REPORT

Yarra Ranges Erosion Management Overlay

Basis for Mapping Amendment

Submitted to:

Yarra Ranges Shire Council
P.O. Box 105, Anderson Street
Lilydale, VIC 3140

Submitted by:

WSP AUSTRALIA PTY. LTD.
Level 11, 567 Collins St, Melbourne, Victoria 3000 Australia

+61 3 9861 1111

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Distribution List

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List of Abbreviations

AGS	Australian Geomechanics Society
DEM	Digital Elevation Model
EMO	Erosion Management Overlay
GIS	Geospatial Information System
GSV	Geological Survey of Victoria
LiDAR	Laser imaging, detection, and ranging
LGA	Local Government Area – area administered by Yarra Ranges Council
MMBW	Melbourne Metropolitan Board of Works
NGOs	Non-Government Organisations (NGOs)
UYVDRA	Upper Yarra Valley and Dandenong Ranges Authority
YRC	Yarra Ranges Council

Geological Units

Qa1	Alluvium	Dvm	Mt Evelyn Rhyodacite
Qc1	Colluvium	Dvc	Coldstream Rhyolite
Tvo	Oligocene Volcanics	Dlwn	Norton Gully Sandstone
Dug	Devonian Granite/Granodiorite	Dlh	Humevale Siltstone
Dcd	Donna Buang Rhyodacite	Sud	Dargile Formation
Dvf	Ferny Creek Rhyodacite	Sla	Anderson Creek Formation
Dvk	Kalorama Rhyodacite		

Executive Summary

Amendment C217 to the Yarra Ranges Council Planning scheme was gazetted on 1 March 2024. That amendment included changes to the provisions of the Schedule to the Yarra Ranges Erosion Management Overlay (EMO) including changes to the exemptions and submission requirements for proposed developments, the addition of an incorporated document and changes to the risk thresholds applicable for risk to property. The amendment did not include changes to the mapped extents of the EMO.

The current mapped extents of the EMO are based on topographic maps developed in the 1960's. Modern digital elevation models based on airborne LiDAR are now available which allow a more detailed assessment of landslide susceptibility than was available when the current EMO extents were developed. A review of landslide susceptibility has been undertaken for the Yarra Ranges local government area with the objective of updating the mapped extents of the EMO.

The term landslides generally refers to the movement of rock or soil down a slope, however, landslides can be classified as a range of different types. Whilst there are various types of landslides that occur in Yarra Ranges, they have historically been broadly classified as either "landslides" or "debris flows"[1], where:

- Landslide refers to the rotational or translational movement of soil down slope whereby it slides along a plane. The mass of displaced soil may remain intact, or somewhat disaggregate
- A debris flow refers to the flow of wet soil and debris downslope, usually channelised along a gully whereby the debris can travel long distances, causing an impact in some cases significantly remote from its source. Landslides can initiate debris flows.

The initial stage of updating the mapping was to update the Yarra Ranges landslide inventory which is a database that includes all known landslides within Yarra Ranges, including those for which their occurrence is a matter of historical record and those inferred from geomorphological indicators (landforms). The landslide inventory was updated to increase the number of landslides in the inventory from 167 to more than 1,100. Most of those were identified on the basis of geomorphological indicators evident within LiDAR derived digital elevation models.

This report sets out the methods by which the EMO mapping was revised. A review was undertaken of the criteria which form the basis of the current EMO by checking the criteria conditions against the spatial prevalence of landslides in the revised landslide inventory. The review indicated that the existing criteria are reasonably consistent with the extent and occurrence of landslides and do not need to be changed.

The criteria used to identify areas susceptible to landslide under the current EMO, which are based on the underlying geology, slope angle and whether the site has been affected by a landslide in the past were applied to the digital terrain model and updated geological mapping. The resulting rasterized mapping was then manually checked and edited to remove anomalous results and to rationalise the mapping in some areas.

The existing EMO includes areas in Montrose which are susceptible to debris flow runout based on a 1992 study which only considered the Montrose area.

[1] Generally consistent with the terminology recommended in AGS 2007c Australian Geomechanics Society Guidelines for Landslide Risk Management, Vol 42, No.1 March 2007.

A 2017 University of Melbourne statewide debris flow study was used in conjunction with the digital elevation models to identify other areas with debris flow susceptibility which are also recommended for inclusion in the EMO.

The revised EMO extents applied to YRSC supplied cadastre maps, results in:

- The removal of approximately 1185 allotments (either partially or fully affected) from the existing EMO.
- The addition of 3172 allotments not previously affected by the existing EMO.
- Net increase of 1987 allotments added to the EMO.
- An overall increase in the area affected by the EMO from approximately 112 km^2 to 136 km^2.

The increase to the area affected by the EMO is largely due to the identification of new areas affected by landslides that had not previously been recognized, noting that most of the EMO area increase is in rural areas.

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1.0 INTRODUCTION

Yarra Ranges Council (Council) has engaged WSP Australia Pty Ltd (WSP Golder), to undertake a review of the mapping component of the Erosion Management Overlay (EMO) within the Yarra Ranges Local Government Area (LGA). The key strategic intent for updating the EMO mapping is to improve the accuracy of the mapping using recently acquired LiDAR derived digital elevation information and knowledge of landslides that have occurred within Yarra Ranges since the original EMO mapping was undertaken in the 1990’s.

This report sets out the basis to amend the mapping provisions associated with Schedule 1 to the Yarra Ranges Erosion Management Overlay (C217yran, dated 1 March 2024). Part of the recommendation is to separately delineate hazards associated with debris flow and landslides on the basis of the different consequences arising from those hazards and to allow the mapping to be split out and treated separately in future ordinance or amendments.

The mapping which forms the current Yarra Ranges Council EMO is based was compiled in the late 1990’s. At that time, the best available topographical information available with which to undertake the mapping was topographic maps compiled in the 1960’s by the Melbourne Metropolitan Board of Works (MMBW). Current technologies, including digital topographic information based on data acquired using airborne LiDAR techniques between 2015 and 2017 allows a more detailed assessment of the areas and extents of the Yarra Ranges that have been affected by landslides in the past and a more accurate application of criteria that indicate where landslides could occur in the future.

The methods adopted to review and revise the extent of the EMO mapping within the LGA are discussed in this report. The mapping arising from the study, including a revised landslide inventory, susceptibility maps and recommended EMO extent are provided as separate GIS deliverables as summarised in Appendix A.

2.0 OBJECTIVES OF THE REVIEW

The objectives of this report are to:

- Describe the process by which the criteria for the current mapped extent of the EMO were reviewed.
- Provide recommendations for revision of the EMO mapping, including revised criteria for inclusion as appropriate.
- Generate updated landslide susceptibility maps using recently acquired LiDAR derived digital terrain information using existing criteria (or amended criteria as appropriate) and recent debris flow studies.
- Recommend a revised mapping extent of the EMO.

3.0 GENERAL METHODOLOGY

Broadly, the following tasks have been undertaken to review the criteria upon which the existing EMO (Table 1) is based and to recommend revised mapping:

1) Review the background to the development of the current EMO and mapping. This task and its outcomes are set out in Section 4.0.
2) Review of relevant data and information pertaining to landslides in the Yarra Ranges, including LiDAR derived digital elevation models. Based on this information, expansion of the existing landslide inventory using remote mapping techniques to identify previously unrecognized landslides across the Yarra Ranges. Furthermore, update the landslide inventory with landslides known to have occurred since it was last updated in 2018 and consider recent studies into debris flow hazard in Victoria. This task and its outcomes are summarized in Section 5.0.
3) Undertake ground truthing to confirm and further refine landslide indications observed in the remote mapping. This task is summarized in Section 0.
4) Compare the updated landslide inventory with the existing criteria for inclusion in the EMO and critically review. Recommend revisions to the criteria for inclusion in the EMO if required. This task is summarized in Section 7.0.
5) Generate new landslide susceptibility maps based on the revised criteria (if applicable based on the review described in Task 4 above) and using recently acquired LiDAR derived digital elevation models and the updated landslide inventory. The revised EMO extent was then developed from the susceptibility maps. This task is summarized in Section 8.0.

4.0 BACKGROUND INFORMATION RELEVANT TO THE CURRENT YARRA RANGES EMO

This section sets out background information and previous studies that have informed the mapping and criteria for inclusion in the current EMO. Whilst landslide generally refers to the movement downslope of soil and rock and there are a range classifications for landslides, historically in Yarra Ranges, landslides have been categorised and “landslide” or “debris flow”. Landslide refers generally to the movement of soil or rock downslope. However, in some circumstances within the Yarra Ranges, landslides can develop into debris flow, which involves the channelisation and flow of debris derived from a landslides over what are sometimes long distances. Debris flow can entrain further debris and trees as they flow down steep gullies and can have significant impact at some distance from its landslide source. In Yarra Ranges, this is known to be more than 1.5 km. This section sets out background information and previous studies that have informed the mapping and criteria for identifying areas susceptible to landslide and debris flow and for their inclusion in the current EMO.

4.1 Topography

The topography in the Yarra Ranges is generally characterized by two broad terrains, the Yarra River valley and the surrounding mountainous areas. The Yarra River valley runs generally from east to west through the LGA, changing from a narrow V-shaped valley where it runs through the eastern, mountainous areas before emerging onto a broad valley with alluvial flats to west of Warburton. To the west of Warburton, the alluvial flats are surrounded by relatively low, rolling hills. The base of the river valley and its tributaries are generally underlain by alluvium, which overlies Silurian and Devonian Sedimentary rocks. The surrounding rolling hills are underlain by sedimentary rocks with some of the hills having a capping of Oligocene Volcanics. Geological conditions are discussed in further detail in Section 4.2.

The mountainous areas include the Dandenong Ranges, an isolated mountain range in the south-western part of the LGA, to the south of the Yarra River valley. Dissected mountainous areas are prevalent in the eastern part of the LGA, to the east, north and south of Warburton and to the east and north of Healesville. The mountainous areas are generally underlain by Devonian Volcanics and Granites, discussed in Section 4.2.

Slope angles in the Yarra River valley vary from generally below 5° in the alluvial flats of the river and its tributaries to more than 20° in the Dandenong Ranges and dissected mountainous areas, however the slope angles are generally less than 10° in the LGA. In the mountainous areas, slope angles are up to 35°, but more typically do not exceed 28°. Very steep slopes greater than 45° are rare and cliffs and gorges are not a feature of the landscape. A relief map of the assessment area based on the LiDAR derived digital elevation model is provided in Figure 1.

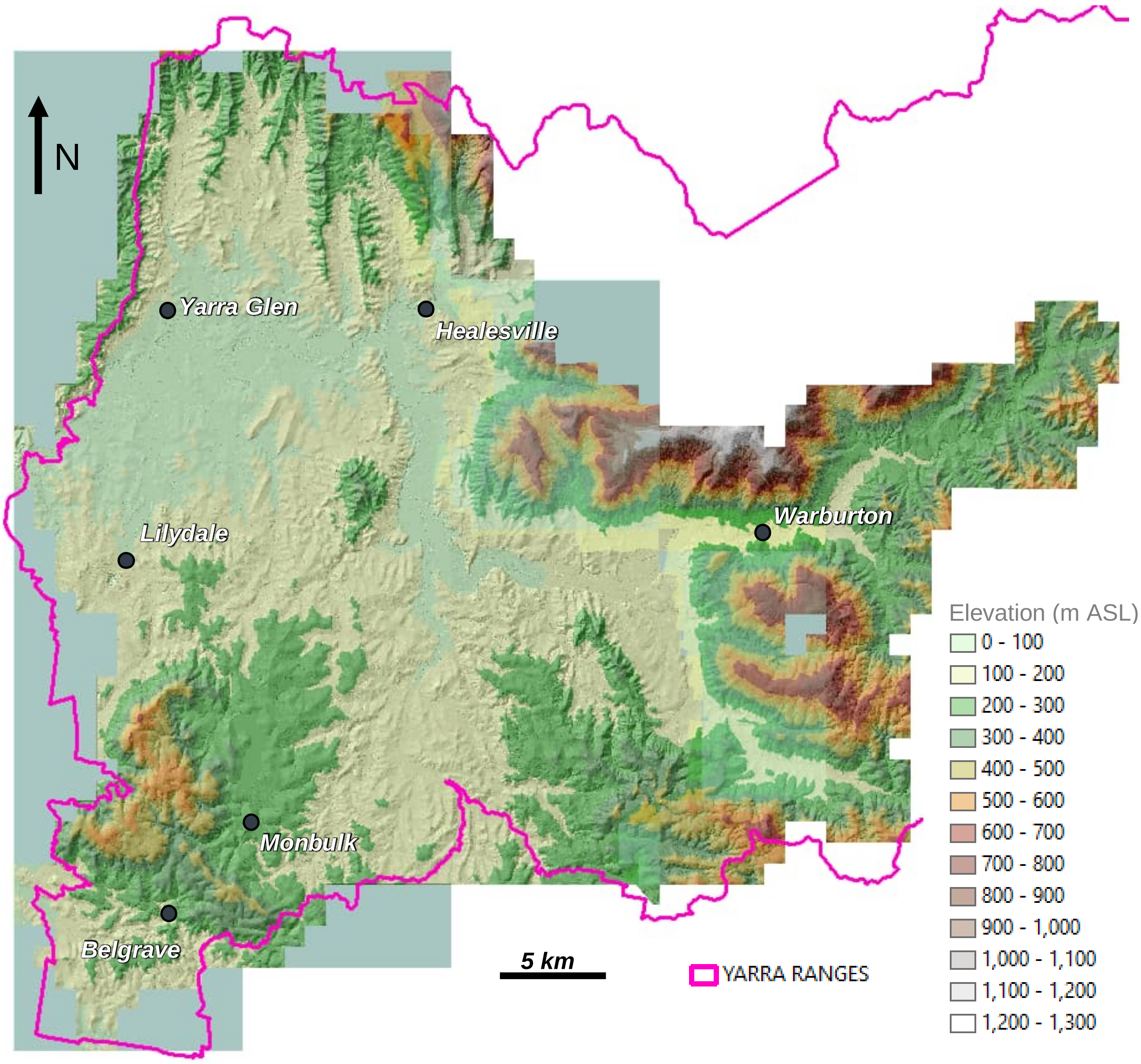

Figure 1: Relief map of the assessment area

4.2 Geology and Geomorphology

The distribution of the major geological units underlying the Yarra Ranges are presented in Figure 2. The geological data has been sourced from the publicly available 1:250 000 Geological Map Series of Victoria. For the purposes of this study, the geological units have been grouped into six major units that are consistent with those used for the landslide susceptibility criteria in the 1999 study on which the current EMO is based (Coffey, 1999) (see Section 4.3). A brief summary of the geological units is provided below from oldest to youngest.

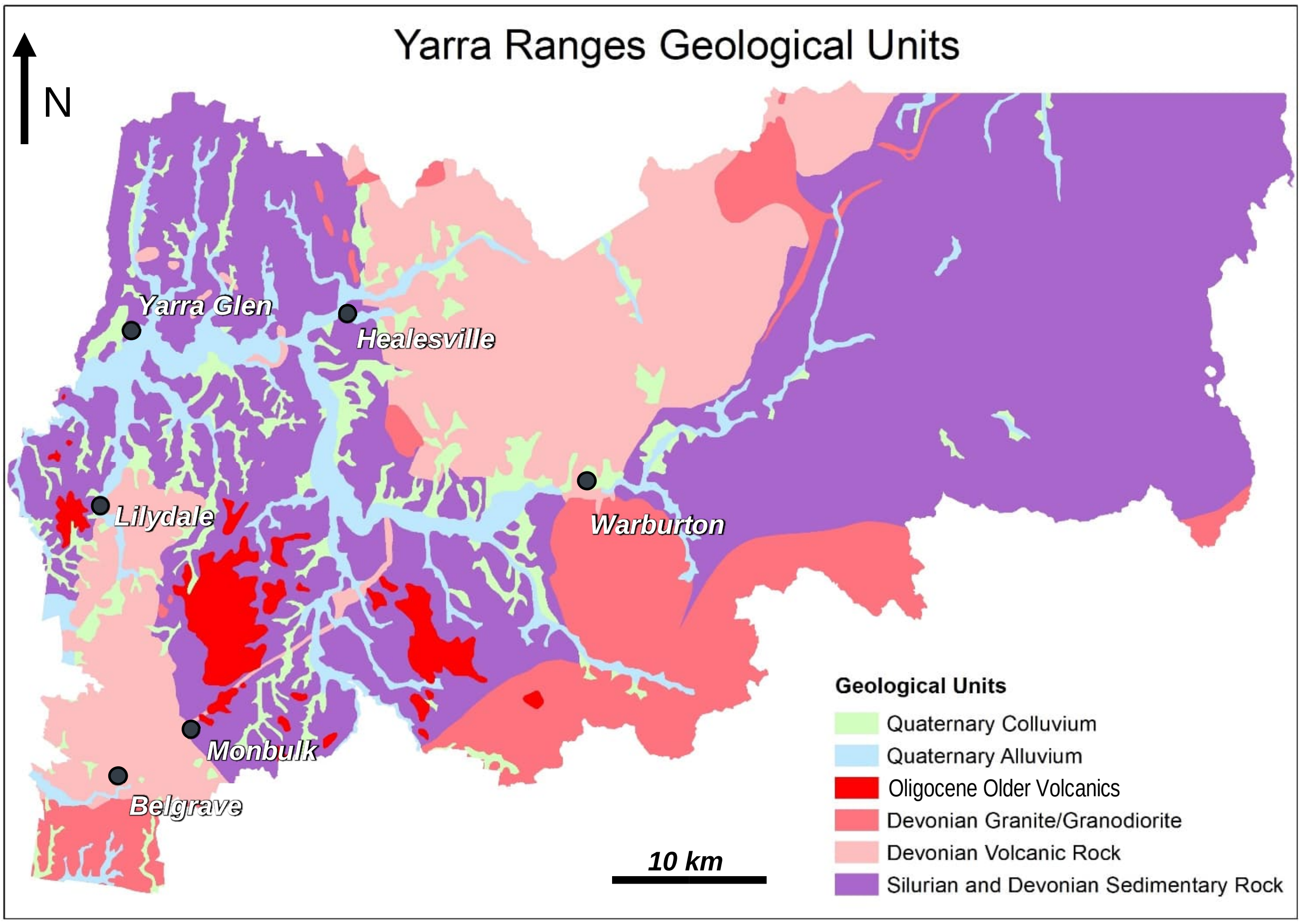

Figure 2: Geological map of the Yarra Ranges Shire, showing grouped geological units used for landslide susceptibility criteria. Geological data sourced from the 1:250 000 Geological Map Series of Victoria.

Silurian and Devonian Sedimentary Rocks

Silurian and Devonian sedimentary rocks form the surface geology across approximately 50% of the Yarra Ranges and underlie the Oligocene volcanic rocks. The sedimentary sequence includes interbedded sandstones, siltstones and mudstones of the Norton Gully Sandstone (Dlwn), Humevale Siltstone (Dlh), Dargile Formation (Sud) and Anderson Creek Formation (Sla). The rocks were folded and occasionally faulted during the Mid-Devonian. Adjacent to Devonian granite/granodiorite and Devonian volcanic intrusions, the rocks are locally metamorphosed to hornfels.

The rocks generally form gentle to moderately steep hilly terrain and usually have a thin soil cover 1 m to 3 m thick overlying weathered rock. Landslides are generally less prevalent in terrain underlain by sedimentary rocks, with creep movement of steeper, south facing slopes comprising thicker residual soils being the most common landslide type in this material. Significant landslides have previously been identified in areas where according to the geological map the underlying geology is sedimentary rock but based on field assessment, the landslides have occurred in unmapped Older Volcanics materials that are present as a relatively thin surficial layer over the sedimentary rock. The landslide at Monbulk-Seville Road (see Section 6.1) is an example of this circumstance.

Devonian Volcanic Rock

The Devonian volcanic rocks form the Dandenong Ranges and the mountainous country to the east of Healesville and north of Warburton. They include rhyolites, rhyodacites and ignimbrites such as the

Coldstream Rhyolite (Dvc), Mt Evelyn Rhyodacite (Dvm), Kalorama Rhyodacite (Dvk), Ferny Creek Rhyodacite (Dvf) and the Donna Buang Rhyodacite (Dcd).

