https://doi.org/10.56295/1ACEG10

SUSCEPTIBILITY AND MITIGATION OF DEBRIS FLOODS AND FLOWS IN THE JENOLAN KARST CONSERVATION RESERVE, NSW, AUSTRALIA: BUSHFIRE AND LA NIÑA IMPACTS

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ABSTRACT

This study assesses debris flood and flow susceptibility within the Jenolan Karst Conservation Reserve (JKCR), New South Wales, Australia, following the 2019 to 2020 summer bushfires and the prolonged 2020 to 2023 La Niña weather pattern. The bushfires significantly altered catchment hydrology by reducing vegetation cover and increasing sediment availability, while the subsequent extreme rainfall events triggered an increase in erosion and debris movement.

A detailed geological, geotechnical, and geomorphological assessment was conducted, incorporating the Melton Ratio to evaluate catchment susceptibility to debris floods and flows. The findings informed engineering solutions, including the design of debris barriers aimed at mitigating sediment transport and protecting downstream infrastructure. The study provides insights into the long-term impact of bushfires and extreme weather events on debris mobilisation, emphasising the importance of proactive mitigation strategies.

1 INTRODUCTION

Debris floods and flows are natural hazards with significant potential to impact infrastructure. These events are particularly common in steep and mountainous terrain where heavy rainfall, geological conditions, and land disturbances contribute to increased sediment mobilisation. Unlike conventional fluvial floods, debris floods and flows transport large volumes of sediment and organic material, which can cause extensive damage to infrastructure.

Following the 2019 to 2020 summer bushfires, the Jenolan Karst Conservation Reserve (JKCR) experienced a notable increase in debris flood and flow activity. The impacts of bushfire altered catchment hydrology by reducing vegetation cover, increasing soil water repellency, and exposing loose sediments to erosion. The bush fires were then followed by a three year La Niña climatic pattern between 2020 and 2023 which delivered record breaking rainfall and widespread flooding across eastern New South Wales, Australia. The bushfires, combined with the subsequent La Niña period, contributed to intensified debris movement and subsequent deposition across the reserve.

Surveyors Creek forms one of three main tributaries to the Jenolan River. The JKCR catchments are prone to debris floods and flows with records of debris flood and flow activity dating back to 1919, including instances where debris floods and flows have caused damage to property and resulted in sedimentation of the Blue Lake being of detrimental effect to the reserves amenity. Between 2020 and 2024, four intense rainfall events have triggered debris flood and flow events, which historically, is a large increase in frequency and occurrence.

This study presents an assessment of debris floods and flows, covering key aspects such as site and geological characteristics, definitions of debris floods and flows, and the impact of bushfires on their generation. It includes a desktop study reviewing site precedents, hydrology, and terrain, alongside site observations. The assessment employs both quantitative and numerical methodologies to evaluate debris flood and flow susceptibility, with findings integrated into the development of engineering design.

2 SITE DESCRIPTION AND GEOLOGY

The JKCR is a geologically significant area located in the Central Tablelands of New South Wales, Australia. It lies approximately 175 km west of Sydney and 30 km east of Oberon. The reserve is renowned for its extensive network of limestone caves that have been shaped by hydrological and geological processes. The caves are situated within a deeply incised, uplifted plateau that is characterised by steep gorges, rugged terrain, and karst formations.

Surveyors Creek is one of three main tributaries of the Jenolan River. Situated to the west of Jenolan Caves, it flows north before doglegging eastward beneath Carpark 1 and Caves House through a series of open and closed culverts before traversing beneath the Grand Arch before entering the Blue Lake, Figure 1. This system is prone to debris floods and flows originating within Surveyors Creek. A notable feature of the lower catchment is Surveyors Creek Dam, located above Carpark 1. This concrete structure provides limited flood and debris retention capacity, estimated at between approximately 1,500 and 2,500 m^3. The catchment is characterised by a steeply incised valley, plunging up to 400 meters from adjacent ridge lines and many slopes exceeding 50°, contributing to high erosion rates and frequent debris floods and flows. Slope steepness increases toward the northern part of the catchment toward Surveyors Creek Dam.

The catchment features quartz sandstone and cherty siltstone of the Silurian Campbells Group after Branagan et al (2014), and overlying colluvial deposits. The quartz sandstone unit is composed of light to dark grey, blocky, fine to medium grained sandstones with minor slates and the cherty siltstone unit is composed of thinly bedded radiolarian-rich black siltstones, interbedded with slates and minor quartz sandstone (Branagan et al, 2014). A key feature of the site is the presence of a persistent layer of surficial loose granular colluvium which overlies the bedrock and provides a primary sediment source for debris floods and flows.

