frequency Duration (IFD) plot shown in Figure 13 displays the Annual Exceedance Probability curves current for the rainfall history of this site, and also the AWT Bulli Pass gauge (no longer operational) maximum rainfall intensities for the period 0000 hours on 15 August to 0000 hours on 19 August 1998. This curve exceeds to 1% Annual Exceedance Probability curve between 2 and 10 hours, and it exceeds the rare 1 in 200 year recurrence curve between the 3 to 5 hour intervals. The modelled rainfall at the head scarp of a central debris flow above the pass is also shown as the dashed heavy line with triangle symbology. This curve is very close to the 2% AEP for 4 and 12 hours, and sits between the 2% and 1% AEP curve at 6 hours and therefore this event is classified herein as a 2% AEP event.

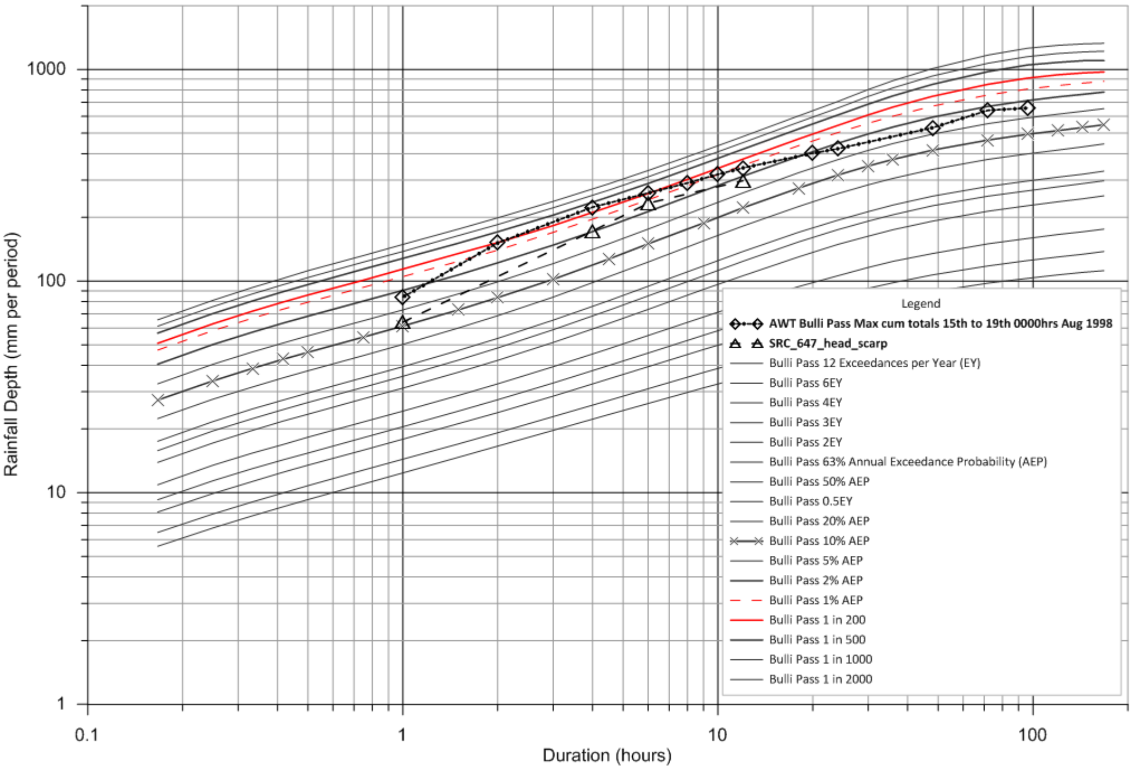


Figure 13: Bulli Pass hairpin BoM all AEP Jan 2020 with actual AWT Bulli Pass August 1998 rainfall and modelled rainfall at the head scarp of central debris flow above the pass

The landslide event across the city of Wollongong and surrounding region triggered more than 142 landslides over the broader 5 day period. One of these landslides was noted as the ‘event’ at Bulli Pass resulting in the road closure. This project has now identified the Bulli Pass event actually comprised approximately 34 discrete landslide events, including 22 debris flows, up to 16 smaller slides and many rockfalls which originated on the slopes above the road (Figure 14). The volume of debris colluvial material that reached the road was estimated to be in the order of about 3,000 m^3 (including material that may have passed the road). Some of the detail mapped as part of this investigation is highlighted in Figure 7. The colluvial debris from these failures flowed down the escarpment slopes and across Bulli Pass and trapped approximately 15 cars (Figures 15 & 16). Some cars were partially inundated up to bonnet level. People were forced to flee their vehicles in an attempt to escape the debris. One car was swept over the downslope embankment by a debris flow with the driver managing to jump out and cling to a tree before watching her car disappear into the darkness below.