These volcanic rocks form moderate to steep mountainous areas and often have a thick mantle of residual soil. Numerous landslides have been identified in the Kalorama and Ferny Creek Rhyodacites underlying the Dandenong Ranges and very large landslide complexes have been identified in the Donna Buang Rhyodacite north of Warburton. Landslides within the Devonian volcanic rocks differ from the Oligocene volcanic rocks in terms of their size and typical failure mechanisms. Landslides in both geological units can be spatially extensive. The landslides in the Devonian volcanic rocks are generally deeper seated and based on the morphology observed, the initial landslides are likely to have a relatively rapid velocity. Landslides in Oligocene volcanic rocks are generally shallower and have a much slower velocity, typically occurring as a complex of creep landslides.

Devonian Granite and Granodiorite

Areas of granite and granodiorite occur at the southern extent of the Yarra Ranges around Belgrave as well as south of Warburton. Smaller areas occur locally elsewhere in the LGA. Granitic magma intruded into the sedimentary basement rocks during the Devonian period, forming the plutons which following millions of years of weathering and erosion are now exposed at the ground surface.

The granitic subsurface materials are highly variable, with massive high strength rock close to the surface in some locations and with other areas having deep soil profiles. Perched groundwater within the deep soil profiles have been known to adversely impact slope stability in the area.

Oligocene Volcanics

The Oligocene Volcanics, also commonly referred to as the Older Volcanics, comprise basalt rock. The basalt is typically deeply weathered to a plastic clay with a thick surface soil layer. The Oligocene Volcanics generally occur as a capping layer of clay soil and extremely or highly weathered rock on hilltops in the Wandin-Silvan, Hoddles Creek and Lilydale areas, as well as other smaller areas. Field observations indicate that the Oligocene Volcanics are generally more extensive than what is represented on the publicly available geological mapsheets, which has implications for landslide susceptibility in the LGA.

The Oligocene Volcanics typically form rolling hills and undulating landscapes. Extensive creep landslide complexes are common in the deep soil profiles, particularly in the Wandin-Silvan and Hoddles Creek areas.

Quaternary Colluvium and Alluvium

Quaternary Colluvium has been identified as underlying some of the larger landslides in the study area. It is also common in the upper reaches of gullies and the surrounding steep slopes. Deposits include poorly sorted gravel, sand, silt and clay with cobble to boulder sized rocks. Landslides can be more common in these transported soils compared to in situ (residual) soils as the transported soils are often poorly consolidated and do not have the relict rock and mineral structure that residual soils can have.

Quaternary Alluvium deposits occur in the base of valleys, with the most extensive deposits in the low-lying areas of the Yarra River valley and its tributaries. Deposits include mixtures of sand, silt, clay, and gravel. The terrain in these areas is gently sloping to flat and is consequently not usually prone to landslides. Elevated terraces of alluvium can occur in the valleys and can be susceptible to landslides, particularly where oversteepening occurs due to erosion.

4.3 History of Landslide Planning Controls

Landslide risk management in relation to development planning has occurred in various forms in the LGA and preceding LGA's since 1981. The evolution of the different landslide planning controls over time is set out below:

- 1981 - The first systematic landslide study and associated planning scheme within the Yarra Ranges area was undertaken for the Upper Yarra Valley and Dandenong Ranges Authority (UYVDRA) (Soil Conservation Authority 1981). Limitations to residential development were based on 5 classes of "Land Capability" which ranged from Very High to Very Low, based on attributes such as slope angle, geology, annual rainfall, and soil type. Landslides were identified using aerial photographs and site observations. Areas identified as restricted for residential development included slopes greater than 25% (slope angle of 14°), areas known to be prone to landslides or subsidence, and areas prone to inundation or flooding.
- 1988 - Coffey undertook a subsequent aerial photo study for UYVDRA which identified many more landslides in the area than were identified in 1981 (Coffey, 1998).
- 1990 - Coffey undertook a landslide study for the Shire of Lillydale (Coffey, 1991), which is now part of the Yarra Ranges LGA. The study allocated a landslide risk level of low, medium or high based on the geology and the slope angle of the land. The study identified that the most likely places where future slope instability could occur is within old landslips, and that specific geological conditions were more susceptible to landslides at lower slope angles, such as the soils formed over the Older Volcanics. All non-public land was classified into landslide risk zones for which different planning controls were recommended.
- 1994 - the same zoning principles were applied by Coffey to the urban policy areas of Healesville and Yarra Glen, and by Golder to the Woori Yallock Township. A modified version of the zoning principles was applied to the former Shire of Sherbrooke on the recommendations of Mitford Engineering Pty Ltd in 1992.
- 1992 - Coffey produced a debris flow risk map (Figure 3) for the Montrose area which indicated areas of very low to high risk. Note that under current landslide management terminology, the appropriate term would be "susceptibility" rather than "risk". This is because the mapping does not specifically take account of the consequence of a debris flow event. The 'risk' level was assessed based on factors such as the topography, slope angle, size of the basal colluvium fan, and evidence of modern landslides. The risk that debris flows posed was highly relevant considering a debris flow in Montrose in 1891 destroyed a house, buried at least one person and killed two horses.

  The Coffey 1991 debris flow study at Montrose included detailed field mapping of geomorphic features indicating past debris flow source areas and runout extents on the north west faces of Mount Dandenong, including the recorded event of 1891. That work found evidence of older debris flows that have previously occurred in that area, some of which were larger than the 1891 event. The risk zones were designated on the basis of that mapping, to include areas where debris flows could initiate, the likely travel path which is typically along gullies, and where the debris is likely to be deposited. Following the study, debris flow planning controls were implemented in relation to debris flow in the Montrose area and areas identified as subject to high or medium risk are incorporated into the current EMO.

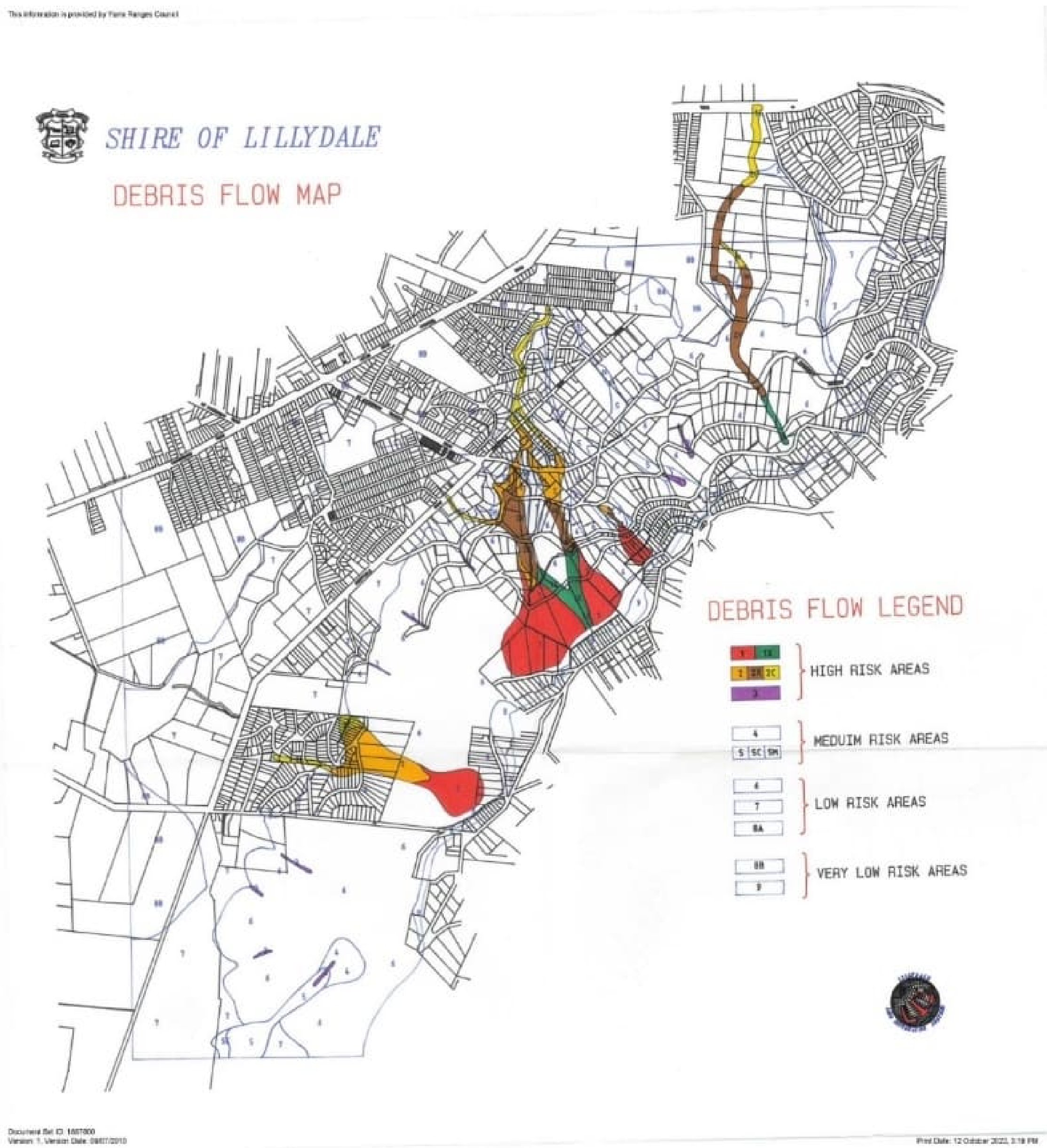

Figure 3: Debris flow risk map for the Montrose area, based on study by Coffey in 1991 and presented in Heine 1992

- 2001 - The current EMO and mapping extent is implemented, with its extent based on the key studies undertaken in 1992 for the Montrose debris flow and the 1999 landslide susceptibility study:
  - Coffey Partners International Pty. Ltd. (1991), *Study of Risk of Debris Flows and Other Landslips, Montrose, Victoria, Vol 1 – 3.* Unpublished report to Shire of Lillydale.
  - Coffey Partners International Pty. Ltd. (1999), *Landslip Zoning of the Shire of Yarra Ranges*, Unpublished report to Shire of Yarra Ranges.

Whilst there have been minor amendments to the EMO mapping that was introduced in 2001, it is largely unchanged since its implementation at that time. For the Coffey 1999 study, undertaken five years after the amalgamation of the former Shires of Healesville, Lillydale, Upper Yarra and Sherbrooke, landslide susceptibility criteria were developed and landslide susceptibility maps were produced covering the Yarra

Ranges LGA. Coffey also recommended planning and development controls in areas susceptible to landslide. Landslide generally refers to the movement of soil or rock down slope, but unlike debris flow, landslides are generally not fluid and travel less distance than debris flows. The Coffey 1999 study included review of historical landslide records and the development of a landslide inventory which informed the development of a series of criteria to indicate landslide susceptibility, with the criteria based on slope angle, the underlying geology and whether a landslide has previously occurred at the site. The criteria presented in the Coffey 1999 report built upon indications of landslide susceptibility set out in an earlier 1988 study undertaken by Coffey for the Upper Yarra Valley and Dandenong Ranges Authority (Coffey, 1988).

On the basis of the Coffey 1999 study, landslide susceptibility across Yarra Ranges was zoned into three main categories, Low, Medium and High, with Medium subdivided into three further categories, M0, M1 and M2 to give 5 categories overall. This system was a bespoke system developed for Yarra Ranges, noting that at the time of the study in 1999, guidance for a study of this kind was limited, with AGS 2000 and AGS 2007 which provide current guidance on landslide susceptibility assessment in Australia yet to be published. Furthermore, the tools available to apply these criteria to the maps were limited to the use of scale rules on hard copy maps, whereas modern GIS systems allow the application of terrain criteria to be automated and undertaken with significantly less effort, greater accuracy and precision.

The study for the Montrose debris flow (Coffey, 1991) was referenced in the Coffey 1999 report, however the 1999 report did not investigate areas susceptible to debris flow in detail and not beyond what was studied in 1992. The assessment of debris flow susceptibility beyond the Montrose area was not undertaken. The areas indicated to be exposed to medium or high debris flow risk in 1991 were incorporated into the Yarra Ranges EMO in 2001 along with those areas assessed as having a Medium 2 (M2) or High (H) classification in the 1999 study.

In 2009, Council discontinued the use of the susceptibility levels set out by Coffey in 1999 and adopted the current approach whereby areas are not zoned but are either included or excluded from the EMO simply on the basis of their having susceptibility to landslide or debris flow. The shaded boxes in Table 1 are the susceptibility criteria which define the current mapped extent of the EMO, based on geology, slope angle, past occurrence of landslide and the medium and high risk areas identified in the Coffey 1991 debris flow study.

Table 1: Summary of the existing landslide susceptibility criteria produced by Coffey in 1991 and 1999, used for development of the current EMO.

Geology	Slope Angle (Shaded boxes are the susceptibility criteria which define the current extent of the EMO).					
	0° to 3° (0% to 5%)	>3° to 9° (>5% to 15%)	>9° to 11° (>15% to 20%)	>11° to 22° (>20% to 40%)	>22° to 26° (>40% to 50%)	>26° (>50%)
Silurian and Devonian Sedimentary Rock	Not susceptible	Low	Low	Medium (M1)	Medium (M2)	Medium (M2)
Devonian Granite/Granodiorite	Not susceptible	Low	Low	Medium (M0)	Medium (M2)	Medium (M2)
Devonian Volcanic Rock (Dvc, Dvm, Dcl, Dvt)	Not susceptible	Low	Low	Medium (M1)	Medium (M2)	Medium (M2)
Devonian Volcanic Rock (Dcd, Dvk, Dvf, Ddh, Ddr, Dcw)	Not susceptible	Low	Low	Medium (M2)	Medium (M2)	High
Oligocene Older Volcanics	Not susceptible	Low	Medium (M2)	Medium (M2)	Medium (M2)	Medium (M2)
Quaternary Colluvium/Alluvium	Not susceptible	Low	Low	Medium (M2)	Medium (M2)	Medium (M2)
Past Landslide (any geology)	High	High	High	High	High	High
High or Medium Debris Flow Risk (Coffey 1991)	Included in EMO, but delineated with separate debris flow classification, Medium or High debris flow risk.					

To inform update of the current EMO, a review was undertaken of the criteria upon which the EMO is currently based, with a view to checking whether those criteria are reasonable to apply to a revised EMO.

4.4 Existing YRC Landslide Inventory

In 2016 Golder Associates Pty. Ltd. prepared a digital landslide inventory for YRC which was made available to geotechnical practitioners via an online portal. The inventory was updated in 2018 and has recently been updated as part of this study. The landslide inventory conveys Council's knowledge of areas where landslides have previously occurred to geotechnical practitioners who undertake work within the LGA. An example screen shot of the online inventory is provided in Figure 4.

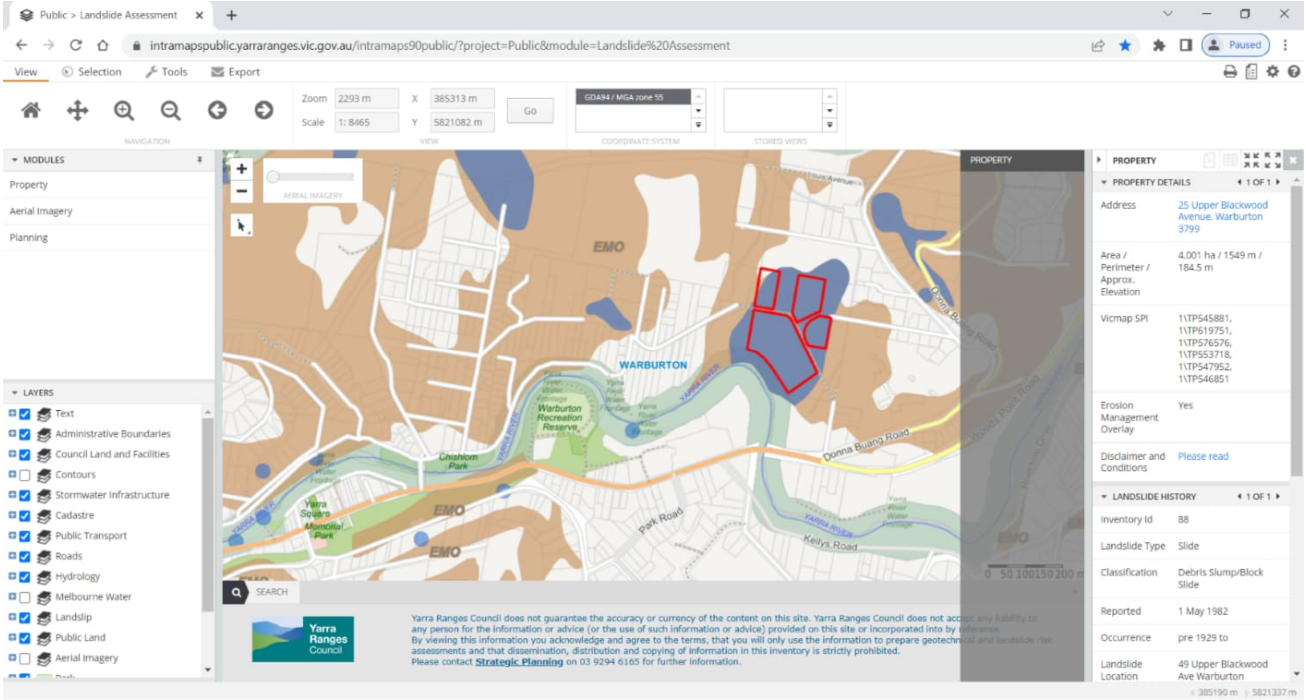

Figure 4: Example screen shot of the Yarra Ranges Council online Landslide Inventory

Prior to this study, the inventory comprised a total of 301 landslides in the inventory including 167 landslide extents that have been mapped as GIS polygons using aerial photos, site walkovers or contour plans, and 134 points where a landslide boundary was unable to be mapped due to small scale or lack of data, but the approximate location is known. The following sources have contributed to the Landslide Inventory:

- The Coffey 1999 study identified 94 landslides across the LGA. Approximately 80 of the landslides have been mapped as polygons and the remainder are points in the inventory. The size of the landslide, geology, street address and comments are generally included. There are limitations to the spatial accuracy of the extent of the landslides as the mapping was undertaken using aerial photography with some site walkovers.
- The Coffey 1991 debris flow study at Montrose produced records of landslides and debris flows on the western slopes of Mount Dandenong. The landslides and debris flows were mapped in the field in detail, including debris flow source zones and runout extents.
- Landslides and records of slope instability from the Golder Associates archives, which includes information obtained while working within the Yarra Ranges area for over 50 years. Information includes geotechnical investigations and site walkovers of naturally occurring landslides within the LGA as well as landslides that have occurred within earthworks.
- Council has maintained asset management records from 2003 to the present which includes information about landslide events that have been reported by members of the public. In most cases, information on the location is limited to an address and is in the database as a location point with low accuracy. Limited information is recorded about the landslide and most of them have not been described by a geotechnical practitioner. Additional landslides were added to the inventory during this study, as described in Section 5.0.

5.0 INFORMATION REVIEW AND UPDATE OF LANDSLIDE INVENTORY

The information reviewed, tasks undertaken and results of the update to the landslide inventory are set out in the following sections.

5.1 Information Reviewed

The following available information relating to landslide processes and identification within the was collated and reviewed:

- Publicly available geological information, including maps and memoirs from the Geological Survey of Victoria. The geological maps used were in electronic GIS format.
- The existing Landslide Inventory for the LGA, last updated in 2018.
- Topographical information including maps and recently acquired LiDAR elevation data.
- Slope stability records within the YRC asset management register.
- Relevant historical publications and photographs including newspapers, historical maps or documented histories for the study area.
- State level studies, including recent work undertaken by The Department of Environment, Land, Water and Planning (DELWP) and the University of Melbourne to map areas that are predicted to be susceptible to debris flow hazards across the state, including within the Yarra Ranges LGA.