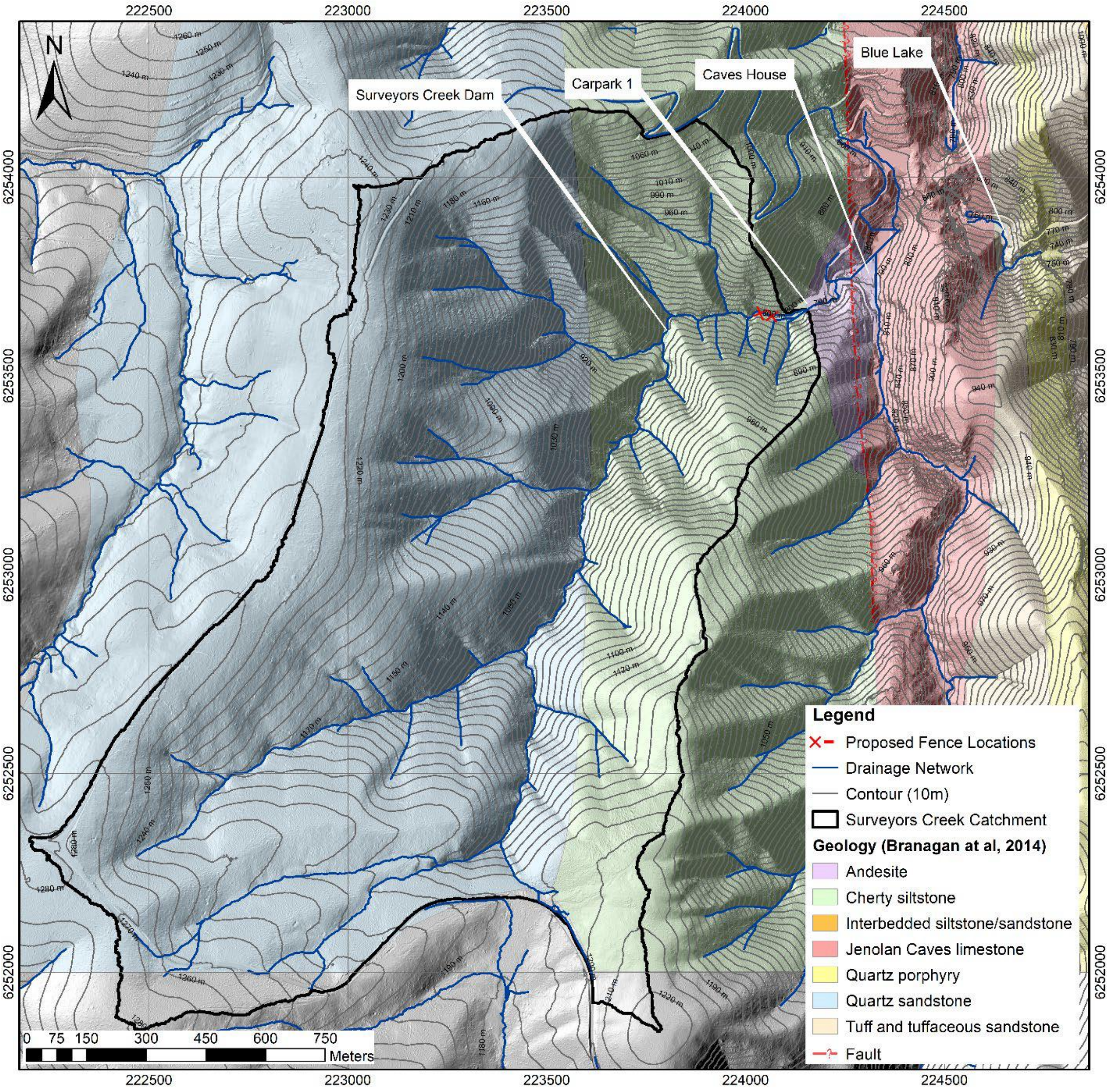

Figure 1: Surveyors Creek catchment and geology after Branagan et al (2014)

3 DEFINING DEBRIS FLOODS AND FLOWS

Debris flows occur when masses of poorly sorted sediment, agitated and saturated with water, surge downslope in response to gravity. The United States Geological Survey (USGS) define debris flows as having a sediment concentration above 60%. The velocities of debris flows vary according to slope angle but can range from walking pace up to 50km/hr in steep terrain. A debris flow can have more destructive potential than a debris flood.

Debris floods are defined by Hutchinson (1988) as hyper-concentrated flows of water laden with gravel, sand, and silt. They are defined by the USGS as a water flow involving 'normal' sediment concentrations, generally between 5% and

10% sediment volumes, though may extend up to 60% (hyper-concentrated flow). A debris flood is not a landslide but is a mass transport phenomenon with destructiveness similar to that of water, but less than that of debris flows. Objects impacted by debris floods are typically surrounded or buried by flood debris but are often undamaged (Hungr et al., 2001).

Both debris flows and debris floods are triggered and controlled by water and have the potential to travel a considerable distance from their source. The extent and effect of debris flows and floods are variable in terms of trigger mechanism, volume, and velocity, and depend on site factors including the geology, geomorphology, hydrology, and climate.

4 THE BUSH FIRE EFFECT

Intense rainfall is the primary trigger for debris floods and flows. However, the bushfires have significantly altered catchment hydrology increasing debris flood and flow susceptibility. Bushfires reduce vegetation cover, expose loose sediments and soil to direct rainfall which in turn increases runoff and erosion, and makes reestablishment of vegetation difficult. Overtime, as tree roots decay, the soil loses reinforcement, which provides an ongoing sediment source. Table 1 summarizes the post-fire effects on debris generation, adapted from DeGraff et al. (2015) and Parise & Cannon (2012). The 2019 to 2020 summer bushfires have significantly contributed to the increased debris movement at JKCR.

Table 1: Effect of bushfires on generation of debris floods and flows

Timeframe Relative to the Fire	Cause of Failure
During	-
Immediately After (0 to1.5 years)	Surface runoff process
	Changes to hydrologic response of drainage basin
Long Term (1.5 to 10 years)	Landslide failures through mobilisation of sediment due to tree root decay
	Changes to hydrologic response of drainage basin

5 DEBRIS FLOOD AND FLOW ASSESSMENT

5.1 SITE PRECEDENT

Factual accounts from previous events, geomorphological evidence and the terrain evaluation presented in the following Sections have informed this assessment. As discussed, several debris floods and flow events have occurred in the past five years with historical photographs documenting debris floods and flows occurrences as far back as 1919.

Figure 2 shows the February 2020 debris event that affected Caves House, the Grand Arch, and nearby buildings, as reported by the Canberra Times. It is understood sand, gravel, cobbles, and boulders were transported by debris floods from all three Jenolan River tributaries, including Surveyors Creek.

Figure 2: Flooding at Jenolan Caves in February 2020 looking towards the western side of the Grand Arch

5.2 HYDROLOGY

JKCR experiences a temperate climate with seasonal temperature variations, occasional snowfall, and bushfire-prone dry periods. Rainfall is relatively evenly distributed annually. Figures 3 and 4 present monthly mean precipitations and maximum daily rainfall intensities from available data sources.