The debris flows also led to side fill failures of the road downslope of the pavement due to scouring and overland flow of channelled water. Several sections of the downslope guard rail were left hanging in the air due to the loss of the shoulder. Numerous rock falls also occurred, some of which impacted vehicles. The largest of the rock falls had dimensions of up to about 2 m across. The rock falls directly impacted many vehicles, including an ambulance, smashing windscreens and windows. Remarkably, these incidents did not result in any loss of life. Because the road was impassable, people had to be rescued on foot, with some people found clinging to the rooves of vehicles. The pass was closed by about 7 pm on 17 August and did not reopen for a number of days, whilst all the debris was removed and new guard rails were installed.

Figure 14: Bulli Pass early morning of 18 August 1998 (TfNSW)

Figure 15: Bulli Pass early morning of 18 August 1998, two inundated and abandoned cars (TfNSW)

Figure 16: Bulli Pass early morning of 18 August 1998, note smashed car windows, rocks on roof and stranded vehicles in distance (TfNSW)

7 LANDSLIDE VOLUME FREQUENCY MODEL

7.1 BACKGROUND

A Landslide Volume Frequency Model was developed for the project to present judgements, knowledge and evidence on the type, size, frequency and volume of future landslides at the site. The development of the model was based the procedures and background outlined by Moon et al. (2005) who applied the model to assess landslide hazard to Lawrence Hargrave Drive (LHD) as part of the now famous Sea Cliff Bridge project between Coal Cliff and Clifton. The sections below outlines the steps taken to apply the procedure to this project.

7.2 SUMMARY OF LANDSLIDE HISTORY RESEARCH AND VOLUME ESTIMATION

Landslide history research and the subsequent development of the landslide inventory was crucial to the development of the landslide volume frequency model. In addition to the comprehensive detail of the August 1998 event summarised above, the following sources of information were reviewed in order to compile a history of documented landslides at the site:

- Archival newspaper articles, by and large sourced through Trove,
- University of Wollongong Landslide Inventory,
- Department of Main Roads (DMR)/Roads and Traffic Authority (RTA)/TfNSW Reports, maintenance records and consultant reports dating back to the 1950's.
- Interviews with TfNSW personnel

The compilation of historical events and incorporating the available data with modern data is a challenge and there is, in this project, a disconnect between the compiled table of landslide events and the mapped landslides shown above in Figure 5. The writers acknowledge that such differences will exist in most projects. It is also common for larger events to be 'remembered', or reported by media, while smaller events often go unnoticed. However, compiling a comprehensive table of landslide events (a segment of which is included as Table 1) is an essential project task as it provides the overall summary of information of the known events.

Table 1: Summary of some of the early landslides found through Trove searches

Date of Event	**Reference**	**Description and Media Extracts**	**Landslide Classification***
Circa 22 February 1890	'The Weather', Sydney Morning Herald, 24 February, 1890.	*"The Bulli Pass-road is considerably despoiled through huge masses of earth and rock having slipped from the mountain side to the highway, completely blocking all but foot traffic, and that only climbing. Splendid tall tree ferns, palms, and ornamental trees stand erect in dislodged blocks of earth and stones at intervals across the rood and are replaced by temporary cascades. One obstructing rock measures nearly 20ft. square. The mountain mail yesterday was conveyed on foot"*	Debris Flows and Rock Falls (Extremely Large)
Circa mid May 1925	'Road Conditions' Sydney Morning Herald, 22nd May, 1925. P14.	*"The Bulli Pass is in good condition, but two big boulders have fallen on the road"*	Rock fall (Medium)
Circa 1 June 1930	'Terrific Cloudburst in NSW', The Register New-Pictorial, 2 June, 1930, P2.	*"A landslide occurred at Bulli Pass, blocking the roadway for hours, and holding up motorists. An opening was made to allow one car through at a time".*	Slide / Debris Flow (Large to Very Large)
Circa 24 January 1933	'Landslide Peril', The Canberra Times, 25 January, 1933, P5. 'Landslide Kills Boy' Sydney Morning Herald, 24 January, 1933.	*"Great difficulty is being experienced in taking food supplies to Stanwell Park owing to the fact that the road over Bulli Pass is completely covered with debris for about a mile".* Elsewhere at Bulgo Beach near Otford, a landslide engulfed a beach hut, killing a boy. Seven members of the same family were also drowned at Stanwell Park camping area due to flood inundation.	Debris Flows and Rock Falls (Extremely Large)
26 February 1934	'Bulli Pass Road Blocked', The Barrier Mail, 26 February, 1934, P1. 'Government Relief to be Sought' The Canberra Times, 27 February, 1934, P1.	*"Main Roads Board employees were working all day yesterday at the scenes of two landslides which blocked the Bulli Pass road. Many tons of earth and rocks which had been loosened by erosion broke away from the higher side of the road. Landslides occurred at two spots, both near the middle of the pass"* The road was not "seriously damaged."	Debris Flows and Rock Falls (Very Large)