Descriptions of pertinent information reviewed is provided in the sections below.

5.1.1 Existing Landslide Inventory

The Landslide Inventory is a live register of observed landslides in Yarra Ranges which is provided to geotechnical practitioners who perform geotechnical assessments and landslide risk assessments within Yarra Ranges (it is not available to the public). The inventory comprises landslides compiled from sources described in Section 4.4. The landslides mapped in the existing inventory were reviewed against the digital terrain model and the extents of previously mapped landslides updated. The existing landslide inventory formed the basis for the expanded landslide inventory which has arisen from this study.

5.1.2 LiDAR Information

LiDAR ground elevation data provides the opportunity to undertake detailed desktop mapping of terrain features that could indicate locations subject to previous landslides, including subtle features that are difficult to observe by other means. The LiDAR information was not available during the development of the current EMO and subsequent amendments, having been acquired between 2015 and 2017.

The following LiDAR data sets were available for the assessment set out in this report:

- 1 m resolution elevation grid generated from LiDAR data acquired in 2015 and 2016 of the Warburton and Healesville areas and surrounds, supplied by Yarra Ranges Council and sourced from DELWP.
- 1 m resolution elevation grid generated from LiDAR data acquired in 2017 of the western part of Yarra the LGA, supplied by YRC and sourced from DELWP.

LiDAR information is not available for the entire LGA. Areas that do not have LiDAR information are:

- relatively small areas near the western LGA boundary between Kilsyth and Chirnside Park and to the south of Belgrave, which have been assessed without the aid of LiDAR, and;
- much of the eastern parts of the LGA, to the east of Warburton and Healesville. However, most of this area is Parks Victoria managed land and as such will not be subject to local planning controls.

The LiDAR data was used to interpret the topography within Yarra Ranges, with a series of derivative maps including hillshade and slope angle generated. The extent of the available LiDAR data, represented as elevation relief, in comparison to the LGA boundaries, represented in pink outline, is shown in Figure 1.

5.1.3 Spatial Datasets

Other electronic GIS datasets that have been used in the desktop landslide mapping process include:

- Geoscience Victoria (GSV) Seamless Geology at 1:250,000 scale
- VicMap 2022 Property Boundaries and Addresses
- VicMap 2022 Road Network

5.1.4 Yarra Ranges Asset Management Register

The Council maintains an asset management register which includes the time and location of landslides and earthworks failures as reported by local residents and observed by Council workers. WSP Golder was provided with the asset management register for the period January 2018 to July 2022. The register was reviewed by an engineering geologist and 54 relevant landslide records were added to the Landslide Inventory. The majority of the landslides added from this source register are small cut and embankment failures which have typically occurred in the Ferny Creek Rhyodacite and Donna Buang Rhyodacite at slope angles greater than 30°.

Further to landslides captured in the asset register, landslides within Yarra Ranges that WSP Golder is aware of due to having assisted Council with assessment and mitigation were added to the inventory, with a further 110 landslides added from this source. This includes a major landslide that occurred in January 2024 on Mount Dandenong Tourist Road in Tremont (see Section 6.1.7).

5.1.5 Publicly Available Landslide Records

A review of landslides that have occurred within the LGA was undertaken using online resources such as Trove and other media databases. These records often lack an accurate spatial reference but do give an indication of the approximate area or town the landslides occurred in. These records also provide an indication of the triggering mechanism of the landslides, with heavy or prolonged rainfall often preceding the landslide event. A total of 18 landslides were added to the inventory from that source.

5.2 Landslide review and identification by LiDAR

The landslide mapping on which the current inventory and EMO are based was undertaken between 1980 and 2000, based on air photo interpretation, historical observations and limited ground truthing. The boundaries of the existing mapped landslides within the landslide inventory have been reviewed using the LiDAR terrain information. The boundaries of the previously mapped landslides were found to be approximate compared to the mapping accuracy that can be achieved from the LiDAR desktop mapping. During the review process 70 existing polygons delineating landslides were edited to better define the landslide extents. An example of remapped landslide boundaries is presented in Figure 5.

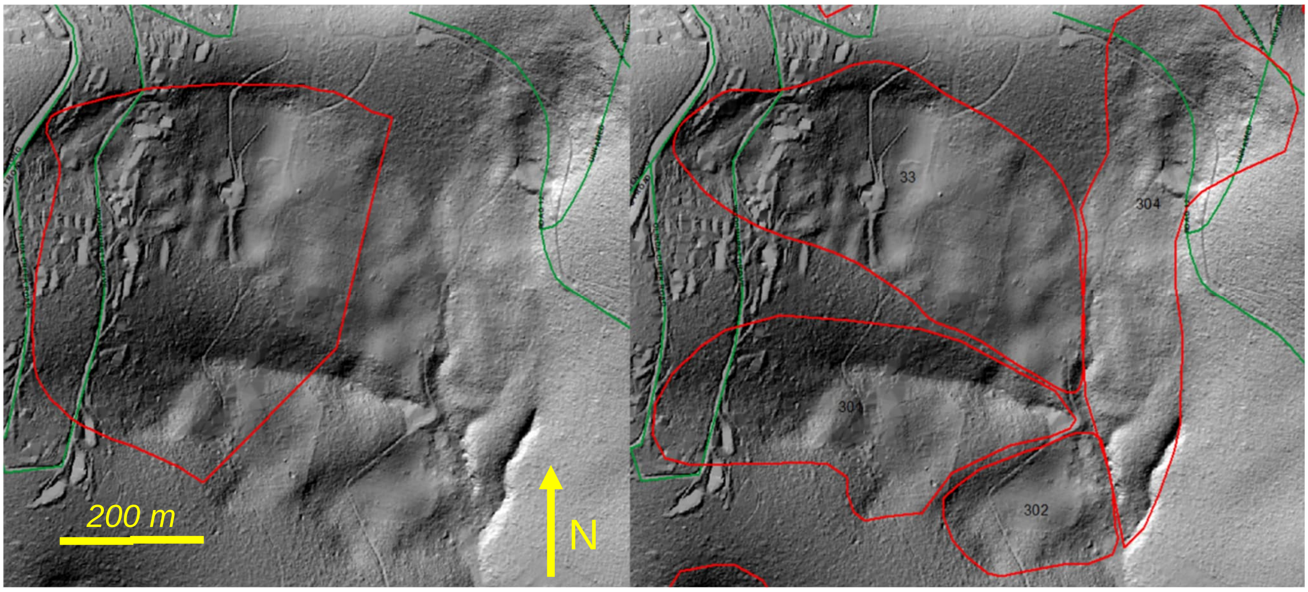

Figure 5: Example of comparison between existing mapped landslide boundaries (left) and revised boundaries identified using LiDAR information (right). Woodhurst Grove, Kalorama

Eighteen previously mapped landslide polygons were confirmed to provide a reasonable representation of the landslide boundaries and approximately 80 landslide polygons were removed from the inventory or combined with other landslide polygons to capture a larger landslide complex than initially identified. An example of landslides removed from the inventory based on the digital terrain information is present in Figure 6.

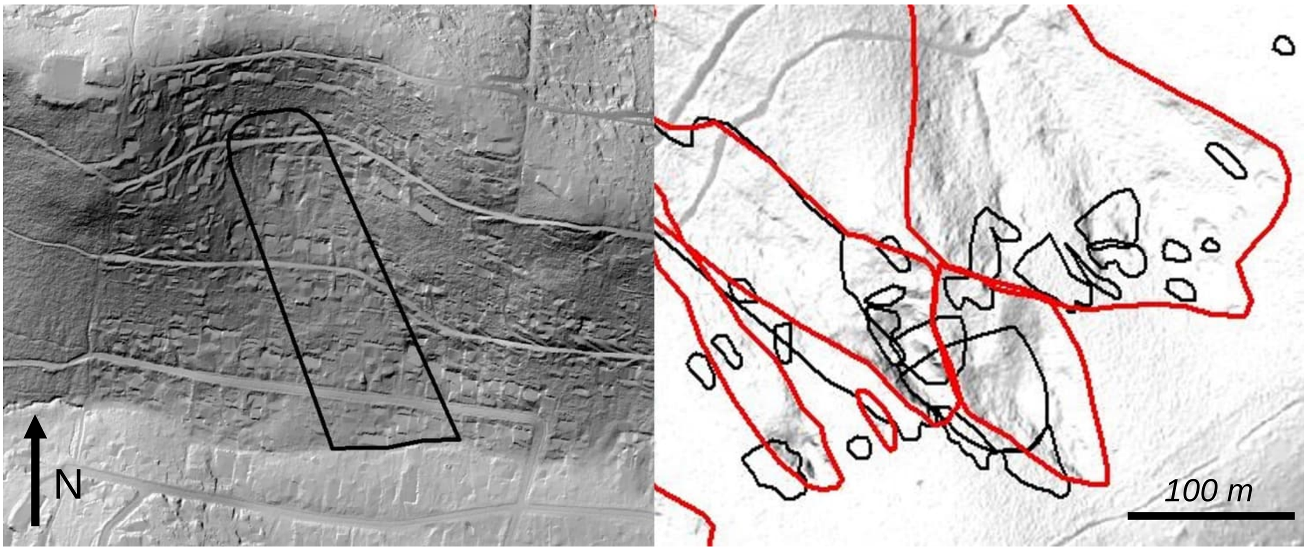

Figure 6: Left: Landslide polygon (black) removed from inventory based on reduced confidence in terrain evidence. Right: Landslide polygons (black) superseded by a new polygon (red) that encompasses a larger landslide area.

Numerous previously unidentified landslides have been observed and mapped based on the digital elevation model. The current inventory includes 167 mapped landslide polygons, including collated information from additional sources other than detailed desktop mapping, covering a total area of 24.4 km^2. The LiDAR derived digital terrain mapping, including consolidation of some of the landslides in the current inventory, has resulted in the addition of 825 landslide polygons, taking the total number of polygons to 912 as of 1 August 2024 covering a total area of 62.5 km^2.

Mapping using the LiDAR derived digital terrain information allows for an assessment of the relative age of landslides. More recent landslides tend to have sharper, more defined features compared to the more subdued features in what are inferred to be older landslides, where the original sharper features would have eroded over time. Without records of the landslide occurrence, the estimation of the age of the landslide has a high level of uncertainty and has not been attempted. As part of mapping landslides from the LiDAR information, a record of those landslides which appear more subdued and therefore are more likely to be relatively older was compiled.

A side-by-side comparison of landslides which have a clear terrain expression compared to a more subdued expression is shown in Figure 7.

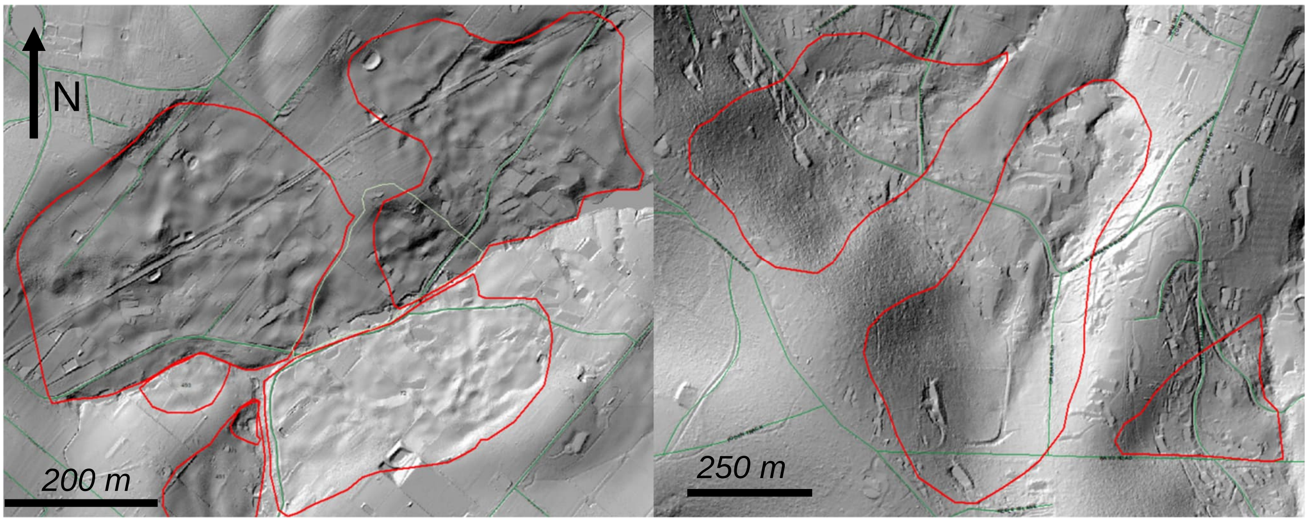

Figure 7: Side by side comparison of landslide expressions identified in LiDAR information. Left: Distinctive hummocky terrain and sharp scarp features indicating more recent landslides. Right: Subdued scarps and debris lobes indicating older landslides.

Recent landslide activity across Monbulk-Seville Road in Seville indicates that landslide reactivation within the Tertiary volcanics can occur on subdued older landslides with low slope angles (<9°). Based on this observation, mapping subdued ancient landslides within the Tertiary volcanics was undertaken. Cases of landslide reactivation on ancient landslides with low slope angles have not been observed within other geological units such as the Devonian Volcanics. Consequently, highly subdued, inferred ancient landslides have not been included in the landslide inventory on the basis they are not prone to reactivation.

Previously unknown landslides identified from the remote mapping using LiDAR, provide valuable insight into the conditions which contribute to landslides within the LGA. The locations and inferred types of landslides identified by the mapping, observed in the field and collated from historical records were used to review the prevalence and characteristics of landslides compared to likely influence factors such as geological conditions and topography. This was taken as important input into the review of the landslide susceptibility criteria as described in Section 7.0.

5.3 Debris Flow

Debris flows initiated by rainfall are known to occur in acid igneous rocks of the Yarra Ranges, including on the western slopes of Mount Dandenong and are postulated to occur on the southern slopes of the Yarra River valley, to the south of Warburton based on the digital terrain mapping.

The debris flows tend to occur on slopes where the difference between precipitation and evaporation is greatest, typically slopes with a northerly to north westerly aspect. These soils maintain strength due to the preservation of suction stresses (similar to a sandcastle). If the suction stresses are lost due to rapid water infiltration, this can lead to a rapid loss of soil strength and ensuing landslide. The debris arising from the landslide can be fluid and flow downslope into channels, scouring out the channels and entraining debris such as soil, rocks and trees as it flows downslope. The debris flow runs out until the solid material is deposited in the channel and the slurry becomes more of a water flow or the slurry fans out on the flatter areas below and loses energy.

The University of Melbourne has spent several years developing a predictive post bushfire generated debris flow model (Nyman 2013, 2017). The statewide model predicts post bushfire debris flow source zones and runout paths using input factors such as initial location, slope angle, geology, gully fall angle and gully sinuosity (meander). The model also predicts the likelihood of a debris flow occurring at each source location given that a bush fire event has occurred. Although the post bushfire debris flow scenario may only be partially applicable to the assessment of landslide generated debris flow susceptibility which is the subject of this report, the generated flow paths and run outs could be useful in assessing areas that may be within the runout path of a debris flow.

The LiDAR derived digital elevation information was also used to identify areas that have been subject to past debris flow. Evidence for debris flow was observed in the Montrose area on the north west facing slopes of Mount Dandenong, consistent with those identified by Coffey in 1991. However, several additional gullies in the Montrose area were identified as potential sources that were not previously identified by Coffey. Furthermore, in their 1991 study, Coffey indicate there are likely to be other areas within the Yarra Ranges susceptible to debris flow, but which were not assessed as part of that study.

Where terrain evidence for previous debris flows has been identified and mapped near the heads of north and north westerly facing gullies in susceptible geological conditions, the runout distance estimations developed by the University of Melbourne were used to estimate the travel distance of debris flow to confirm and supplement the extents mapped in the Coffey 1991 study. This includes areas to the south of Warburton and to the east and south of The Basin.

5.4 Summary of Landslide Inventory Updates

Based on the sources described above, as of 1 August 2024 a total of 1,016 landslides had been added to the landslide inventory from the asset management records, publicly available landslide records and the desktop LiDAR terrain mapping. The landslide inventory is considered a live document, with landslide events added as they occur. A summary of the landslide inventory updates is presented in Table 2.

Table 2: Summary of identified landslides by source

<table>
<tr><th colspan="2">Source</th><th>No. of Landslides in Revised Inventory</th></tr>
<tr><td colspan="2">Landslides within current inventory</td><td>167</td></tr>
<tr><td colspan="2">Existing landslide polygons adjusted*</td><td>70</td></tr>
<tr><td colspan="2">Existing landslide polygons removed or merged</td><td>-80</td></tr>
<tr><td colspan="2">New landslide polygons mapped using LiDAR</td><td>825</td></tr>
<tr><td colspan="2">Landslide points in the Yarra Ranges asset management register</td><td>134</td></tr>
<tr><td colspan="2">Landslide points added from WSP Golder studies, investigations and reports</td><td>110</td></tr>
<tr><td rowspan="3">Landslide points added from publicly available information</td><td>Trove</td><td>18</td></tr>
<tr><td>SES</td><td>6</td></tr>
<tr><td>Bicycle Network</td><td>3</td></tr>
<tr><td colspan="2">TOTAL</td><td>1183</td></tr>
<tr><td colspan="2">No. of Landslides in Current Inventory</td><td>167</td></tr>
<tr><td colspan="2">NET INCREASE</td><td>1016</td></tr>
</table>

6.0 GROUND TRUTHING

Several site visits were undertaken to ground truth features identified in the digital terrain mapping and to assess landslides with known historical and recent activity. Site visits were undertaken to assess landslides and to evaluate debris flow source zones and run out paths.

On 21 and 22 December 2023, engineering geologists from WSP Golder visited multiple landslide sites across Yarra Ranges, accompanied by a representative from Council. Field visits to targeted landslides were based on the following factors:

- Areas where recent landslide movement has been reported, such as adjacent to 205 Owens Road in Woori Yallock and 101 Monbulk-Seville Road in Wandin East.
- Documented landslides that have had physical impacts or planning impacts on properties, such as Blackwood Avenue in Warburton and Woodhurst Grove, Kalorama.
- New landslides that have been identified in the digital terrain which have the potential to include numerous additional properties within the revised EMO, such as at Eacotts Road, Hoddles Creek and parts of the Wandin-Seville area.
- Landslides that appear subdued in the digital terrain, to determine if reactivation of the landslide is sufficiently likely to warrant inclusion in the EMO, such as potential ancient landslide scars, that now appear as gullies in The Patch and Belgrave areas.
- Areas where potential features interpreted as debris flow source areas and run out paths were identified in Warburton and The Basin.

In addition to the site visits undertaken specifically for this study, it is important to note that WSP Golder has been providing landslide management services to Yarra Ranges Council for many years and in that time visited many landslide sites, including recent landslides that occurred during the 2019 to 2022 La Niña and storm events. This includes the January 2024 landslide on Mount Dandenong Road, Tremont which resulted in the destruction of a house and which has been considered as part of the ground truthing exercise.

A summary of the key findings and their applicability to the revision of the EMO for select site visits is presented below. A map indicating the locations visited is provided as Figure 8.