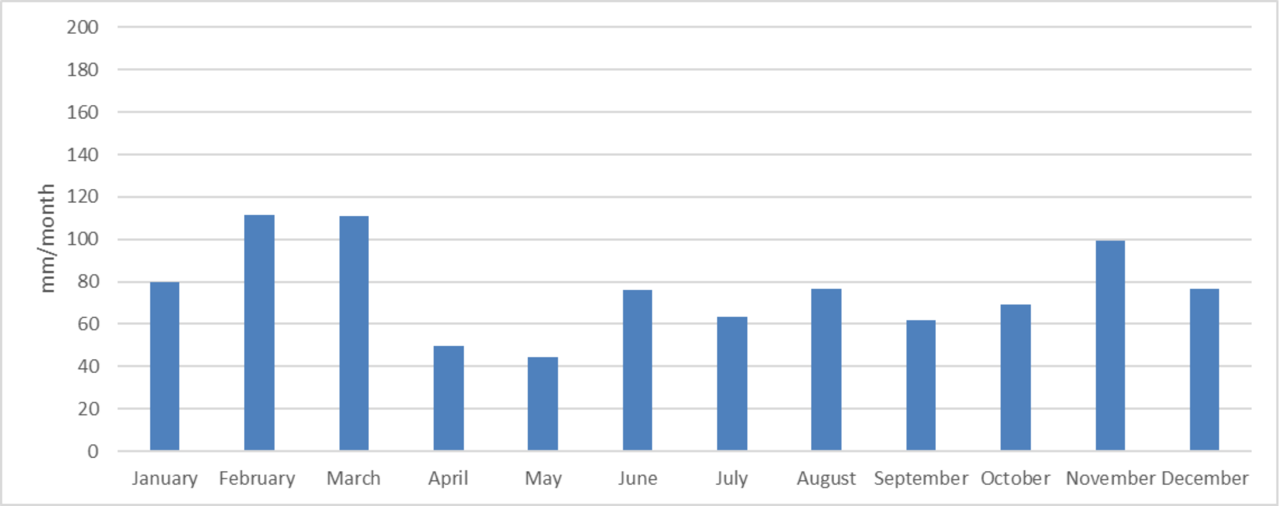

Figure 3: 2000 to 2023 monthly mean precipitation

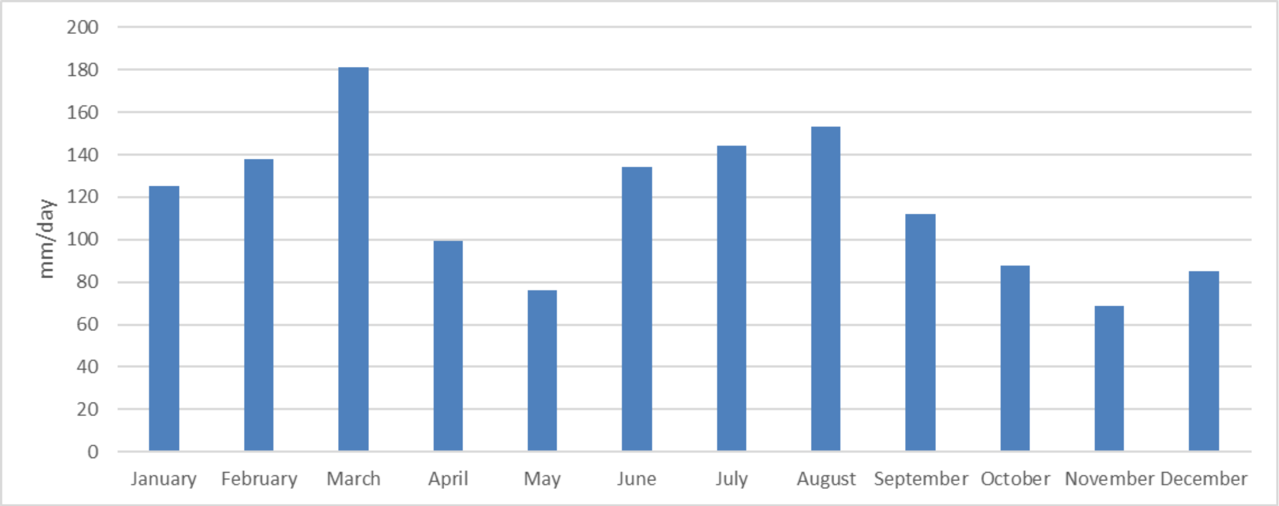

Figure 4: 1905 to 2023 short term rainfall intensity (maximum single day rainfall per month)

As part of our work at the JKCR, Intensity – Frequency – Duration (IFD) curves have been formulated, Figure 5. The major, recent storm events that have triggered debris floods / flows are presented in red on the IFD curves and include:

- February 2020 (an approximate 1:100 year event)
- March 2021 (an approximate 1:75 year event over 24 hours, or a 1:20 year event beyond 24 hours)
- July 2022 (an approximate 1:5 to 1:10 year event)
- April 2024 (an approximate 1:5 to 1:10 year event).

Figure 5 also plots the largest storm events recorded between July 2022 and April 2024 in green, that did not result in observable debris floods or flows. Analysis of Figure 5 suggests debris events are triggered when rainfall exceeds approximately 85 mm over 24 hours, or 110 mm over 48 hours, representing between a 1 in 2 and 1 in 5 year event.