**Note: Classification of landslides follows the scheme of Cruden and Varnes (1996). See Table 2 below for Volume classification.*

7.3 DEVELOPING THE VOLUME FREQUENCY CURVE

The critical project element is the 1.1 km long Bulli Pass road and the assessed hazard events are those that reach the road from the natural slope, above the road, excluding the existing, man-made rock cuttings as these had already been extensively remediated. The August 1998 event became an important design critical 'event' as much was known about it. It was large volume, low frequency event that badly damaged the road. All the August 98 landslides were grouped as 1 event, with an assessed volume of 3,000 m^3 with a conservative but quantitatively assessed Annual Exceedance Probability of 2%, a frequency of 1 in 50 years based on the rainfall analysis shown in Figures 12 and 13. In the landslide volume frequency model presented in this paper all the August 1998 landslides were grouped as one event.

The volumes of each landslide event were estimated based on the descriptions provided in the archival newspaper records, the University of Wollongong Landslide Inventory as well as more recent road maintenance records held by TfNSW. An TfNSW employee who responded to an approximately 0.5 m^3 rockfall event in 2012 was interviewed by the project team and he commented that about 2 or 3 rockfalls occur at the site each year, however they are typically smaller than the 2012 rockfall.

Establishing a relevant project volume classification simplifies the process and the one adopted for this project is shown in the first four columns of Table 2. The average annual number of landslides in each volume category can be estimated early in the investigation based on available evidence and then, as further data comes to hand and the slope failures mechanisms in the project area are better understood, the model can be revised accordingly. A Medium volume rockfall that occurred in November 1961 is shown in Figure 17, and a Very Small rockfall that impacted a car in January 2015 during the later stages of this project is shown in Figure 18. The final assessed average annual number of landslides reaching or crossing the road in each volume category is presented in Table 2 and the Volume Frequency Process Rate Curve developed for the project is shown on Figure 19.

Table 2: Landslide volume classification developed for this study

Volume of Debris Reaching Road (m3)	Volume Classification	Typical Dimensions on Road (m)		Average annual number of landslides in volume category reaching or crossing the road
		Debris (m)	Rockfall Blocks (m)	
<0.01	Extremely Small	-	0.15 across	2
0.01 - 0.1	Very Small	-	0.5 x 0.3 x 0.2	1.5
0.1 - 1	Small	-	1 x 0.6 x 0.5	0.9
1 - 10	Medium	4 x 2 x 0.4	2 x 1.5 x 1	0.6
10 -100	Large	8 x 8 x 0.5	5 x 3 x 2	0.3
100 - 1,000	Very Large	Several slides up to about 1 m thick on the road and some debris (from above the road) below the road	10 x 6 x 5	0.1
1,000 - 10,000	Extremely Large	Numerous slides/flows along length of site up to about 1m thick on road and some debris (from above the road) below the road	Not credible	0.02
>10,000 - 30,000	Maximum credible	Max. credible combined slides/flows on road assessed 17,000m^3 including some debris (from above the road) below the road. More than half the road covered by debris.	Not credible	0.001