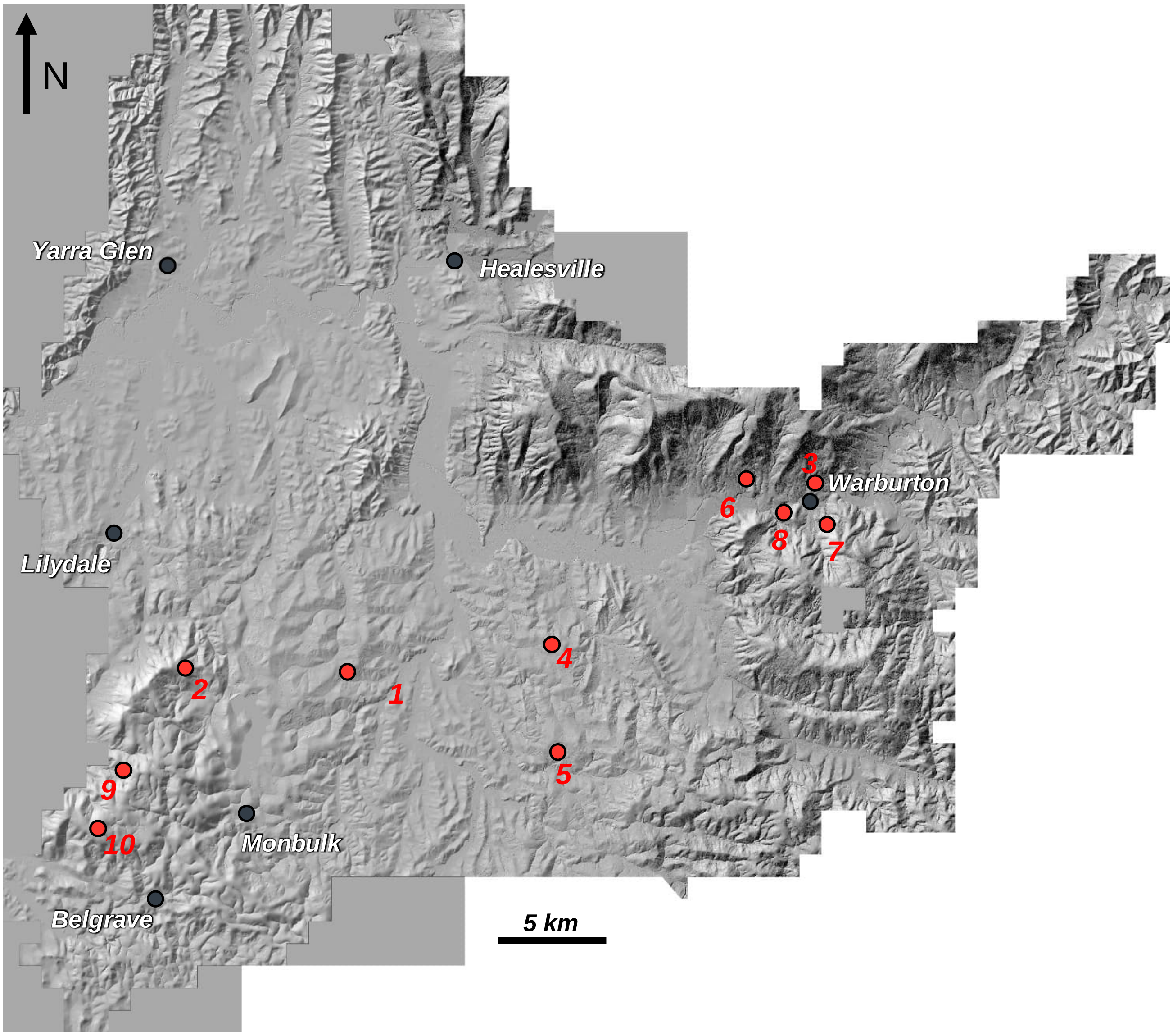

Figure 8: Locations of sites visited. Numbers correspond with site numbers in descriptions in Sections 6.1 and 6.2.

Sites visited with landslide and debris flow hazard were separately assessed as set out subsequently.

6.1 Existing Landslide Sites

The following existing landslide sites were visited as part of the ground truthing exercise.

6.1.1 Site 1 - Monbulk-Seville Road, Seville

A relatively large landslide occurred in October 2022 occurred across Monbulk – Seville Road in Seville which caused damage to the road, an adjacent house and a dam upslope of the road (Figure 9). The recent ground movement appears to have occurred on ground that could have previously been subject to landslide. However, based on LiDAR terrain information, the evidence for a previous landslide is subdued and had not previously been identified (Figure 10), nor was the area in which the landslide occurred within the extent of the current EMO. The overall slope angle at the site is about 5°, which is not steep enough to meet the requirements for inclusion in the EMO based on the existing slope angle criteria (Table 1).

It is possible that the landslide is associated with nearby development including a dam and earthworks which triggered reactivation of the ancient landslide. It may also indicate that landslides in the Tertiary Older Volcanics are susceptible to remobilisation at lower slope angles than is assumed in the susceptibility mapping which informs the current EMO extent. Had this area been subject to the EMO, the dam and earthworks which are inferred to have contributed to the landslide reactivation may have been constructed differently or not at all, possibly preventing the damage that has occurred. This case provides evidence and a basis to include ancient subdued landslides within the Tertiary Older Volcanics within the EMO.

This case has provided an additional learning regarding the accuracy of the publicly available geological mapping that is used to develop the EMO. According to the 1:250,000 scale and the 1:50,000 scale geology maps, the majority of the landslide was mapped as being underlain by siltstone geology (Figure 10). Field observations and intrusive geotechnical investigations indicate that the landslide is actually within Tertiary Older Volcanics. This issue represents a limitation to landslide susceptibility mapping at a regional scale, as the process relies on applying slope angle criteria to specific geologies based on the published geological information. Further discussion on the methods used to address the uncertainty of the geological mapping, particularly with regard to Tertiary Older Volcanics, is provided in Section 7.0.

Figure 9: Recent infrastructure damage, Monbulk-Seville Road, Seville. Left: Damage to road. Top right: Landslide scarp through dam wall. Bottom right: Damage to property.

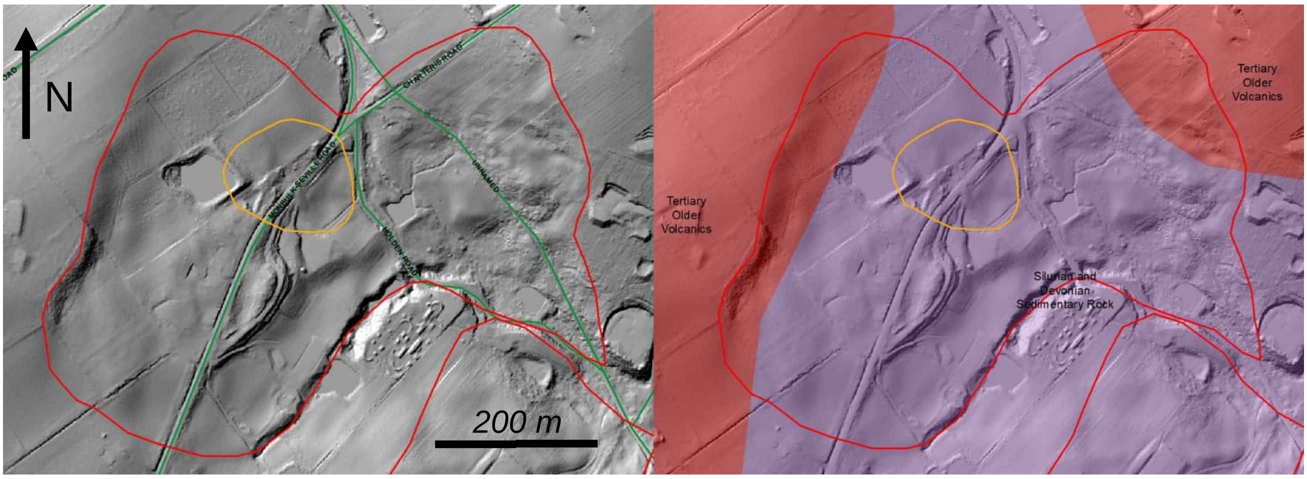

Figure 10: Left: Digital Terrain Model showing inferred approximate extents of the recent landslide at Monbulk-Seville Road (orange line) within the extent of a subdued previous landslide area (red line). Right: 1:250,000 scale geology map placing majority of landslide in siltstone (purple) close to Tertiary Older Volcanics boundary (red).

6.1.2 Site 2 - Woodhurst Grove, Kalorama

This is an example of a location at which revised mapping informed by LiDAR indicates the boundaries of existing landslides to be different to what had been previously assumed and mapped (Figure 5). The purpose of the site visit was to check whether the indications gained from the LiDAR appeared reasonable, noting that this is a residential and forested area. The site visit observations confirmed the new landslide boundaries. Along Woodhurst Grove, outcrops of colluvial materials were observed within the landslide polygons and outcrops of residual soil derived from in-situ rock were observed between the two landslides (Figure 11).

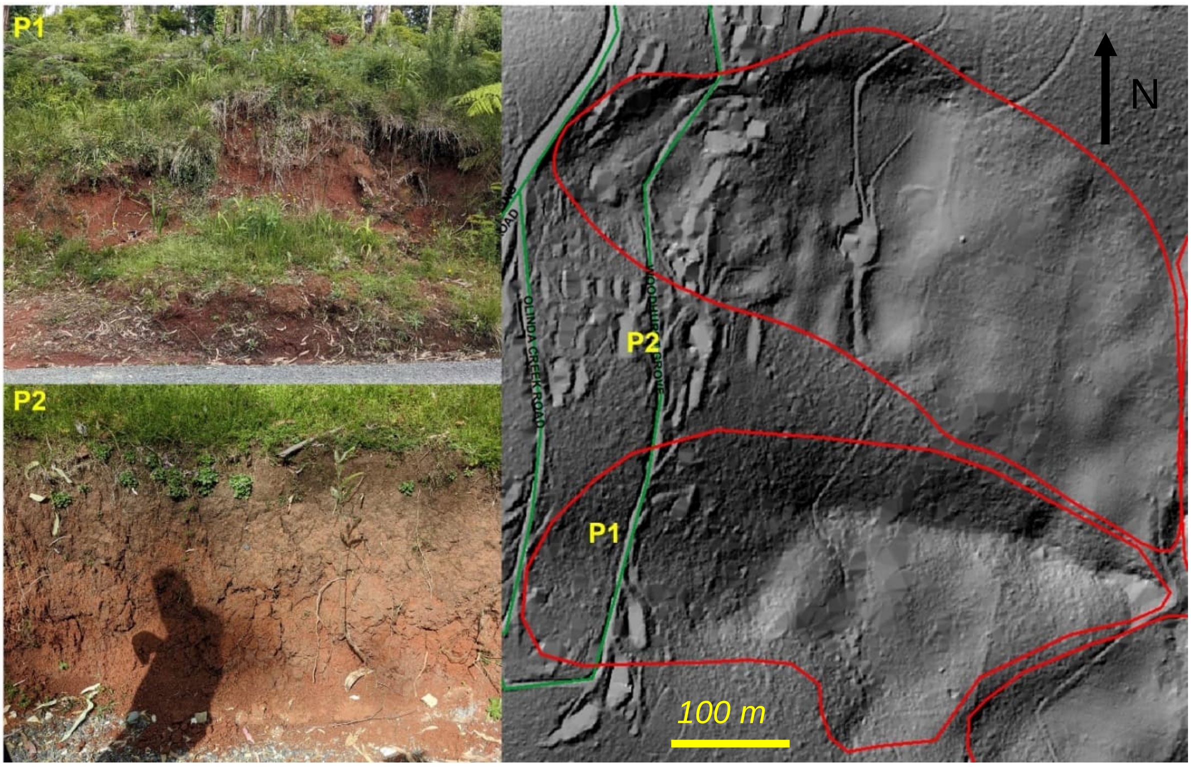

Figure 11: Landslide mapping at Woodhurst Grove. Top left: colluvium outcrop with location shown as P1 in hill-shade (right). Bottom left: residual soil outcrop with location shown as P2 in hill-shade (right).

6.1.3 Site 3 - Blackwood Avenue, Warburton

This is a site at which a landslide has occurred and the extent and recent activity of the landslide is well known and documented. The site visit was intended to verify that landslides interpreted from LiDAR information are reasonable based on comparison with surface observations and landslide events. The site visit confirmed that the landslide boundaries mapped using the digital terrain are consistent with those observed in the field and previously mapped (Figure 12).

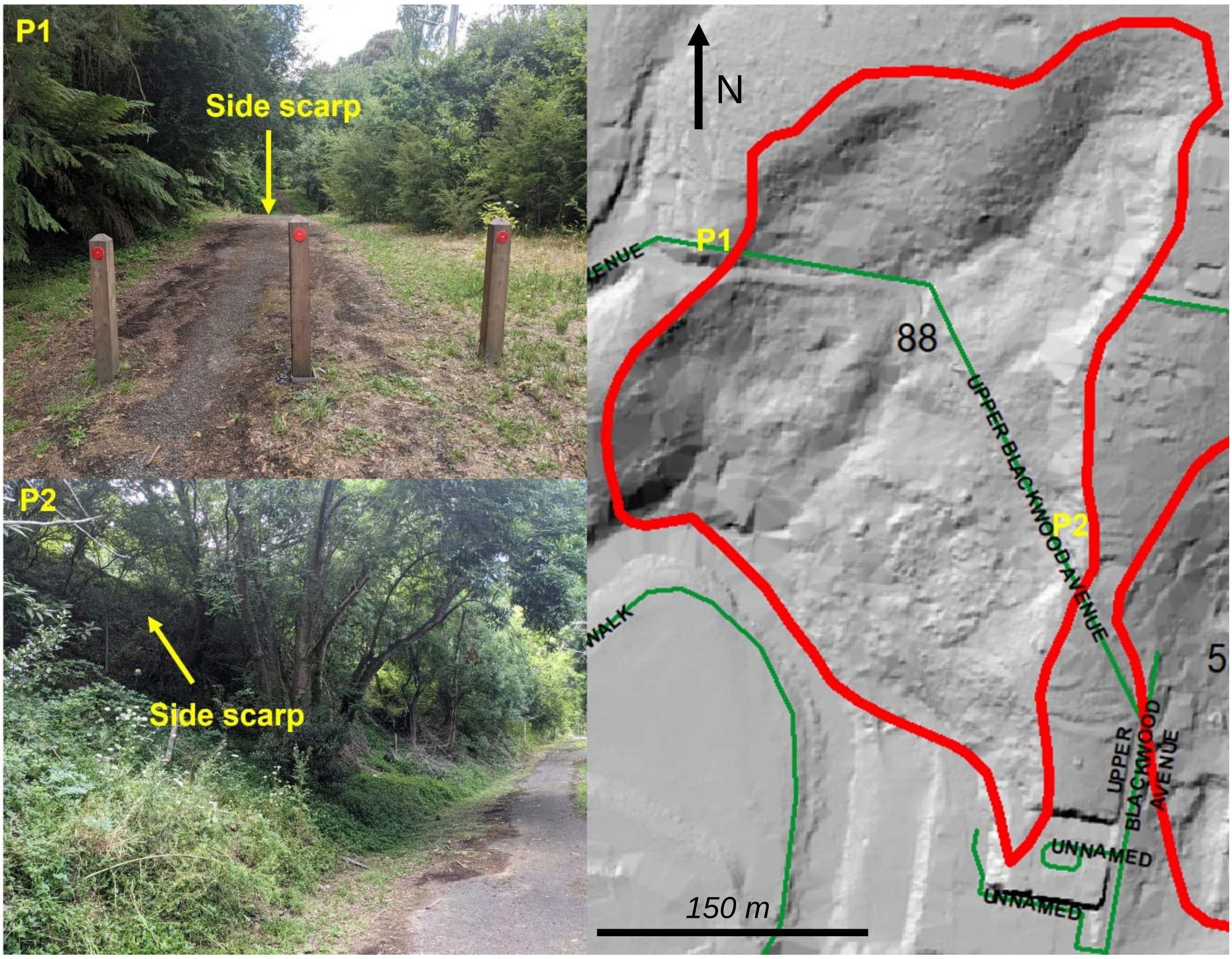

Figure 12: Landslide at Blackwood Avenue, Warburton. The location of the side scarps observed in the field (left) are consistent with the landslide boundaries mapped using the digital terrain (right)

6.1.4 Site 4 - Owens Road, Hoddles Creek

This site was visited due to the unusual appearance in the digital terrain and known issues with ground movement in the base of the valley (Figure 13). The landslide is known as a potential earth flow or swamp due to the relatively flat ground surface with rippling. Site observations confirmed this location is likely to be an earth flow – a fluid landslide whereby the ground 'flows' due to its high moisture content. Field observations such as these help to inform the landslide mechanism which then allows for the appropriate hazard management and planning controls to be implemented.

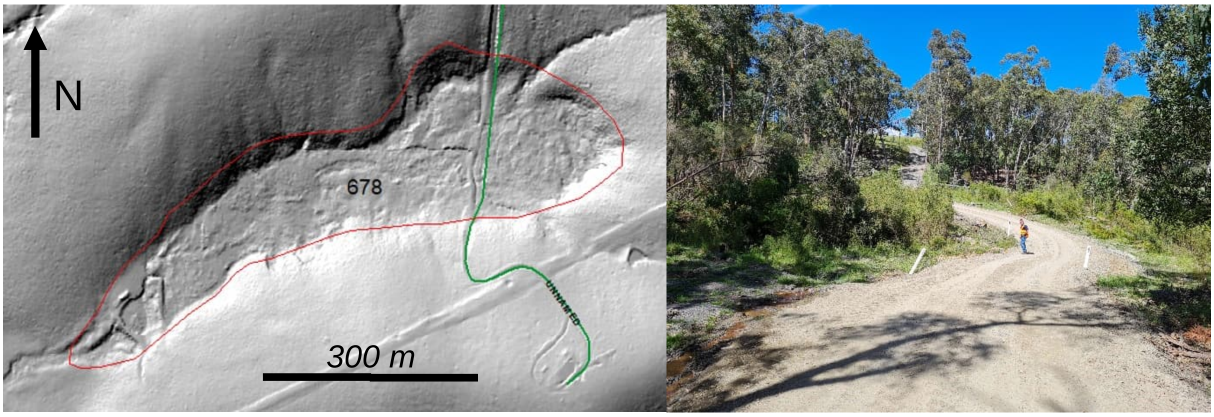

Figure 13: Earth flow identified in the digital terrain model at Owens Road, Hoddles Creek. Left: Landslide boundaries mapped using the digital terrain. Right: Owens Road deviating due to slow earth flow movement.

6.1.5 Site 5 - Eacotts Road, Hoddles Creek

This location was visited as it has the potential to add several properties into the EMO that are not within the current EMO. The landslide is clearly identifiable in the LiDAR terrain based on the hummocky ground surface and relatively prominent scarp features. However, this landslide has not been identified or reported on in previous studies. The field observations confirmed the presence of a headscarp (Figure 14) likely derived from landslide. The hummocky terrain was also apparent in the field. However, without the aid of the LiDAR terrain information, it would be difficult to assess this area as a landslide complex based only on surface observations alone, due to the large scale and gentle terrain. The site provides an example where the LiDAR terrain information facilitates a more comprehensive identification of landslide compared to physical mapping on the ground.

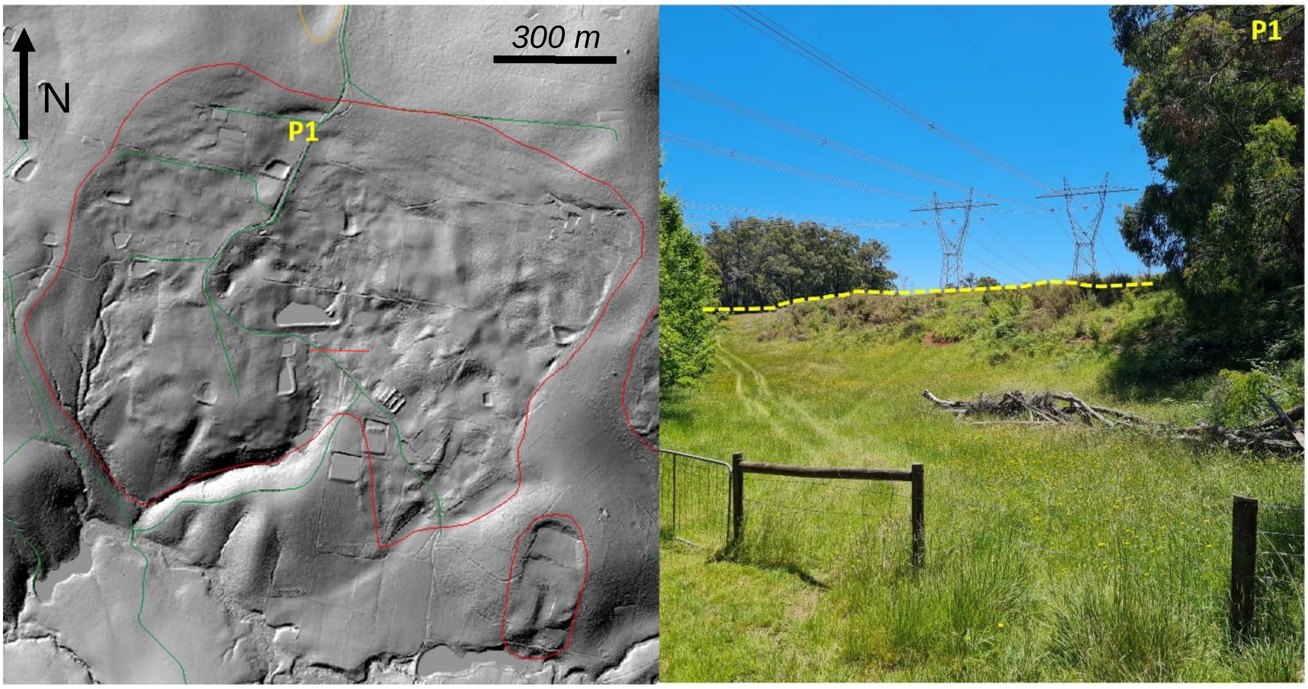

Figure 14: Landslide in the Tertiary Older Volcanics at Eacotts Road, Hoddles Creek. Left: The extent of the landslide is clearly identifiable in the terrain, the location of the headscarp photographed (P1) is shown. Right: Field photo of the headscarp.