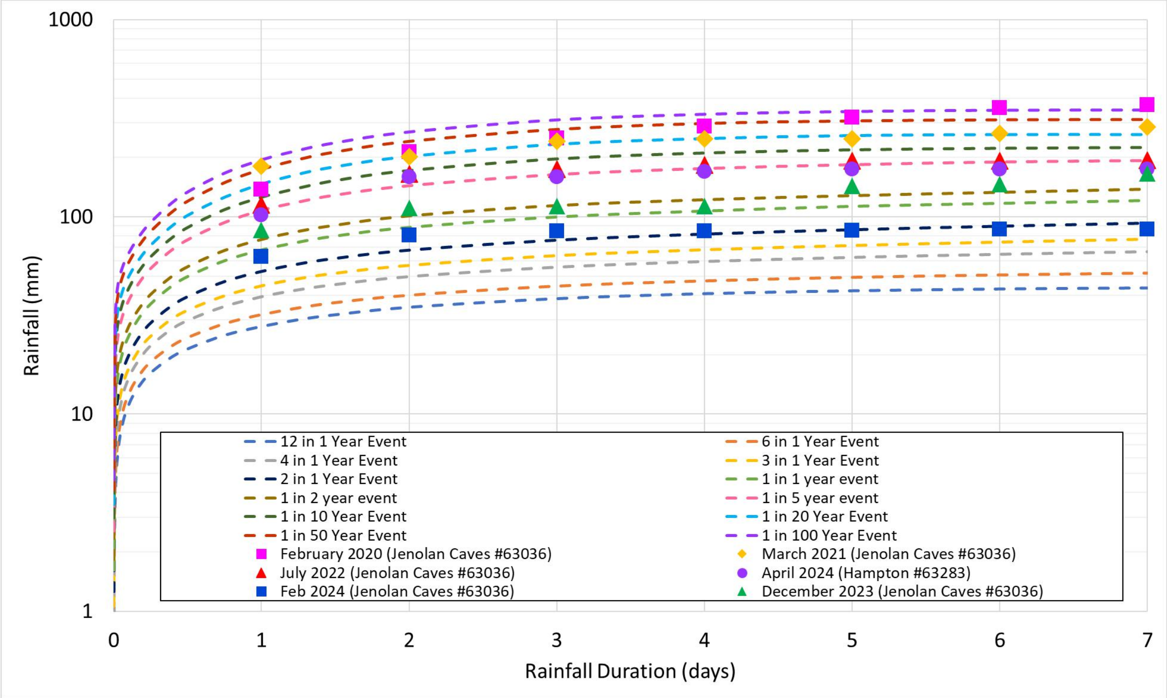

Figure 5: IFD curves for the JKCR. Recent storm events that resulted in debris floods or flows are presented in red and recent storm events that did not result in debris floods or flows are presented in green

5.3 TERRAIN ASSESSMENT AND SITE WALKOVER

A terrain assessment was undertaken prior to a site walkover and geomorphology mapping campaign. The terrain assessment is presented with the qualitative susceptibility assessment in Section 5.4.2. The assessment is based on geomorphological signatures observed in the DEM topography which was subsequently verified and updated in the field via the use of a mobile GIS application.

A focus of the terrain assessment was identification of sediment in storage that may be susceptible to mobilisation leading to generation of debris floods or flows. The following terrain units were identified across the site:

- Bedrock
- Scree
- Colluvium overlying bedrock
- Colluvial Apron
- Alluvium
- Anthropogenic.

Bedrock is observed along some ridges and within stream beds. Typically, scree slopes and boulder fields have formed below outcropping rock providing a source of sediment in storage.

A typical feature of the JKCR topography is the presence of a thin surficial layer of colluvium overlying bedrock, Figure 6. The surficial layer is typically loose, angular, sandy fine to coarse gravel with silt, trace cobbles and is estimated to be less than one metre thick in most cases. It is interpreted to be the primary source of sediment in storage. Development of the thin, granular colluvium is attributed to several factors including:

- Steep slopes and high erosion rates promoting rapid runoff, minimal topsoil development and slow vegetation establishment
- Extreme climate contributing to mechanical breakdown of bedrock
- High insitu stress resulting from deep valley incision (unloading of overlying rock reducing vertical stress, leading to basin uplift, rock mass dilation, fracturing and accelerated erosion).

Colluvial aprons are formed along the flanks of Surveyors Creek which is actively eroding and over steepening portions of the lower valley slopes, Figure 7. Material accumulation is interpreted to be a product of gravity driven, slope wash processes (such as landsliding) that deposit near the source and provides a source of sediment in storage. Due to the relatively steep gradient of Surveyors Creek and the resulting erosive force, the stream bed has incised down into bedrock resulting in only isolated deposits of alluvium.

Figure 6: Examples of loose colluvium present on the hill slopes

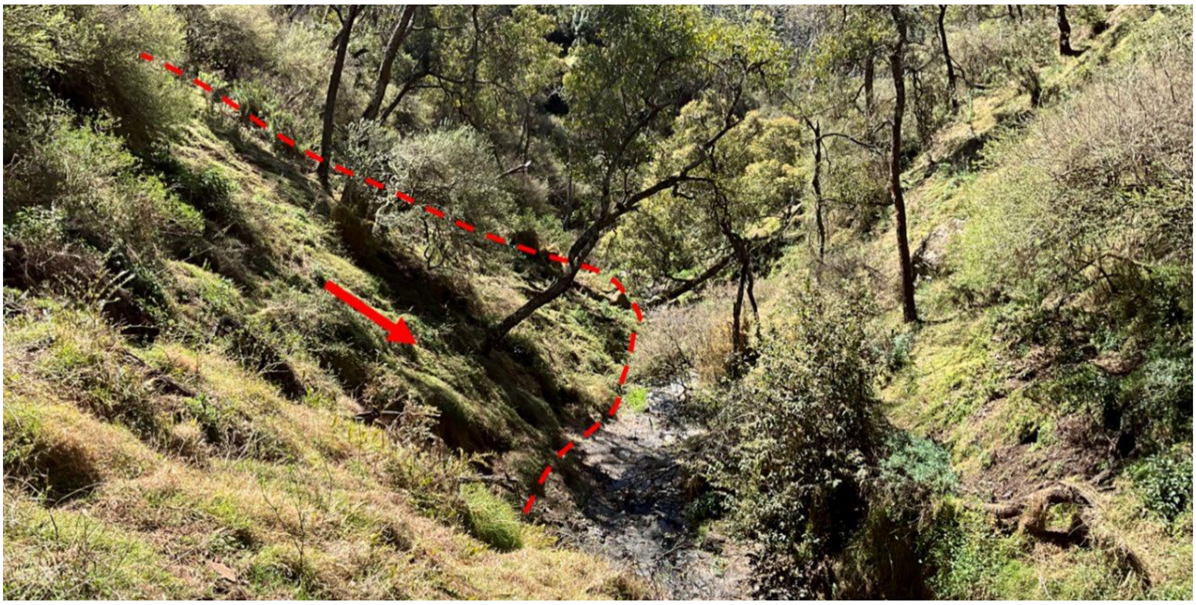

Figure 7: Colluvial apron formed through landsliding along the flank of Surveyors Creek

5.4 DEBRIS FLOOD AND FLOW SUSEPTIBILITY

5.4.1 Preamble

Assessment of debris flood and flow susceptibility was undertaken utilising a GIS based approach. The assessment has adopted both a qualitative evaluation and a numerical approach to assess debris flood and flow susceptibility.