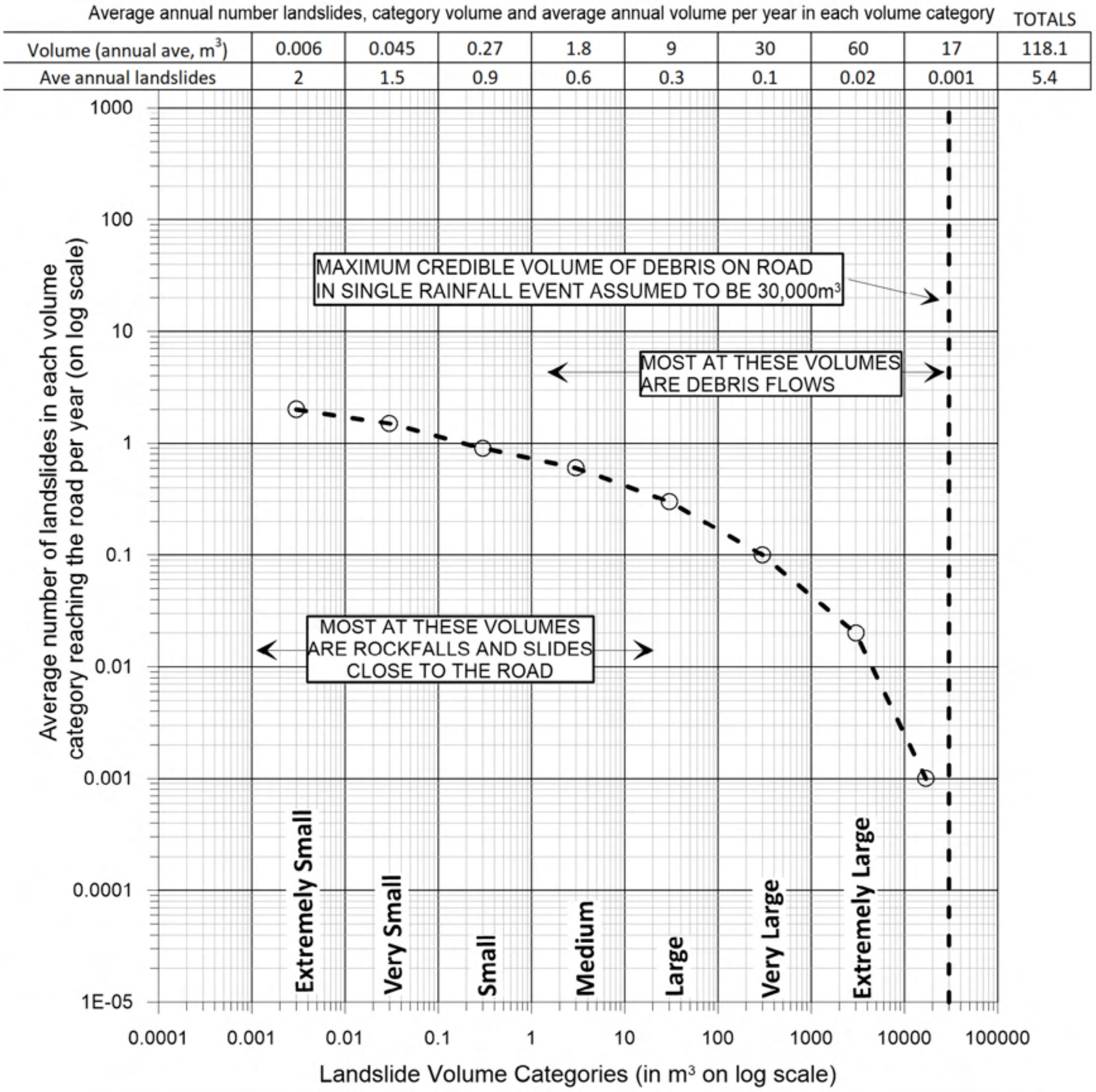
Figure 17: ‘Large’ sized rockfall, November 1961 (Wollongong City Libraries)

(a) (b)

Figure 18: (a) Windscreen and roof damage to vehicle from ‘Very Small’ 28 January 2015 rockfall, (b) Damage to vehicle interior and subject rock.

7.4 VOLUME FREQUENCY PROCESS RATE CURVE

The Volume Frequency Process Rate Curve in Figure 19 identifies, in the top right corner, that a total volume of 118.1 m^3 is the long-term average volume of debris reaching or crossing the road annually and is heavily influenced by infrequent Very Large and Extremely Large events. One constraint that is important is to consider is the maximum landslide volume that is conceivable at the site. For this project a maximum volume was judged to be 30,000 m^3. As discussed in Moon et al. (2005) judgements about the maximum credible volume depend on the slope geometry, and knowledge and understanding of the slope geology and potential failure mechanisms. This was largely based on other escarpment deep seated slides within the Bald Hill Claystone and or Bulgo Sandstone and these are not common. To fix a graph point for this type of event, a midpoint between 10,000 and 30,000, an average volume of 17,000 m^3 was selected with a low return frequency of 1 every 1000 years was estimated based on the engineering geological judgement of the team.