6.1.6 Site 6 - Wonga Road, Millgrove

A site visit was undertaken at this location due to the relatively smooth features of this landslide in the digital terrain model indicating it is likely subdued. The visit was to assess whether the area is in fact underlain by a landslide or whether the features observed are the result of creek dissection. A colluvium outcrop was observed in a cut along Wonga Road which confirmed the likely presence of a landslide. Rock fragments were observed in an upturned tree root on the western side of the creek that appeared to be in situ rock rather than colluvium, inferring the mapped extents of the landslide (Figure 15).

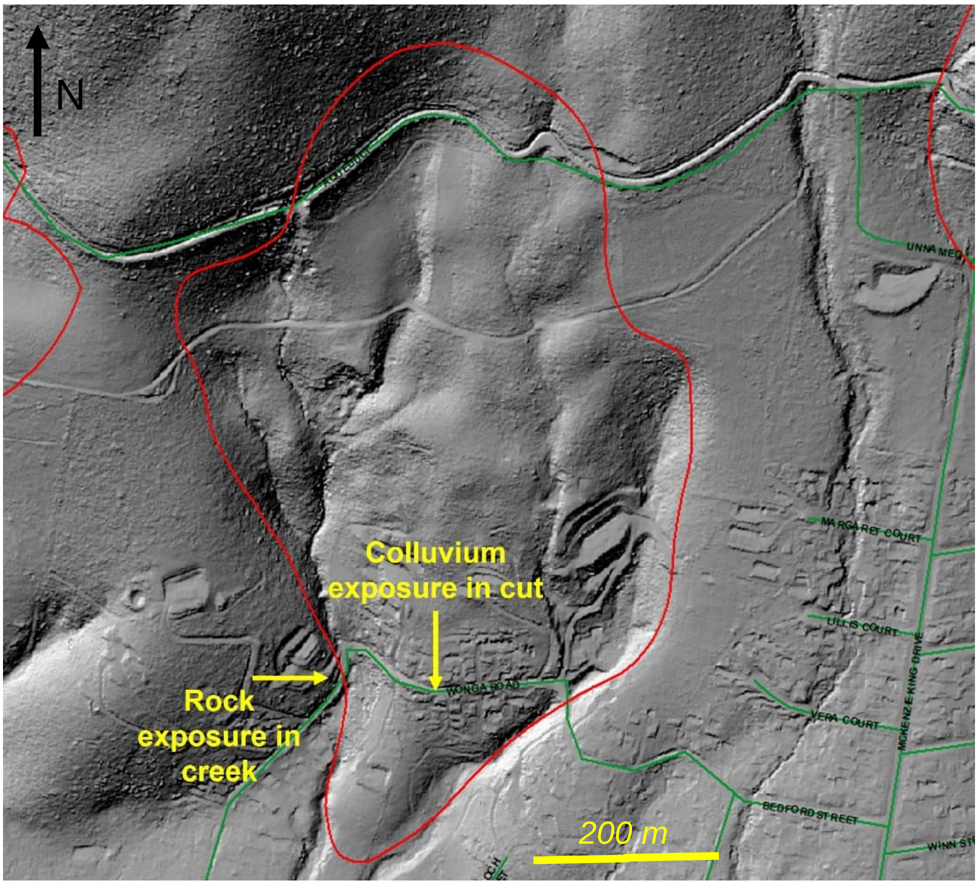

Figure 15: Subdued landslide at Wonga Road, Millgrove

6.1.7 Site 10 – Mount Dandenong Tourist Road, Tremont

A landslide occurred at this location on 8 January 2024 which caused the complete destruction of a house and initiated an emergency response with which WSP Golder was involved. As part of the remote mapping to update the landslide inventory, which occurred prior to the landslide occurring, past landslides were identified at the location of the Tremont landslide, as indicated by the yellow polygons in Figure 16. The red polygon in this figure is the approximate extents of the January 2024 landslide.

The landslide was a shallow translational landslide which occurred on a steep slope with slope angle of up to 55°. The landslide source area has plan extent of about 20 m to 30 m wide and 20 m to 30 m upslope (Figure 17), with the debris runout extending downslope by about 70 m and being partially arrested through impact with a house. The maximum depth to the sliding plane is about 3 m, reducing to about 1 m on the periphery of the landslide, and with an estimated volume of between about 500 m^3 and 1000 m^3. The landslides caused the toppling of several trees which exacerbated the consequences and was triggered by high rainfall, noting that the landslide source area was a point of surface water flow accumulation.

The plan extent of the January 2024 landslide lies within polygons previously mapped and identified as landslides. However, based on the observations of the 2024 landslides, the landslide inventory was revised by combining the three landslides mapped at this location and expanding the overall extent of the landslide as indicated in Figure 16.

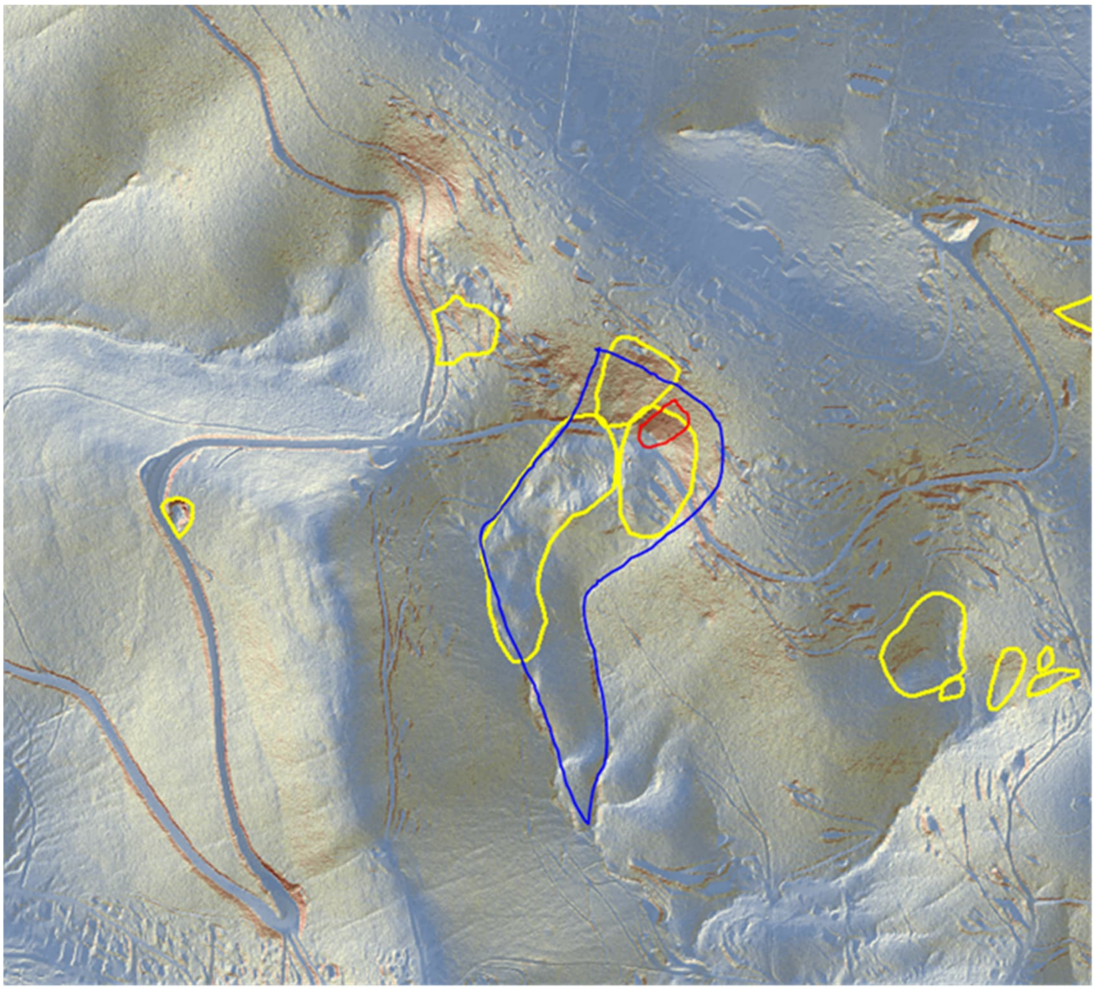

Figure 16: Extent of January 2024 landslide (red polygon) along with previously mapped landslides (yellow polygons) and revised extent of area affected by landsliding (blue polygon) following ground truthing

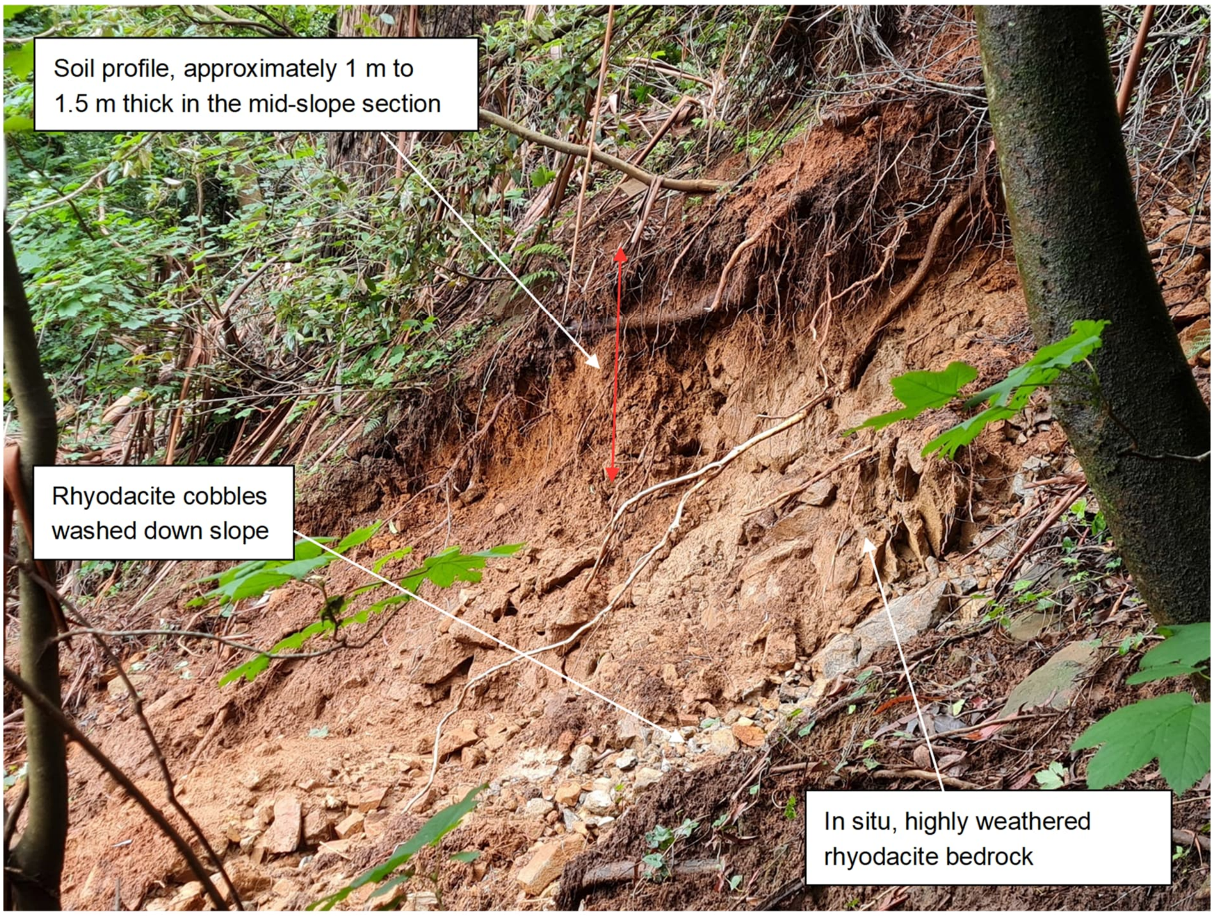

Figure 17: Headscarp of January 2024 landslide, Mt Dandenong Road, Tremont

6.2 Debris Flow Site Visits

Features indicating previous debris flows have been observed in the Montrose area and are well documented by Coffey (1991 and 1992). However, debris flows in other parts of the LGA had not been assessed for the purposes of incorporating areas susceptible to debris flow into the EMO.

Two other areas were identified during the LiDAR terrain mapping as having potential for debris flows, the north facing hill slopes to the south of Warburton and the west facing hill slopes to the east of The Basin. It should be noted that if a debris flow initiated in the gullies in the hill slopes above The Basin, debris which travels down the gullies would impact properties that are located within the Knox City LGA.

Signs of ancient debris flows may be more difficult to identify in the field compared to landslides, as the volume of material removed from the initiation area is typically lower, the debris is deposited downslope over a longer run out distance and the material deposited in the channel downslope that may remain after a significant period of time, typically boulders, may have come from other sources such as rockfalls.

6.2.1 Site 7 - Pheasant Parade, Warburton

A gully adjacent to Pheasant Parade, Warburton was visited to check for evidence of past debris flow events. Further up the gully, evidence of potential debris flow initiation areas was observed in the LiDAR terrain information. The gully is linear adjacent to Pheasant Parade, with relatively little vegetation as it is in a residential block. Viewed from the road, in situ granodiorite rock outcrops were observed on the flanks of the gully, with some cobbles and small boulders present in the base and on the side slopes of the gully, near the outcrops. The source of the cobbles and small boulders is unclear, possibly deposited by a debris flow, formed in situ or transported a short distance down the adjacent slopes.

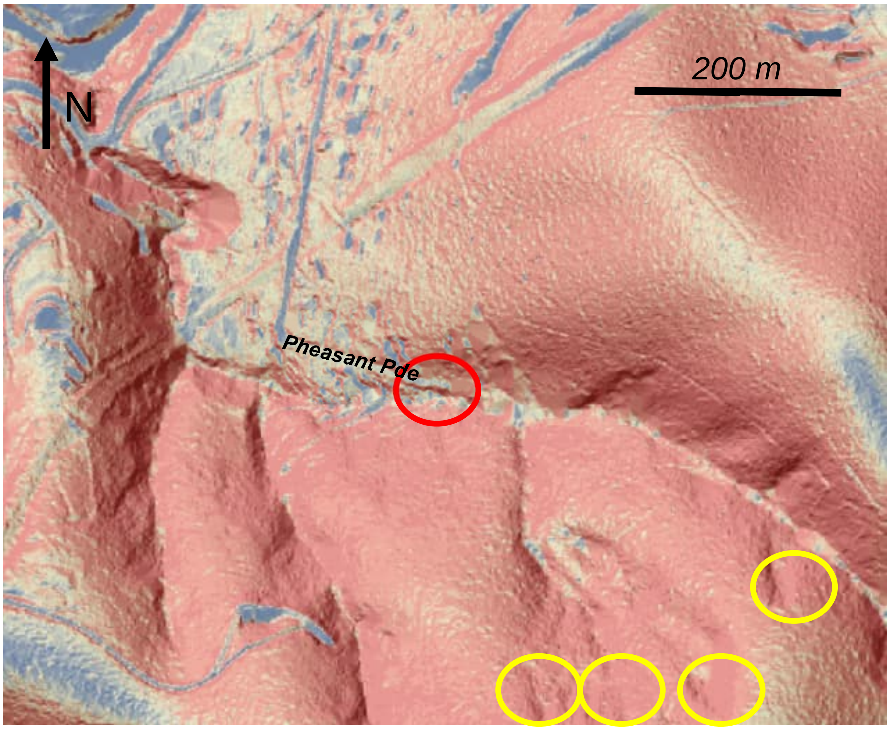

Figure 18: Potential source locations of debris flows identified in the LiDAR information (circled yellow), downstream site visit observation location (circled red), Pheasant Parade, Warburton

6.2.2 Site 8 - Warburton Rail Trail, west of Warburton

Landslides identified in the LiDAR derived terrain information in the hillslopes to the west of Warburton township were observed from the Lilydale-Warburton Rail Trail between Hooks Road and Scotchmans Creek Rd. The landslide scar features have a morphology that could be related to debris flows, with relatively narrow, direct travel paths down slope towards the Yarra River.

In the field it was assessed that the landslides are relatively shallow features comprised of soil and rock rather than debris flows, as signs of subsequent creep movement of the debris lobe at the toe of the landslide was observed.

In a cutting in the rail trail, consolidated colluvium with angular gravel and cobbles was observed, inferred to be landslide debris, which was assessed to not be material derived from debris flow. Evidence of previous landslides was observed upslope of the cutting. Considering the strength and degree of consolidation of the material, it is inferred that the landslide event depositing the material is likely pre-Holocene (>10,000 years).

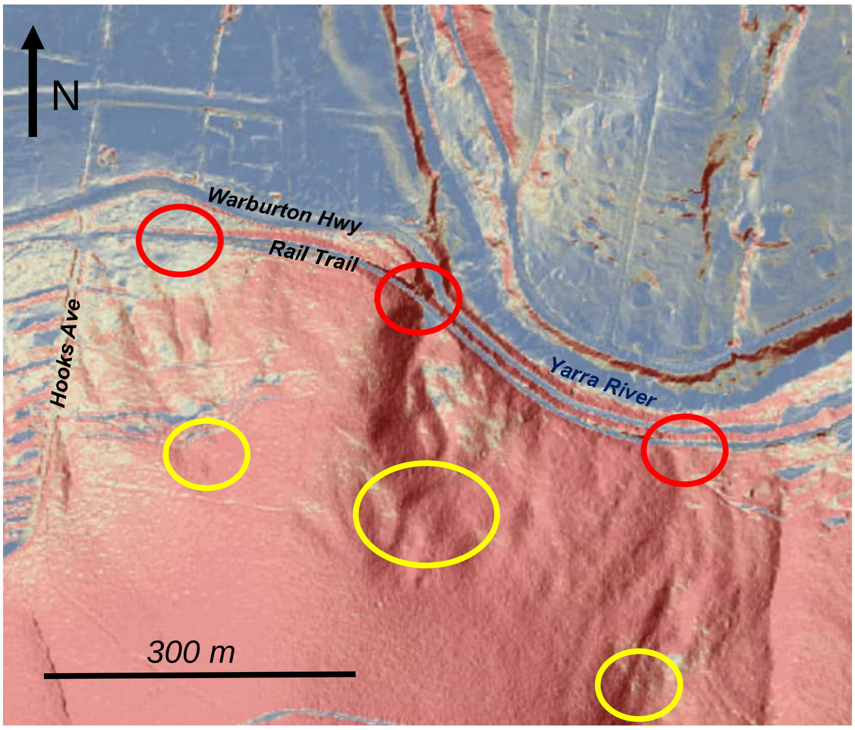

Figure 19: Potential source locations of landslides/debris flows identified in the LiDAR information (circled yellow), downstream site visit observation locations (circled red), west of Warburton

6.2.3 Site 9 - Mountain Highway, The Basin and Sassafras

Two locations of accessible gullies in The Basin area were assessed for signs of historic debris flows, one on Mountain Highway near Ferndale Road and one at the end of Bowen Avenue. The gullies are generally a V-shaped incision, which is different to the more typical U-shaped gullies formed by debris flow scour. A number of minor features have been identified and interpreted as possible debris flow initiation areas up the gullies from these locations. At the Mountain Highway location, geological features indicative of past debris flow such as transported boulders were not observed. At the Bowen Avenue location, subrounded rhyodacite boulders were observed in the base and lower slopes of the gully, adjacent to the creek. Similar to the Pheasant Parade site, the source of the boulders is uncertain, but debris flow cannot be precluded.