5.4.2 Qualitative Assessment

A qualitative assessment of debris flood and flow potential has been undertaken considering the physical and geomorphological attributes of each catchment that feed into Surveyors Creek. This has included consideration of the following metrics, many of which were observed during the site walkover:

- Catchment area
- Slope gradient
- Steam / gully axis gradient
- Evidence of landsliding
- Evidence of debris in storage.

Table 2 summarises the qualitative assessment for individual metrics throughout the wider catchment. 'Debris Potential' (DP) has been assigned to each catchment to communicate the qualitive potential for generation of debris floods or flows based on some common susceptibility metrics widely referenced in the literature, Figure 8. Each catchment has been allocated a DP based on a qualitative appraisal as follows:

- Major debris potential
- Moderate debris potential
- Minor debris potential.

Table 2: Qualitative assessment of debris flood and flow potential

Catchment ID	Catchment Area (m^2)	Mean Slope Gradient (°)	Mean Stream / Gully Axis Gradient (°)	Evidence of Landsliding	Evidence of Debris in Storage	Debris Flood / Flow Potential
1	310,345	10	7	Minor	Not visited	Minor
2	603,727	17	11	Minor	Not visited	Minor
3	300,151	18	11	Minor	Not visited	Minor
4	228,102	22	21	Minor	Yes (1)	Moderate
5	199,788	27	20	Yes	Yes	Moderate
6	366,102	27	25	Yes	Yes	Major
7	176,617	33	23	Yes	Yes	Major
8	128,923	35	26	Yes	Yes	Major
9	147,097	31	27	Minor	Yes (1)	Moderate
10	86,114	34	26	No	Yes (1)	Moderate

[1] Loose surficial colluvium layer across the catchment

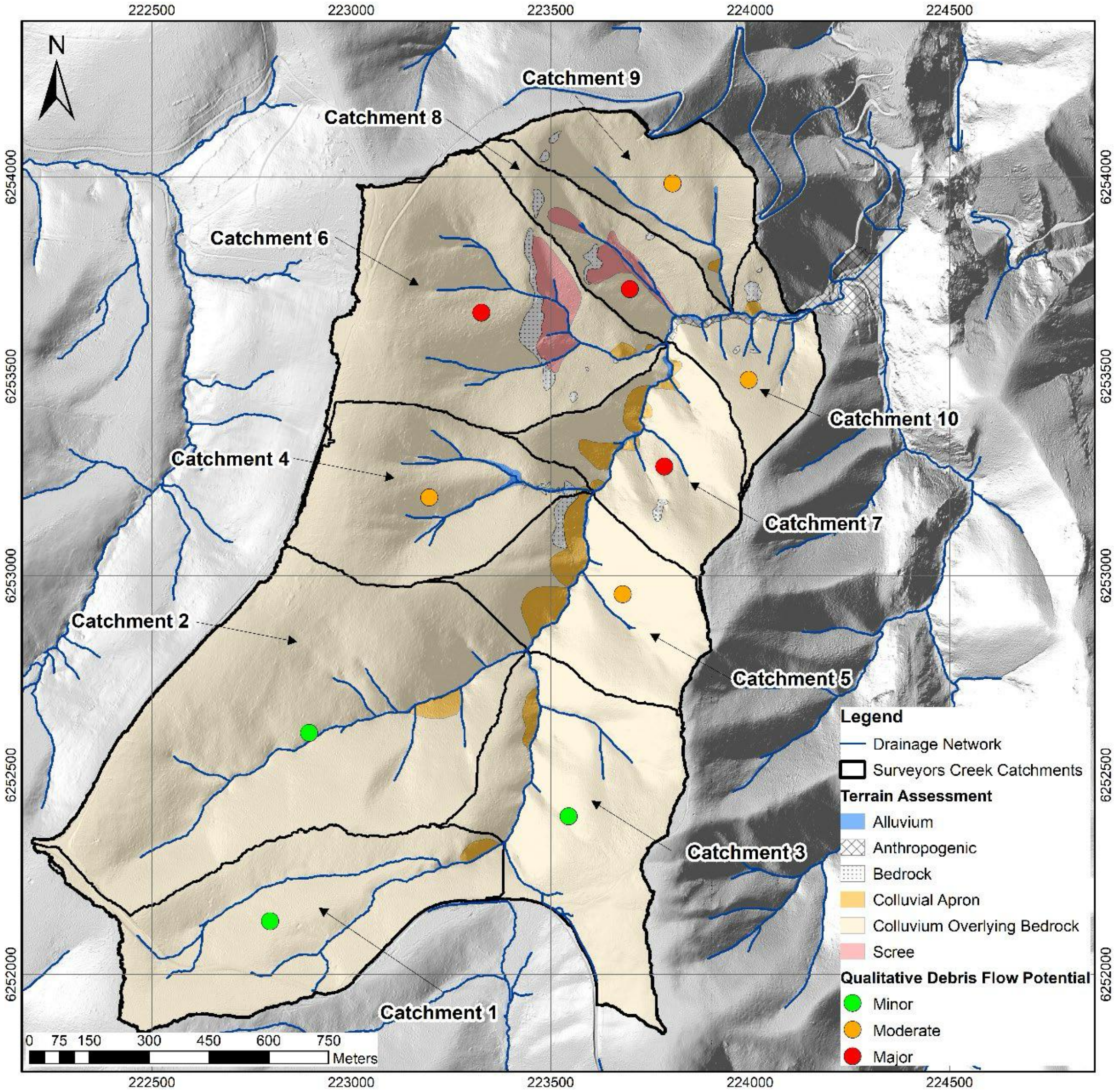

Figure 8: Terrain analysis and quantitative debris flood and flow susceptibility assessment

On this basis, debris flood/flow susceptibility broadly increases toward the north of the catchment where increased debris is observed in storage coupled with a significant increase in slope gradient.