Average annual number landslides, category volume and average annual volume per year in each volume category

Volume (annual ave, m³)	0.006	0.045	0.27	1.8	9	30	60	17	118.1
Ave annual landslides	2	1.5	0.9	0.6	0.3	0.1	0.02	0.001	5.4

NOTES

1. In this model, landslides triggered by a particular rainfall (eg. the August 1998 debris flows) are shown as a single event rather than many individual events.
2. In most years there are less landslides than the long term average.

Figure 19: Landslide Volume Frequency Process Rate Curve for Bulli Pass

Flentje (2012) determined through geomorphological reconstruction that the long term average rate of Illawarra Escarpment retreat over the last 70 million years was approximately 0.6 m per 1000 years and it would be expected this would have fluctuated possibly an order of magnitude above and below the average rate with climatic variations (i.e., glacial and interglacial periods, with likely shorter duration fluctuations as well). The LHD coastal slopes and cliffs project determined that the Bulgo Sandstone cliff and slope rates of retreat were between 3 and 0.3 m per 1000 years respectively. The 0.6 m per 1000 years, or 0.6 mm per year over a surface area of approximately 1000 m long by an average of 250 m (the surface area upslope of the pass road) would provide an annual debris field of approximately 150 m^3 onto the road from all forms of erosion. The proposed Bulli Pass process rate of 118.1 m^3 per year represents approximately 80% of this long term average rate of Illawarra Escarpment retreat, over the last 70 million years, which the project team is entirely comfortable with. The assessed rate of 118 m^3 may indeed just be the landslide component of the erosion, with an additional 20% being removed through slopewash and other alluvial processes as a fine component through streams and culverts which is not recorded.

8 RISK ASSESSMENT

The Landslide Volume Frequency Model approach used knowledge of geology, geomorphology and landslide processes to bring together historical information and judgements about the frequency of larger events to help understand the risks to road users at Bulli Pass. The model provides judgements about the frequency of different volume events although most of the larger events will consist of many individual landslides (as discussed in Section 6) For this project, being an TfNSW road, The TfNSW Guide to Slope Risk Analysis (Version 4) was used to assess risks. The TfNSW system (Stewart et al. 2002) is a societal slope assessment system based on an underlying quantitative framework and was developed to systematically analyse geotechnical risks associated with slopes adjacent to roads in NSW. This system, which is now widely used on Australian roads, uses 'rules' and ratings to evaluate the likelihood and magnitude of the hazard and their consequences. There are five 'Assessed Risk Levels' ranging from ARL1 (highest risk level) to ARL5 (lowest risk level). A summary of assessed risks for hazards resulting in high risks is presented in Table 3.

As shown in Table 3, the highest assessed risks at the site are all associated with rock falls, although it is acknowledged that TfNSW also consider ARL2 sites as 'high risk'. The higher risk associated with rockfalls is a function of the higher frequency of occurrence and vulnerability ratings specified in the TfNSW system.

Table 3: Risk Assessment Summary

Hazard	**Scenario**	**Assessed Risk Level**
Extremely Small Rockfall	Car impacts rock	ARL2
Extremely Small Rockfall	Rock impacts car	ARL1
Very Small Rockfall	Car impacts rock	ARL1
Very Small Rockfall	Rock impacts car	ARL1
Small Rockfall	Car impacts rock	ARL1
Small Rockfall	Rock impacts car	ARL1
Medium Rockfall	Car impacts rock	ARL2
Medium Rockfall	Rock impacts car	ARL2
Medium Debris Flow	Car impacts debris	ARL2
Large to Very Large Debris Flow	Car impacts debris	ARL2
Extremely Large Debris Flow	Car impacts debris	ARL2

9 CONCLUSION

This paper has outlined how all reasonably available sources of knowledge including field mapping, geology, geomorphology, landscape evolution, local landslide processes, rainfall, personal accounts and historic media records can be used to develop Landslide Volume Frequency Models. Despite the quantity of data able to be assembled, local knowledge, particularly relating to landslide processes and process rates are equally as important in the calibration of the model. The model was defensible and proved to be a powerful tool to communicate hazards to key stakeholders.

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