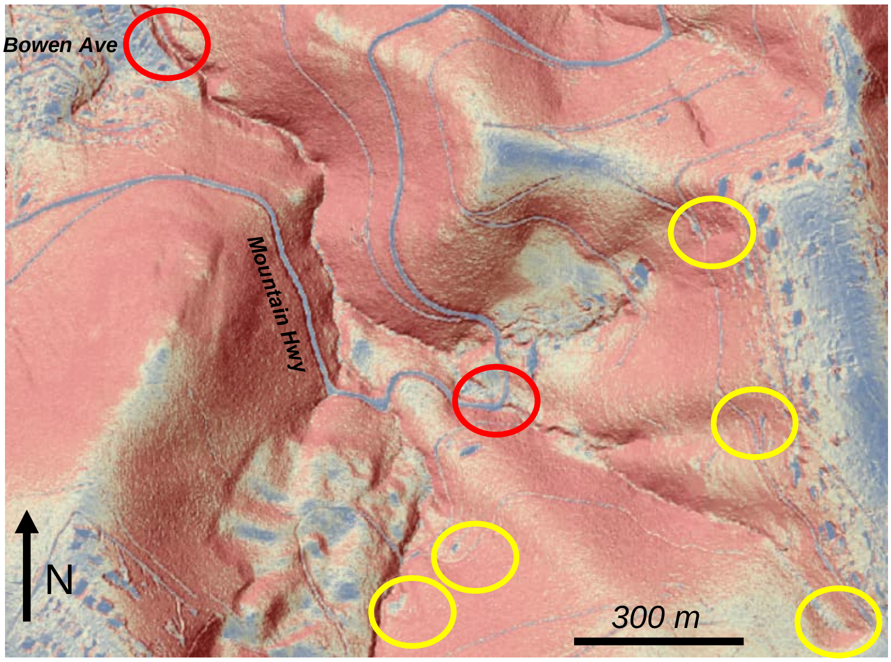

Figure 20: Potential source locations of debris flows identified in the LiDAR information (circled yellow), downstream site visit observation locations (circled red), The Basin

7.0 REVIEW OF LANDSLIDE INVENTORY AGAINST EXISTING CRITERIA

The expanded landslide inventory was reviewed to gain insights into landslides and landslide processes that have affected the LGA which are discussed in this section. Critical review of the existing criteria for inclusion within the EMO (Table 1) was undertaken by comparing the criteria with the landslide inventory. This section also sets out the work undertaken to review the landslide inventory and generate the landslide susceptibility maps.

7.1 Observed Landslide Characteristics

The landslide inventory features were observed in a GIS workspace which allowed mapped landslides to be compared to various likely influencing factors such as slope angle, geology and slope aspect. Analysis of the landslide inventory yields the following observations:

- A significant number of previously unidentified landslides have been mapped in the Wandin-Silvan-Seville area and the Hoddles Creek area, in areas the geological map indicates are underlain by Silurian sedimentary rock with some Tertiary Older Volcanics hilltop caps. Landslides have been identified in the mapped Silurian Sedimentary geological units which have similar morphology to the landslides in the adjacent Tertiary Older Volcanics areas and suggest inaccuracy of the geological map.
- Landslides in the Tertiary Older Volcanics often appear to form 'complexes' over large areas, with the morphology indicating different parts of the complexes may be active at different times. Areas that may have been previously active landslides can have very subtle terrain features. The recent Monbulk-Seville Road landslide (Section 6.1.7) is an indication that the landslide complexes could remobilize in sufficiently adverse conditions. No evidence was obtained for 'first time' landslides in the Older Volcanics having occurred within recorded history. The landslides in this material are inferred to have first occurred under different geological conditions to those at present and recent movement is inferred to be a reactivation of an older landslide.
- Significantly fewer landslides were identified in the area of Oligocene Older Volcanics immediately west of Lilydale compared to the Monbulk-Seville-Silvan area. The landslide morphology is also different, with large landslide complexes not observed.
- In the Dandenong Ranges, a significant number of landslides have been identified, generally on the steeper slopes at the base of valleys. The features appear to be subdued by erosion processes to varying amounts. Based on known landslide occurrences, landslides within the Dandenong Ranges are of different ages, up to the present. Many of the landslides identified and included in the landslide inventory occur in areas that are not applicable to the EMO i.e. Parks Victoria areas.
- Landslides were generally not identified in the areas to the south of Belgrave South, which is underlain by granodiorite.
- Few landslides were identified in areas underlain by Silurian sedimentary rocks to the north and south of the Yarra River, generally north of Seville and west of Healesville. Some localised areas of creep movement were identified on south facing slopes. Although historical reports indicate debris flows have occurred in the Myers Creek area in recorded history, geomorphological evidence for a prevalence of debris flows was not identified.
- The landslides identified on the southern slopes of Mount Donna Buang, to the north of the Warburton township, are much larger in number and scale than the current landslide inventory indicates. The intermittently active Blackwood Avenue landslide complex in Warburton indicates potential for reactivation of parts of the debris lobes of the landslides in sufficiently adverse conditions. The landslide initiation

areas are often in areas where the EMO is not applicable i.e. Parks Victoria areas. However, the debris lobes often extend downslope into areas where EMO controls could apply.

- Features potentially representing debris flow sources were identified in the upper part of gullies in the slopes to the south of Warburton. Although many of these features are in areas where the EMO is not applicable i.e. Parks Victoria areas, the debris flows could run out to the toe of the slope at the Warburton township and into the Yarra River or its major tributaries.
- Some landslides not in the current inventory were identified in locations where residential buildings are currently present.

Known landslide events which have been observed and documented in recorded history have been used to infer the potential frequency and probability of landslide reactivation to assist between identifying landslides that are ancient and unlikely to present a future hazard and those that could reactivate. Discussion of the characteristics of the landslide processes and hazards identified is provided subsequently, grouped based on the underlying geological conditions. A discussion of landslide triggers based on inventory indications is also provided.

7.1.1 Quaternary Alluvium

No significant landslides were observed within the alluvial deposit materials within the base of the Yarra River Valley, only small scale slumping of relatively low oversteep slopes formed by erosion of unconsolidated soils has been observed. The travel distance associated with the slumping is usually small and the slumping does not present a significant hazard.

The creep movement in flat base of the valley at Owens Road, Hoddles Creek (Section 6.1.4) appears to be within alluvium or mixed alluvium/colluvium deposit.

7.1.2 Devonian Volcanics, Dandenong Ranges

In the Devonian Volcanics of the Dandenong Ranges, a significant number of deep seated and shallow landslides were observed. Based on how subdued the landslide features appear to be within the digital terrain information, the landslides are inferred to have varying ages. Significant landslides have been documented over the last 150 years, for example at Woodhurst Grove and Barbers Road Kalorama, with high landslide frequency documented in the 1930’s and 1950’s. Notably, factors contributing to landslide may have been different at that time, for example less vegetation due to logging. However, the prevalence of the landslides observed that are inferred to be older than recorded history and the inferred range in the age of the landslides indicates that landslides have been occurring in these areas for tens of thousands of years and can be expected to continue to occur into the future. Source areas were generally observed to be in areas with slope angles of about 26° (2H:1V), the steepest naturally formed slopes within the Dandenong Ranges. There does not appear to be a significant prevalence of landslides on slopes with a particular aspect (i.e. the compass direction that the slope faces).

The size of the landslides in the Devonian Volcanics of the Dandenong Ranges could be considered as small to moderate, with a single landslide potentially affecting several urban residential blocks. Features indicative of partial reactivation were observed in some landslides, however many of the landslides involve a clear zone of depletion (zone from where material has detached) and clear zone of accumulation (zone in which material has travelled to and accumulated). The travel distance of the landslide debris is variable, with some landslides travelling to the base of the slope, some landslides not travelling a significant distance downslope and others developing into fluid, channelized debris flows which travel a significant distance downslope. It is likely that multiple factors contribute to the travel distance, such as the moisture content of the soils and resulting debris, the volume of material mobilized, the depth of sliding i.e. whether underlying rock is included, and the slope angle. Examples of landslides identified in the digital terrain model are shown in Figure 21.

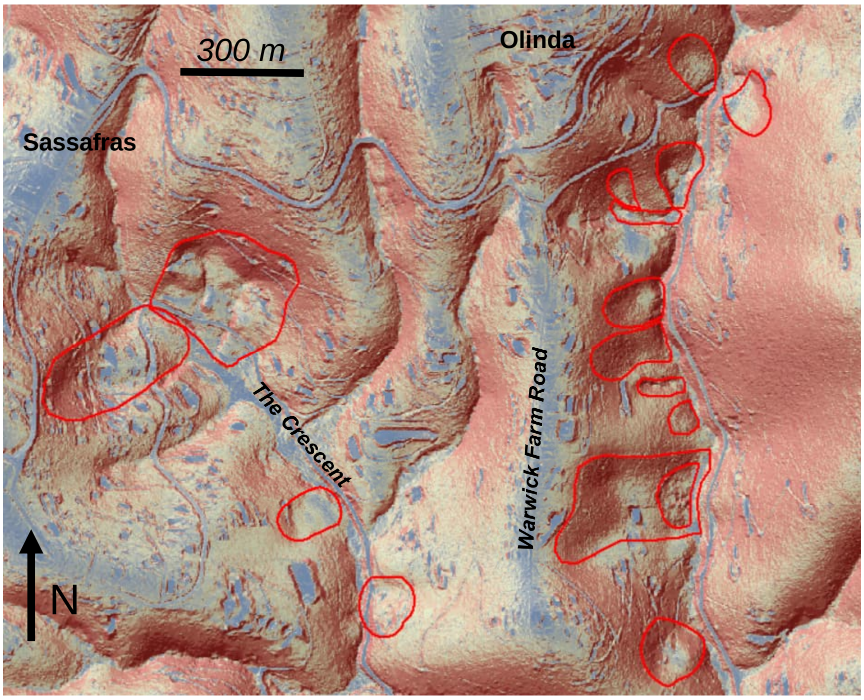

Figure 21: Some landslides identified in the rhyodacite volcanic rocks in the Dandenong Ranges (red polygons), Sassafras.

7.1.3 Devonian Volcanics, Warburton-Healesville area

In the Devonian Volcanics to the north of Warburton and to the east of Healesville, very large landslide complexes were observed, with features inferred to be signs of reactivation. Large scale landslides such as those observed in the digital terrain information have not been observed in recorded history and are inferred to be relatively ancient. However, reactivation of part of a lobe of material from a large scale landslide has occurred which has impacted numerous dwellings at Blackwood Avenue, Warburton. Smaller scale landslides have also been observed in the same landscape. Source areas were generally observed to be in areas with slope angles of greater than 26° or 2H:1V. However, partial reactivation of the original landslide materials could occur on flatter slopes, depending on site specific conditions. There does not appear to be a significant prevalence of landslides on slopes with a particular aspect. The travel distance of the observed landslides is typically relatively long, with evidence that at least some of the debris travelled hundreds of metres from the source slope areas to the north of Warburton to the toe of the slope.

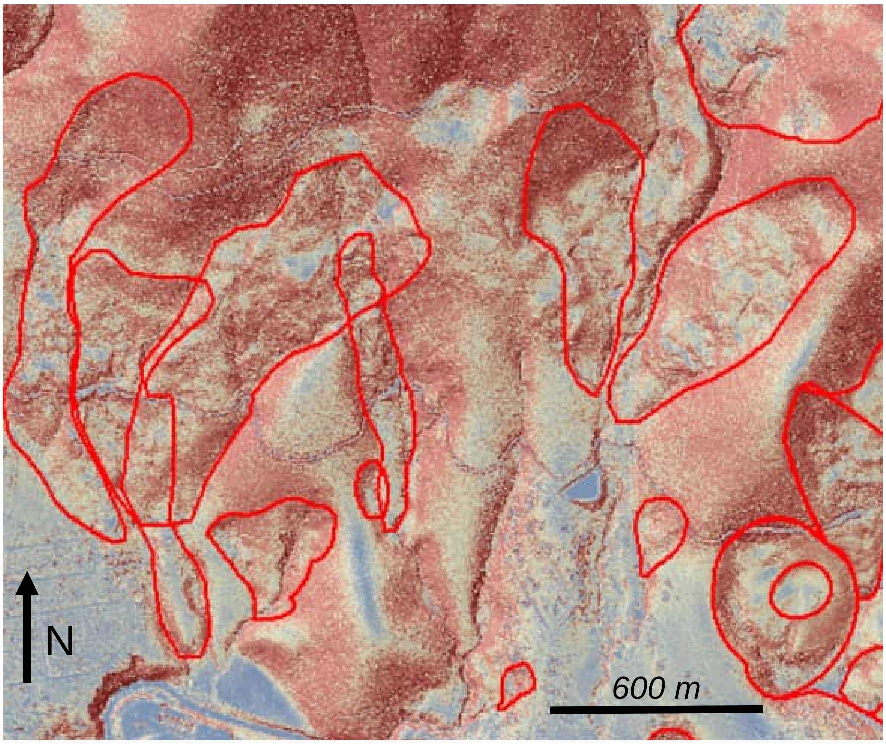

Figure 22: Some large scale landslides identified in the rhyodacite volcanic rocks in the mountain ranges (red polygons), north west of Warburton.

7.1.4 Silurian and Devonian Sedimentary Rocks

Landslides are less prevalent in the Silurian and Devonian sedimentary rocks compared to other units. The landslides identified are typically of small to moderate scale and shallow rather than deep seated, comprising surficial soils. Shallow small scale slumping of soils occurs where groundwater and slope conditions are conducive and where creep slope movement has been identified in the steeper slopes within the LiDAR terrain information, for example south facing slopes on the main ridgelines to the north of Yarra Glen, where higher soil moisture conditions are likely to prevail compared to north facing slopes that are exposed to more sunlight. The creep movement appears to mostly occur on slopes with angles greater than 26° or 2H:1V. An example is shown in Figure 23.

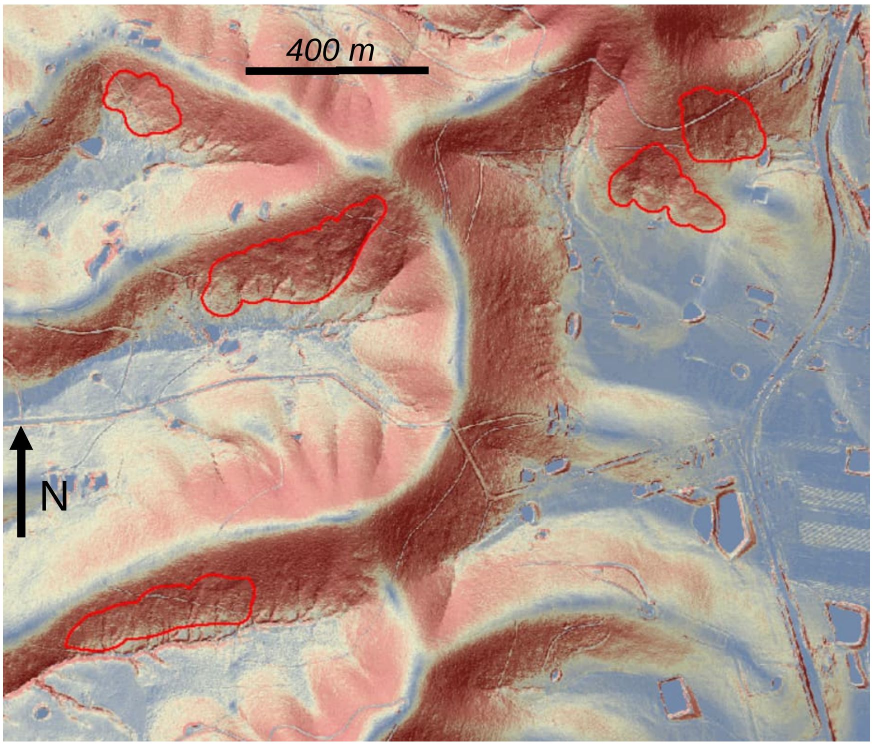

Figure 23: Areas of slope creep movement (red polygons) in areas of siltstone geology identified by LiDAR terrain mapping, Steels Creek and Dixons Creek

Landslides have been identified in areas that are mapped as underlain by Silurian and Devonian Sedimentary rocks, particularly in the Wandin-Seville-Silvan area and Hoddles Creek area. However, fieldwork observations indicate that the landslides may be related to the presence of Oligocene Older Volcanics at the landslide site rather than the sedimentary rocks, in which case the published geological mapping is not correct. Or, that the Oligocene Older Volcanics are located immediately upslope, in which case the landslide may be a consequence of conditions at the contact between the Older Volcanics and the underlying sedimentary rocks. A good example of the geological uncertainty is the Monbulk-Seville Road landslide site described in Section 6.1.1. An example of an area of uncertainty represented in Figure 24 which shows landslides within the capping of Older Volcanics (orange) extending to the nearest water courses. The hatched area on Figure 24 represents the interpreted likely extents of the Older Volcanics, which differs from geological map indications.

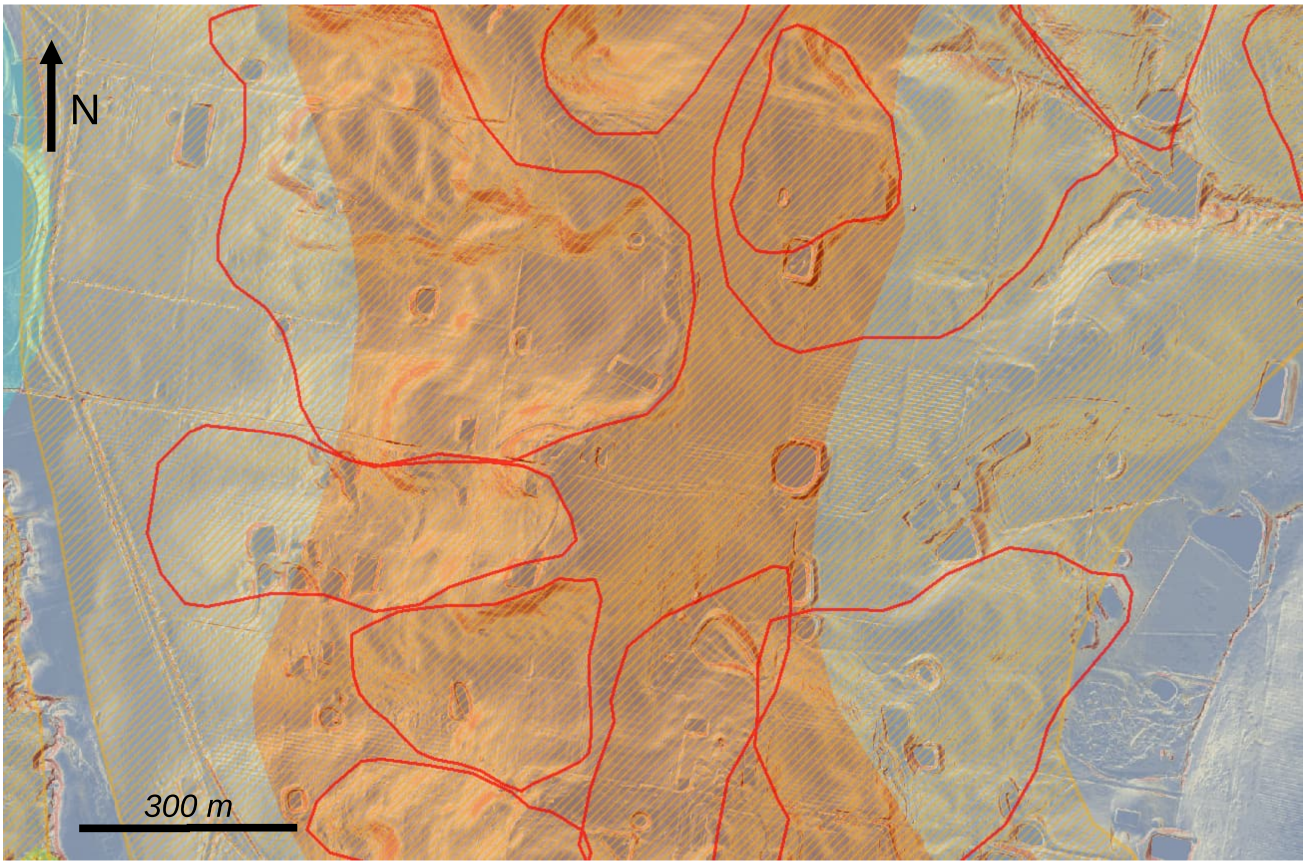

Figure 24: Example of 'halo' area (orange hatched) mapped around the published mapped extents of the Tertiary Older Volcanics (Tov - solid orange) to account for uncertainty in the extents of the Tov and the likely influence on mapped landslides (red outlines).