5.4.3 Numerical Assessment

Morphometric catchment parameters of Surveyors Creek tributaries have been used to assess the susceptibility to debris floods and flows using the Melton Ratio (MR) after Melton (1957). The ratio is defined as:

$$R = H \, / \, \sqrt{A} \tag{1}$$

Where:

- R is the Melton Ratio
- H is the relief of the catchment, defined as the difference between the highest and lowest elevation
- A is the area of the catchment.

The MR for those Surveyors Creek catchments assessed are presented on Figure 9. Walsh and Davies (2010) define the following MR for defining susceptibility after Jackson et al (1987) and Wilford et al (2004):

- MR ≤ 0.30 – conventional fluvial processes are dominant (i.e., normal flooding)
- MR ≥ 0.30 & ≤ 0.6 – catchments that are prone to debris floods
- MR ≥ 0.6 – catchments that are prone to debris flows.

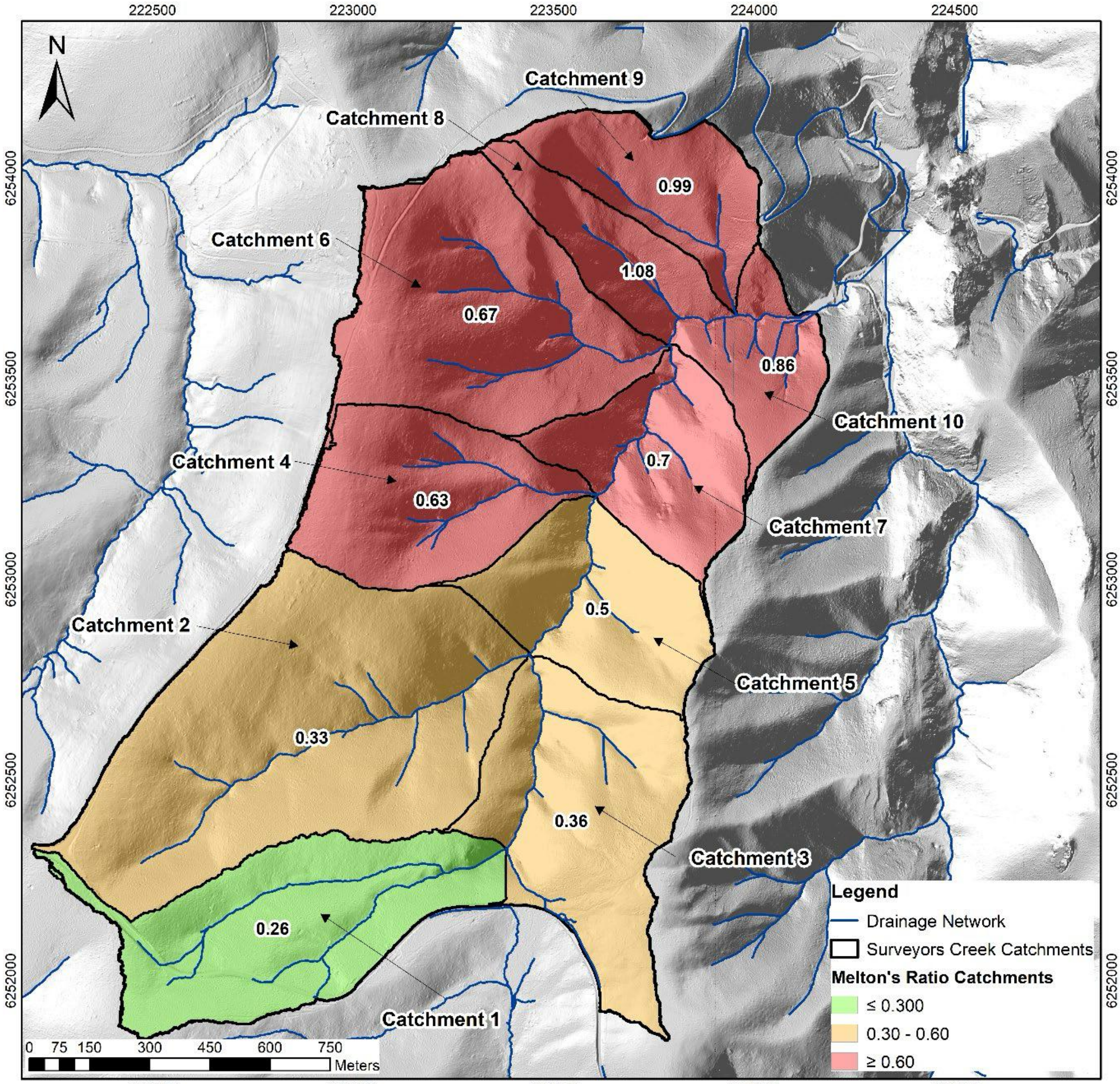

Figure 9: Melton Ratio numerical debris flood and flow susceptibility assessment

6 ENGINEERING DESIGN DEVELOPMENT

6.1 BASIS OF DESIGN

Based on site precedent, the debris susceptibility assessment and acknowledging that the JKCR will be prone to debris floods and flows until vegetation is re-established, it was recommended that a debris retention system be installed to complement the Surveyors Creek dam by providing additional debris catch capacity.

Recognising that debris generation is a natural and ongoing process, design of additional debris retention aims to reduce debris migration by retaining material within Surveyors Creek. This management strategy allows debris removal to occur 'offline' (away from public amenities) minimising operational disruptions and preserving the reserves amenity.

Design of a debris retention system requires estimation of typical debris volumes and the required retention capacity; this can be estimated by:

- Direct assessment – calculation of debris volumes from previous events
- Empirical assessment based on catchment area (NZGS, 2023)
- Hydraulic assessment – calculation for a range of annual recurrence intervals by multiplying clearwater flood volumes by a debris bulking factor (NZGS, 2023).

In this study debris volumes have been calculated utilising the direct and empirical assessment methodologies.

6.2 DEBRIS VOLUME AND THE REQUIRED RETENTION CAPACITY

6.2.1 Direct Assessment

The direct assessment estimates debris volumes based on past events and site-specific data. Following the April 2024 storm (approx. a 1:5 year event, see Figure 5), approximately 500 m^3 (up to 35 % of Surveyors Creek Dams retention capacity) of debris was retained behind Surveyors Creek dam.

Although no historical records exist to quantify other single event debris volumes originating from Surveyors Creek, previous Blue Lake infilling events (Feb 2020, March 2021, April 2024) provided further basis for estimating debris volumes.

The Blue Lake has an estimated debris retention capacity of 15,000 to 20,000 m^3 and is fed by three catchments:

- McKeowns Valley catchment (approximate catchment area = 21.5 km2)
- Camp Creek catchment (approximate catchment area = 2.65 km2)
- Surveyors Creek catchment (approximate catchment area = 2.57 km2).

Assuming each catchment has a similar sediment generating potential and contributes a volume of debris to the Blue Lake proportional to the catchment area, the approximate contribution of debris to the Blue Lake from each catchment is estimated as:

- McKeowns Valley – 80 %
- Camp Creek Catchment – 10 %
- Surveyors Creek Catchment – 10 %.

Based on this proportional contribution, Surveyors Creek may have deposited as much as 2,000 m^3 of debris into the Blue Lake in the February 2020 or March 2021 event. It is therefore estimated Surveyors Creek requires a minimum retention capacity of 2,000 m^3 for comparable events. This required catch capacity calculated is broadly equivalent to the capacity of Surveyors Creek Dam provided sediment buildup behind the dam is minimised.

6.2.2 Empirical Assessment

Figure 10 presents a summary of some empirical relationships between catchment area and debris volumes for granular debris flows (NZGS, 2023).

The total catchment area of Surveyors Creek (~2.6 km2) is presented on Figure 10 in green indicating:

- A 50th percentile volume estimate after Marchi et al (2019) of 4500 m3
- Typical volumes between approximately 12,500 and 55,000 m3 for most other authors
- A 98th percentile volume estimate after Marchi et al (2019) of 125,000 m3.

The empirical volume estimates above consider the entire Surveyors Creek catchment rather than just those catchments assessed to be prone to debris flows. When considering catchments prone to debris flows (i.e., MR ≥ 0.6, see Section 5.4.3), the total catchment area is ~1.2 km2 as shown on Figure 10 in red, indicating:

- A 50th percentile volume estimate after Marchi et al (2019) of 2,500 m3
- Typical volumes between approximately 6,000 and 32,000 m3 for most other authors
- A 98th percentile volume estimate after Marchi et al (2019) of 62,000 m.

Based on the empirical assessment, and considering only those catchments assessed to prone to debris flows (i.e., MR ≥ 0.6), Surveyors Creek Dam capacity is exceeded above the 50th percentile volume estimate after Marchi et al (2019).