Areas underlain by sedimentary rocks have a higher susceptibility to post bushfire debris flow compared to areas underlain by Volcanic and granitic rocks (Nyman 2017). Whilst this study does not seek to map areas susceptible to post bushfire debris flow, the potential for post bushfire debris flow to originate in areas underlain by sedimentary rocks is noted here.

7.1.5 Tertiary Older Volcanics

A significant number of landslides has been identified in the deeply weathered soils of the Tertiary Older Volcanics. The landslides have been observed to occur by various mechanisms, with shallow soil landslides, deep seated landslides and soil creep movement observed. The landslides of all mechanisms can be extensive, with large parts of the Wandin-Seville-Silvan area underlain by Tertiary Older Volcanics identified as being underlain by large landslide creep complexes. As demonstrated by the October 2022 Monbulk-Seville Road landslide (Figure 10) which occurred in an area with an average slope angle of approximately 5°, partial reactivation of landslide areas is possible in areas with slope angles of less than 9°. The prevalence of landslides in Tertiary Older Volcanics does not appear to be influenced by slope aspect. An example of a creep landslide complex in the Tertiary Older Volcanics is presented in Figure 25.

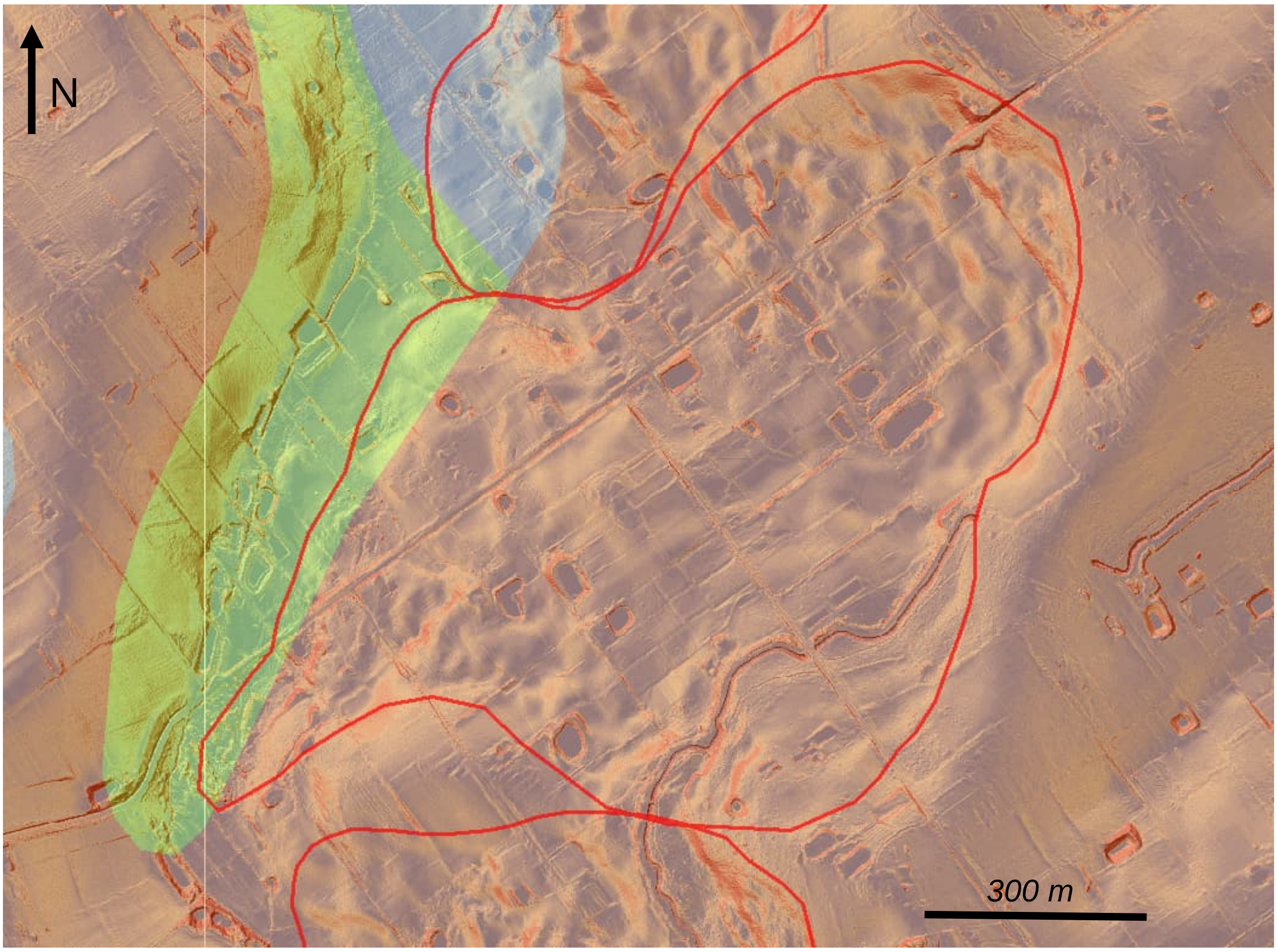

Figure 25: Example of creep landslide complex (red outline) in Tertiary Older Volcanics (orange), Silvan

As described in Section 7.1.4 the boundary between the Oligocene Older Volcanics and underlying Devonian and Silurian sedimentary rocks is not consistent with indication gained from the LiDAR information. Many of the zones between the mapped extent of the Older Volcanics and the nearest water course to the boundary appear to either be underlain by Older Volcanics or the slope stability is influenced by nearby Older Volcanics (for example Older Volcanics colluvium on hillsides below Older Volcanics caps on hilltops). As described in Section 8.0 the mapped extents of Oligocene Older Volcanics were manually adjusted based on LiDAR information and the amended geological maps used to develop the landslide susceptibility maps and recommended EMO.

7.1.6 Quaternary Colluvium

Two types of colluvium are mapped in the LGA, slopewash colluvium which has been transported by erosion processes downslope and is mapped as present in the base of valleys in the upper Yarra Valley, and landslide colluvium. The mapped landslide colluvium in the LGA is at the location of very large landslides that have occurred on the southern slopes of Mount Donna Buang, to the north of Warburton such as Blackwood Avenue (Section 6.1.3).

The susceptibility of mapped Quaternary Colluvium to landsliding is typically dependent on the site conditions, including the parent rock type, thickness of the colluvium layer, slope angle and slope aspect. Landslides can occur in slopewash colluvium and reactivation of landslide colluvium can also occur, such as the Blackwood Avenue landslide. Colluvium is generally considered more susceptible to landsliding than residual soils at similar slope angles, as the relict parent rock structure is not present and the density and associated shear strength of the materials is less.

The landslide colluvium on the slopes north of Warburton shows signs of reactivation events having occurred in the past. Extensive erosion channelling of the landslide colluvium appears to have occurred, which is likely to be a significant factor in causing landslides by unfavourably changing the slope geometry. The currently intermittently active area at Blackwood Avenue appears to have occurred due to erosion undercutting of the toe of a lobe of landslide colluvium.

Where saturated or with high water pressures, slope wash or colluvium can cause low angle landslides (termed turf slides in the Coffey 1999 report), such as that at Owens Road, Hoddles Creek.

7.2 Landslide Triggers

A discussion on landslide triggers based on indications from the inventory is set out subsequently.

Rainfall

A high proportion of documented landslides in Yarra Ranges are initiated by water infiltration which raises pore pressures within the ground and causes an associated loss of soil strength. Pore water pressures generally increase due to rising groundwater levels, or where the near surface soil layers saturate due to the infiltration of surface water from rainfall. Groundwater flow can be complex, with the ground having variable permeability. An example of groundwater driving landslides is in the Oligocene Older Volcanics where it overlies Silurian and Devonian sedimentary rocks. The fine grained sedimentary rocks are less permeable than the typically extremely weathered volcanic materials, with groundwater potentially forming a perched layer in the volcanics, which can drive slope instability in the volcanic materials, particularly where the layer of volcanics is relatively thin, such as near the surface contact of the geological units. At these locations a groundwater spring could erode the materials at the contact, oversteepening the slope. An example of this circumstance is presented in Figure 26.

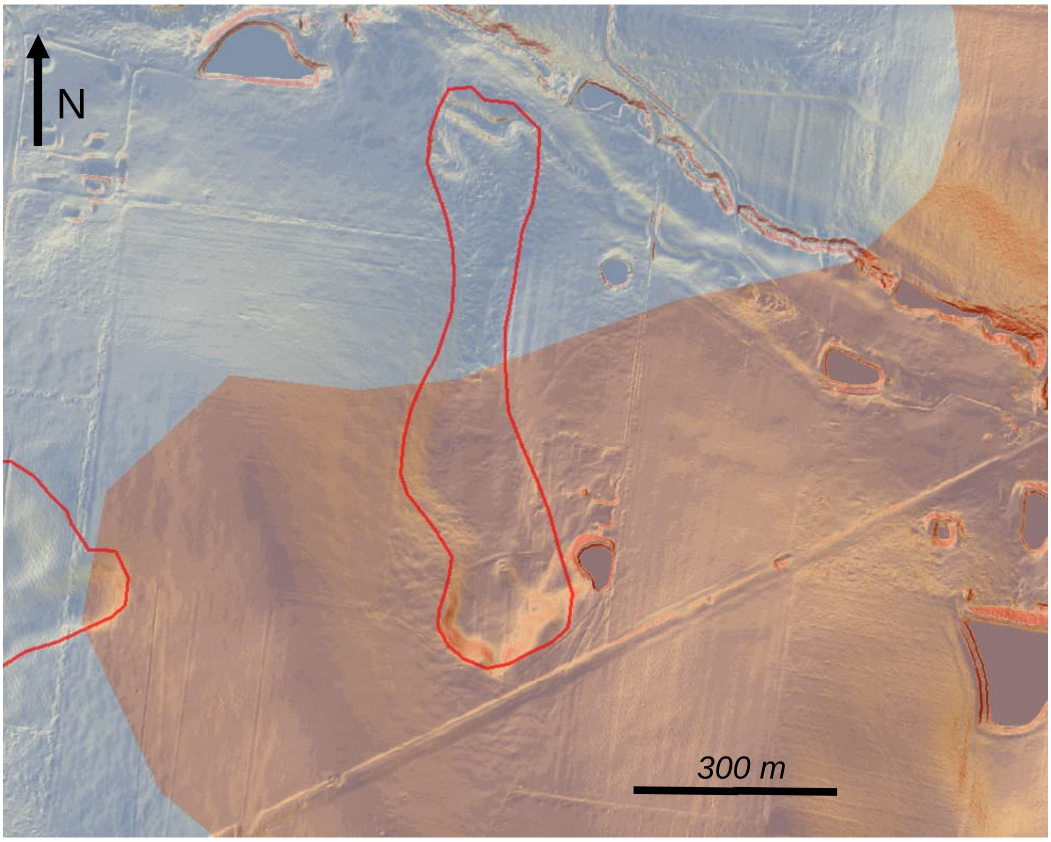

Figure 26: Regressive erosion and landsliding at the contact between Tertiary Older Volcanics and the underlying Silurian and Devonian Sedimentary Rocks, postulated to be driven by a groundwater spring at the contact.

Rises in regional groundwater levels are typically associated with longer term prolonged rainfall periods where the inflow rate of water to the system exceeds the drainage rate over a period of time. Deeper seated landslides such as those within the Tertiary Older Volcanics are more likely to be triggered by higher regional groundwater levels.

Landslides in the Devonian volcanics can occur due to specific high rainfall events such as storms, where there is a sudden high rate of water infiltration which can cause a rapid loss of soil strength. Shallow landslides and debris flows are more likely in this scenario.

Earthquakes

Earthquakes occur occasionally in the Yarra Ranges, however the level of seismicity is considered to be low, with nearly all earthquakes of a magnitude less than 2.0 but occasionally up to 6.0. A magnitude 5.9 earthquake which occurred in the Woods Point area in September 2021, caused some damage to road embankments including cracking and minor instability, however no significant landslides were triggered by this event.

7.3 Comparison between Landslide Inventory and Existing Criteria

The indications of the landslide inventory including the documented landslide processes were compared against the existing criteria for inclusion in the EMO to check whether the existing criteria reasonably highlight areas where landslides have and could occur. The methodology by which this was undertaken and the results of the comparison are set out subsequently.

7.3.1 Landslides

Comparison between the revised landslide inventory and the current susceptibility criteria (Table 1) included assessment of the causal factors for landslide in the LGA based on the expanded landslide inventory. The three current criteria variables; slope angle, underlying geology and the presence of an existing landslide were assessed for influence in landslide susceptibility and other potential variables such as slope aspect. The conclusion was reached that the available evidence does not support altering the existing landslide susceptibility criteria. The evidence for this conclusion is set out below.

The existing landslide susceptibility criteria were developed in 1999, generally on observational evidence and judgement. Landslides which have occurred since development of the existing landslide susceptibility maps in 1999 have generally occurred within areas mapped as susceptible to landslide and are consistent with the existing slope angle and geology criteria developed at that time and currently used to inform landslide susceptibility and the extent of the EMO. The identification of a significant number of previously unrecognized landslides arising from the LiDAR terrain mapping is also consistent with the existing criteria in that the new landslides mapped are generally within susceptible areas. Figure 27 to Figure 32 present slope angle data as histograms for areas both within and outside of mapped landslides across each geological unit.

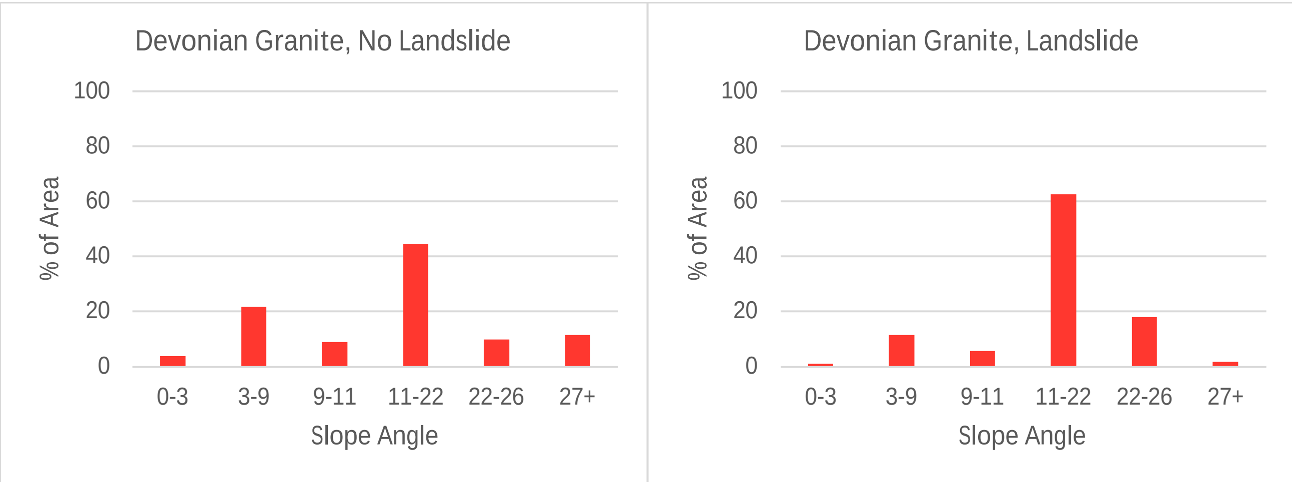

Figure 27: Slope angle distribution in Devonian Granite, outside and within landslides

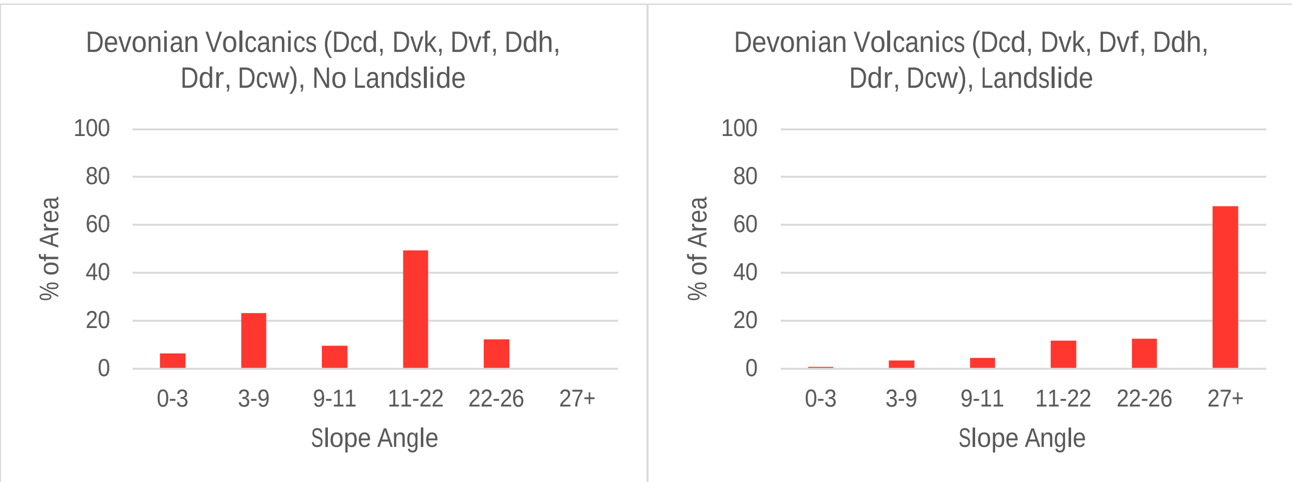

Figure 28: Slope angle distribution in Devonian Volcanics (Dcd, Dvk, Dvf, Ddh, Ddr, Dcw), outside and within landslides