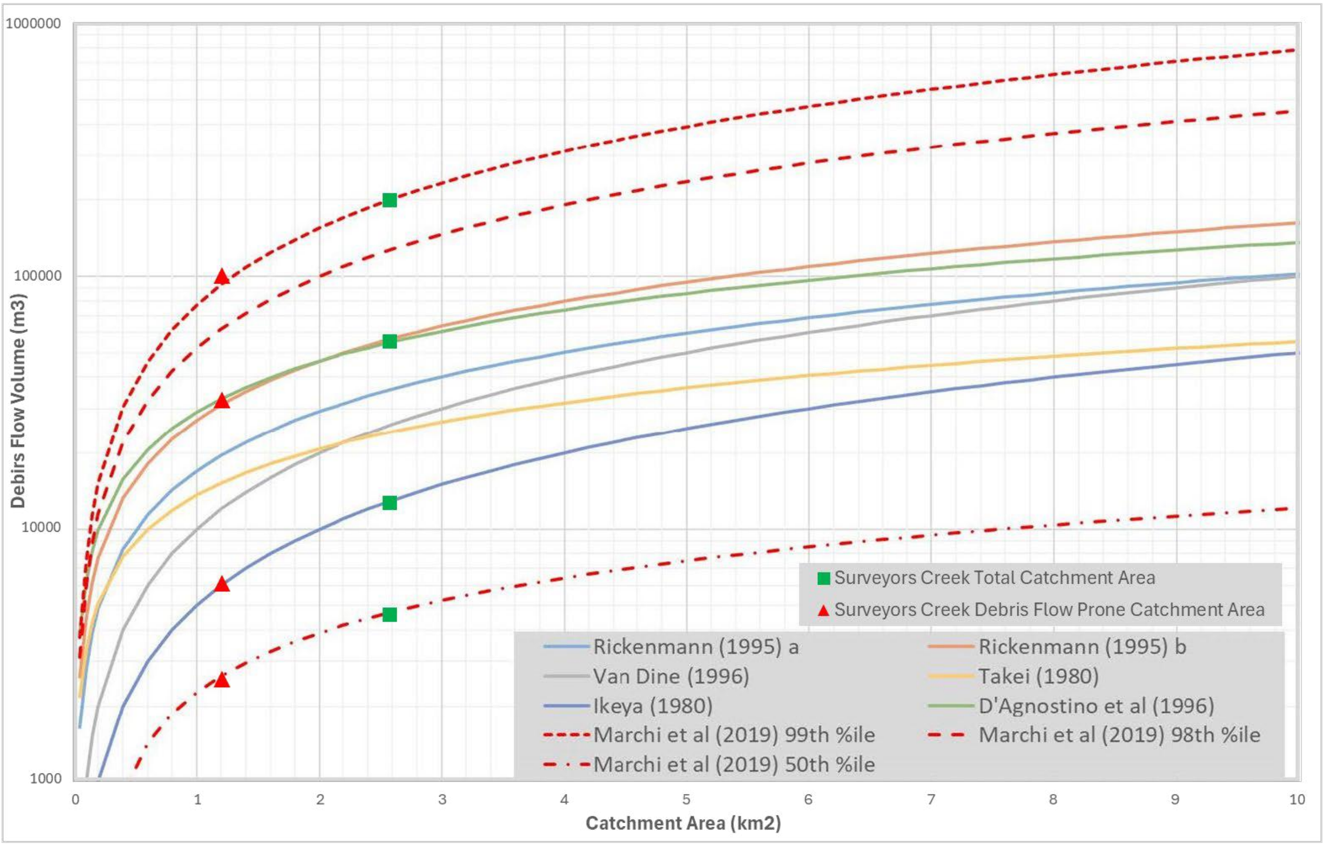

Figure 10: Relationship between debris volume and catchment area (after NZGS, 2023)

6.3 MITIGATION OPTIONS

There are several different options to provide additional debris catch capacity including:

- Debris retention basins
- Check dams
- Flexible barriers (debris fences)
- Natural barriers (placed boulders, logs etc.).

Given site constraints, ease of construction, and the ability to catch debris while allowing water to pass, flexible barrier(s) were recommended to provide additional catch capacity as required.

6.4 DEBRIS FENCE DESIGN

The primary design considerations included in the proposed debris mitigation system are discussed in the following sections.

6.4.1 Location

Due to site constraints, two potential locations for debris fences between the Surveyors Creek Dam and Carpark 1 (see Figure 1) were assessed which aim to provide a balance of the following:

- Location relative to active tributaries and debris sources
- Cross sectional area and subsequent retention capacity
- Accessibility for both construction and ongoing maintenance (including debris removal).

6.4.2 Retention Capacity

Both debris fence locations were calculated to have a retention capacity between 350 and 450 m3, or between 700 m3 and 900 m3 if debris fences are installed at both locations.

Including Surveyors Creek Dam this brings the debris retention capacity of Surveyors Creek to between 1,850 m3 and 2950 m3 if one debris fence is installed, and between 2,200 m3 to 3,400 m3 if both debris fences are installed.

Our assessment indicated there are no other practical alternatives to provide additional catch capacity without significant expenditure and therefore the retention system cannot achieve typical empirical capacities reported in the literature. Installation of the debris fences would increase the debris retention capacity by up to 30% if both fences are installed providing additional protection in the system if Surveyors Creek Dam reaches capacity. Options to increase the dams retention capacity were not considered due to heritage and cost relative to the proposed fences. Based on the direct assessment of debris volume, the system achieves the required capacity for similar events that have occurred over the past five years, providing some redundancy in design, particularly if Surveyors Creek or the debris fences are not at 100% capacity prior to an event.

6.4.3 Specification and Design Parameters

Due to the creek dimensions at the nominated locations, the Geobrugg VX System was recommended which incorporates a primary ring net mesh, support ropes and anchors. It was further recommended that rock armour be placed to support the flanks (anchors) from scour and erosion under both normal flow and flood (debris) events.

Debris floods are expected to be the dominant mechanism with higher frequency that debris flows. The following debris type and density have been adopted for design which assume sediment concentrations consistent with an upper bound debris flood density:

- Debris type:
    - Debris composed of sandy fine to coarse gravel, cobbles, boulders, and driftwood
- Debris density between:
    - 50% debris (2,200 kg/m3) and 40% water = 1,600 kg/m3 and
    - 30% debris (2,200 kg/m3) and 60% water = 1,200 kg/m3.
- Debris velocity:
    - Less than 5 m/s, consistent with typical debris flood velocities.

The intention of the debris fence system is to intercept and retain debris prior to it reaching the Blue Lake. From field observation we anticipate sandy fine to coarse gravel is the dominant material type to be retained, and for this purpose a finer secondary mesh to capture finer debris was recommended to be installed as part of the fence design.

It should be understood that the system is a filter barrier that allows flow to pass through whilst retaining larger sediment. The system is not designed to retain fine materials which are anticipated to filter through the debris fence under normal flow conditions. However, it is expected that some retention of finer particles will occur during events where debris fills up behind the fence and reduces flow velocity, however if sediment levels are not maintained behind the debris fence it is expected that finer sediments will erode and filter downstream over time.

Additional parameters required for debris fence design include anchor bond strength and specific hydraulic parameters (debris impact velocity and peak discharge) which are not reproduced in this paper.

6.4.4 Maintenance

Effective performance and longevity of debris fences require ongoing maintenance and inspection. This includes replacing damaged components and management of debris levels, particularly following rainfall events that have approached the documented thresholds known to increase debris flood and flow susceptibility. Within Surveyors Creek this also includes maintenance of debris levels within the dam to maintain the systems retention capacity.

The proposed debris fences have been located such that debris levels can be maintained from the upstream side via the use of excavators, however there may be a need from time to time to maintain debris levels from the downstream side which requires disassembling and reassembling of the debris fence(s).

7 CONCLUSION

This study has assessed the susceptibility of debris floods and flows in the Jenolan Karst Conservation Reserve following the 2019 to 2020 summer bushfires and the prolonged La Niña climatic pattern that extended from 2020 to 2023. By integrating geological, hydrological, and geomorphological analyses, along with the application of the Melton Ratio, we have identified key factors contributing to debris mobilisation and transport within Surveyors Creek.

The findings highlight that bushfire-induced vegetation loss, coupled with intense rainfall, significantly increases the likelihood of debris flood and flow events. Catchments in the north of the study area exhibit the highest susceptibility, with debris in storage observed on steep slopes.

To enhance site resilience, flexible debris fences have been proposed to supplement the retention capacity of Surveyors Creek Dam. These structures provide a pragmatic, cost-effective approach to intercept debris and minimise downstream impacts on the Blue Lake and adjacent infrastructure. While the mitigation measures proposed in this study provide immediate risk reduction, ongoing monitoring, maintenance, and adaptive management are essential to ensure long-term effectiveness.

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