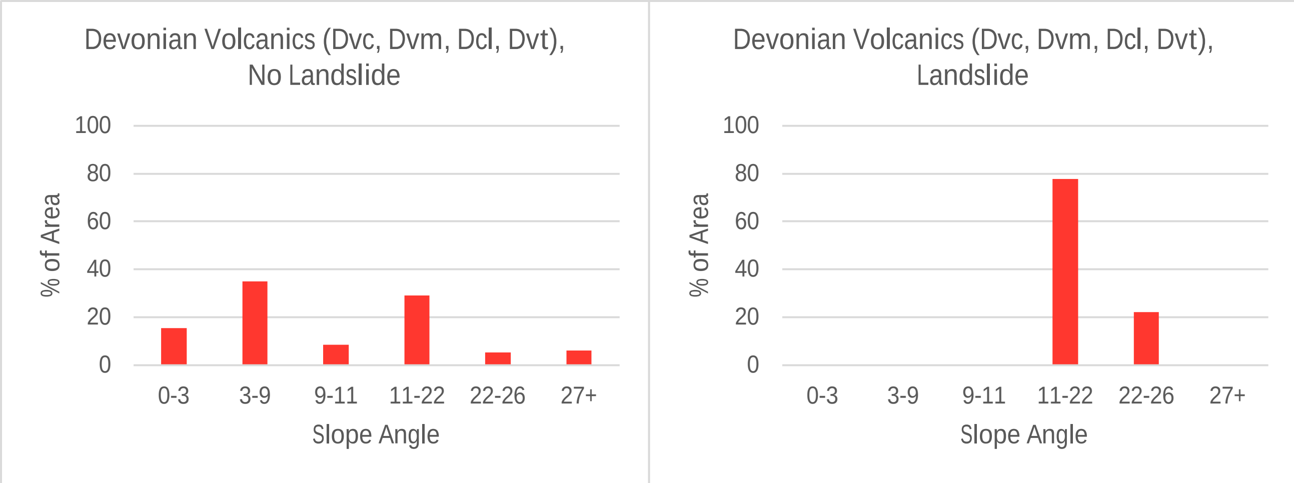

Figure 29: Slope angle distribution in Devonian Volcanics (Dvc, Dvm, Dcl, Dvt), outside and within landslides

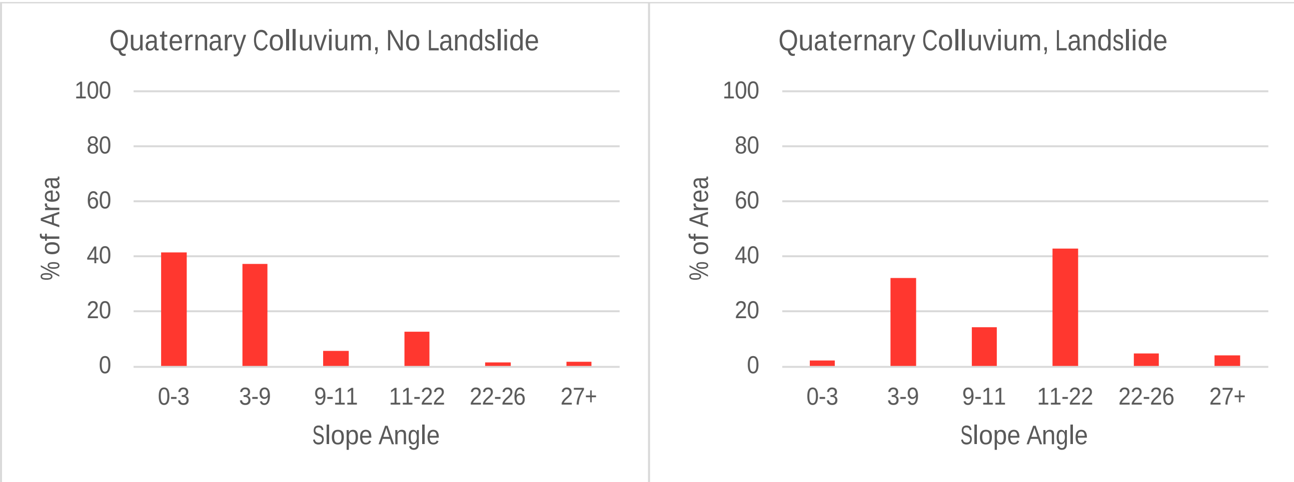

Figure 30: Slope angle distribution in Quaternary Colluvium, outside and within landslides

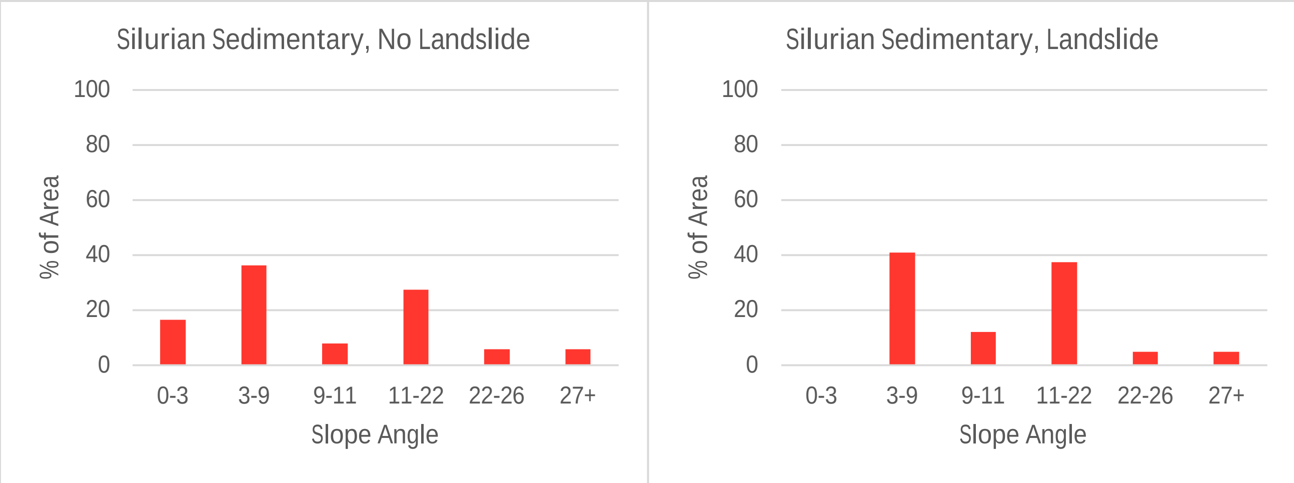

Figure 31: Slope angle distribution in Silurian Sedimentary Rocks, outside and within landslides

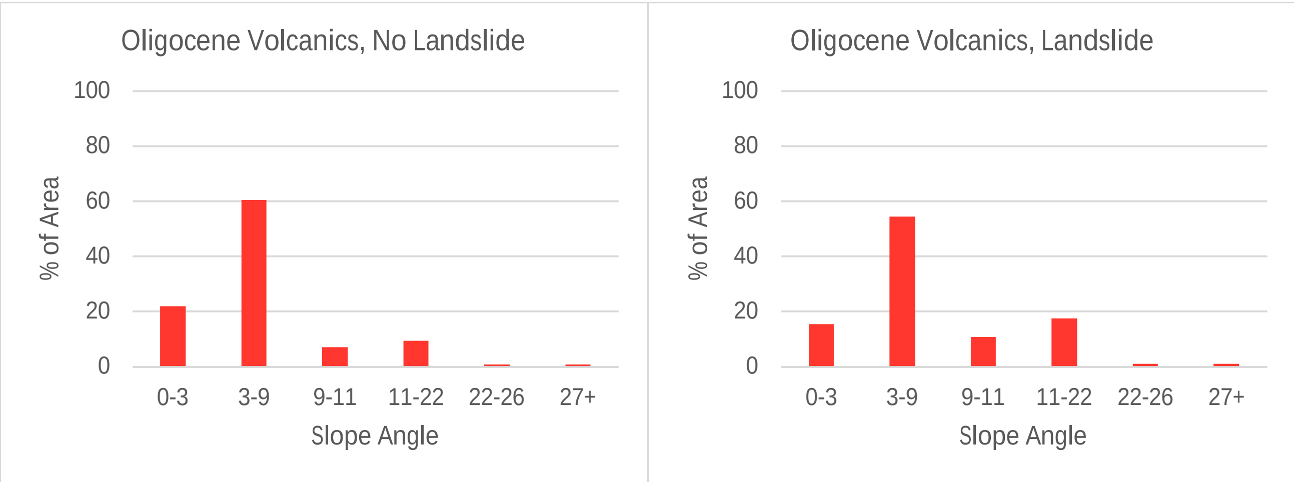

Figure 32: Slope angle distribution in Oligocene Volcanics, outside and within landslides

Figure 27 to Figure 32 indicate that:

- The distribution of slope angles within the Devonian Granites is similar for areas both affected by landslide and not affected by landslide. This observation coupled with the low number of landslides within the geological unit is consistent with it having a low susceptibility to landslide and the information supports the criteria used in the current EMO which does not identify this unit as susceptible to landslide.
- In the Devonian Volcanics, in particular the Dvf which is the geological unit with the greatest number of landslides identified, there is a distinct difference in the slope angle within areas affected by landslide and not affected. In areas unaffected by landslide, there is a high proportion of slope angles below 22° compared to areas affected by landslide in which slope angles are more than 22°. Based on this evidence, the slope angle prior to landslide is greater than 22° which is consistent with the existing landside susceptibility criteria.
- In the Oligocene Volcanics, the similarity between the landslide affected and non-landslide affected areas is confirmed by the slope angle distribution. The high proportion of slope angles below 9° suggests that long term stability is generally achieved at slope angles at or below 9°, consistent with the current criteria.

- There is a low proportion of slope angles above 22° in the Silurian sedimentary rocks, indicating generally stable conditions below that slope angle. There is also a similar distribution between areas affected by landslide and not affected which is consistent with the low susceptibility of the Silurian sedimentary rocks and the existing EMO criteria.
- For Quaternary Colluvium, stable slope angles are less than about 11°, consistent with the existing EMO criteria. A higher proportion of steeper slope angles in the landslide areas is likely due to the undulations associated with the relatively chaotic placement of the landslide colluvium.

Whilst the data does not perfectly align with the existing susceptibility criteria, it is generally consistent and based on this information, there is no clear case or justification for altering the existing criteria.

There is a possible exception to the slope angle criteria currently used with respect to the Monbulk-Seville Road landslide, which has occurred on an average slope angle of approximately 5°. Based on updated geological information from recent investigations and the digital terrain mapping, this is assessed to be a reactivation of a previous landslide, possibly triggered by poor development and by the prolonged rainfall induced by the 2019 – 2022 La Niña events.

Consideration was given to reducing the medium susceptibility threshold in the Older Volcanics from 9° to 5° to reflect the slope angle on which the Monbulk-Seville landslide occurred. Based on the landslide inventory, all documented landslide movement within the Older Volcanics involves the reactivation of existing landslides. Rather than lowering the slope angle threshold everywhere in the Older Volcanics, it was decided to undertake detailed mapping of areas within and adjacent to the Older Volcanics to delineate all areas that appear to have been affected by landslide in the past. Landslide affected areas show good contrast in the LiDAR. All areas identified as having been impacted by landslide in the past are considered to have high susceptibility. However, first time landslides in the Older Volcanics are not known in recorded history and so a higher slope angle threshold was found to lower the slope angle susceptibility threshold where the Older Volcanics are not affected by landslide.

For the other geological units, although more landslides have been identified than were previously known, the relative prevalence of landslides within different geological units remains consistent as do the slope angles at which landslides have been observed to occur. On this basis, we conclude there is no compelling evidence to warrant changing the existing landslide susceptibility criteria.

A further comparison was made by producing landslide susceptibility maps based on the current criteria set out in Table 1 but using the LiDAR derived topography to derive slope angles and the 1:250,000 scale geological maps. This was done by:

- Importing the landslides mapped as part of the updated landslide inventory into a Geographical Information System (GIS).
- Importing the 1:250,000 Seamless Geology of Victoria provided by the Geological Survey of Victoria into the GIS workspace.
- Applying a 10 m raster grid across the area and calculating the maximum slope angle across each 10 m by 10 m raster grid square using the LiDAR elevation information.
- Applying the criteria as set out in Table 1 to assess each square as either Not susceptible, Low, Medium (M0, M1, M2) or High susceptibility. This results in a ‘pixelated’ landslide susceptibility map as indicated in Figure 33.

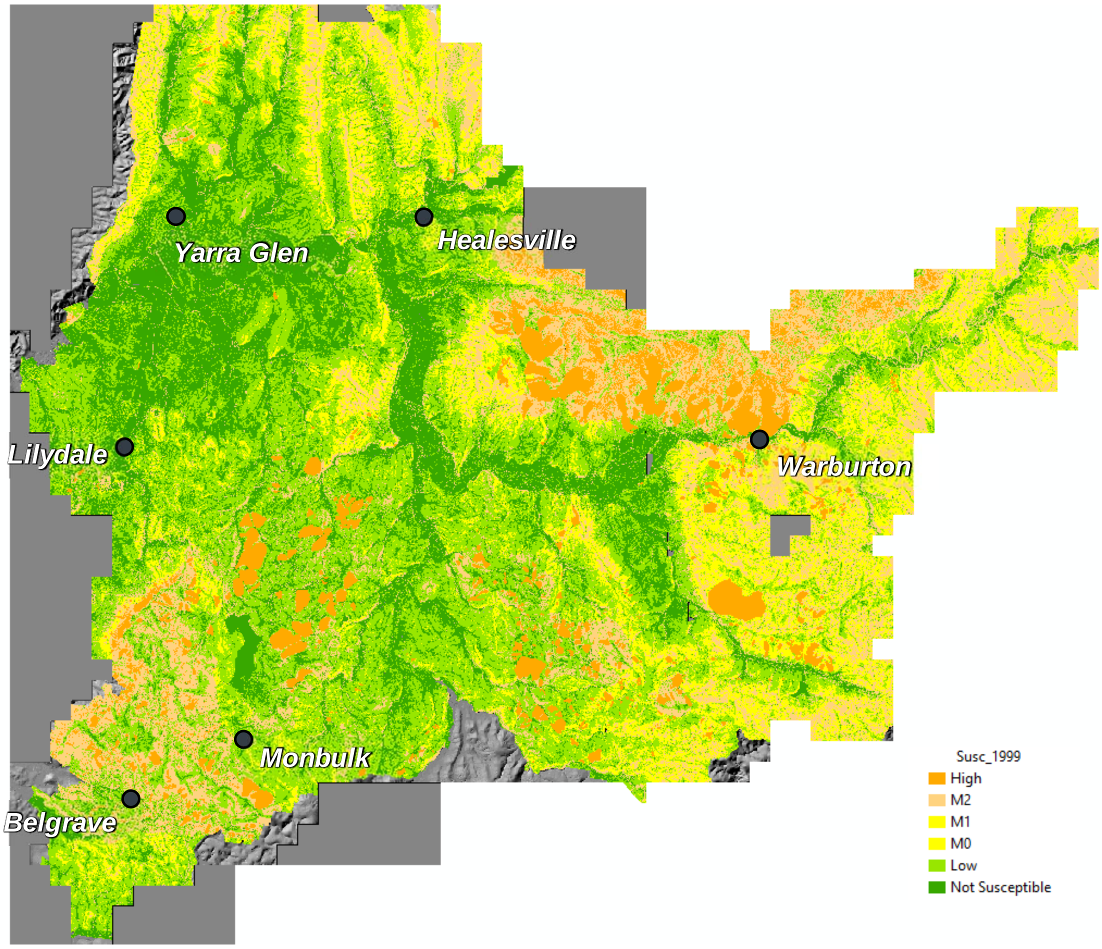

Figure 33: Pixelated susceptibility map derived by applying criteria in Table 1 in a 10 m x 10 m grid

The resultant susceptibility map was then reviewed and checked to assess whether it encompassed a high proportion of mapped landslides, and therefore that the current criteria for landslide susceptibility remains applicable. This was found to generally be the case, with the exception of some areas underlain by Oligocene Older Volcanics where there is an apparent discrepancy between geological map indications and landslide occurrence (see Sections 7.1.4 and 7.1.5).

7.3.2 Debris Flows

High and Medium debris flow risk areas in the Montrose area based on the Coffey 1991 study were incorporated into the Yarra Ranges EMO in 2001. The assessment of debris flow susceptibility beyond the Montrose area was not undertaken. Instances of significant debris flows in the populated areas of the Yarra Ranges have not been observed since the 1891 event. As such the amount of available field information on the frequency and distribution of debris flows has not changed since 1991 and there is no basis with which to revise the 1991 findings.

The suitability of the methods by which Coffey (1991) identified areas susceptible to debris flow were assessed for applicability in areas away from the Montrose area. Published literature and previous experience of debris flows was used to assess potential susceptibility of debris flows away from the Montrose area, including the University of Melbourne post bushfire debris flow study (refer Section 5.3). The methods by which debris flow run out extents were assessed in the University of Melbourne studies for post bushfire debris flow were applied to estimate the run out extents of landslide induced debris flow, noting that this is probably a conservative approach because post bushfire debris flows are typically more fluid and flow further than landslide induced debris flow.

The comparison in Figure 34 shows consistency between the distal extents of the 1891 debris flow, which is known from historical records and the estimation from post bushfire debris flow based on the run out distances estimated in the University of Melbourne post bushfire debris flow study. On this basis, the University of Melbourne debris flow runout estimations appear to provide a reasonable representation of debris flow runout in the Yarra Ranges.

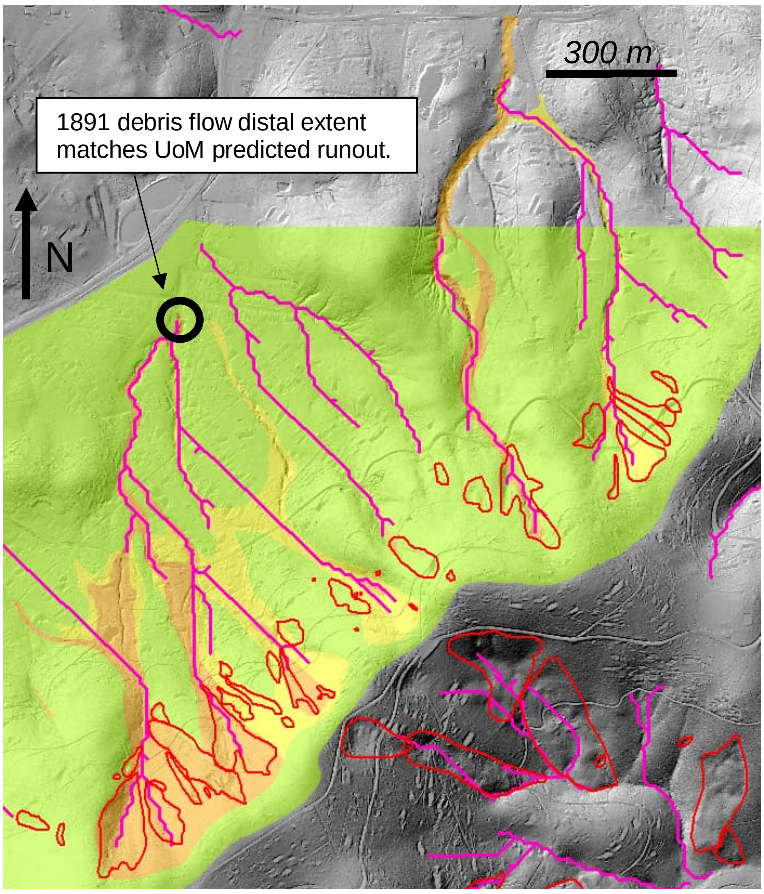

Figure 34: Comparison between University of Melbourne estimated post-bushfire debris flow run out distances (magenta lines) and current EMO debris flow risk areas at Montrose. Orange = high risk, yellow = medium risk, green = low risk. 1891 debris flow distal extent circled.

8.0 SUSCEPTIBILITY MAPPING REVISION

This section sets out the methodology to develop revised susceptibility maps and EMO mapping using the existing criteria as set out in Table 1, but incorporating the LiDAR digital elevation model, updated landslide inventory, University of Melbourne debris flow runout estimations and modified geological maps.

The maps described are provided as digital GIS compatible deliverables. See the register of digital deliverables set out in Appendix A.

8.1 Inputs to Susceptibility Maps

Whilst the existing criteria for inclusion within the EMO are unchanged, the terrain attributes to which they are applied have been updated from those to which they were applied when the current EMO was developed in the late 1990's. In summary, this includes:

- 2015 to 2017 LiDAR derived digital elevation model used to more accurately measure slope angles.
- 1:250,000 scale seamless digital geology produced by the geological survey of Victoria, with manual adjustments made to the boundaries between Oligocene Older Volcanics and Devonian/Silurian sedimentary rock. The adjustment to geological boundaries involved extending the mapped extent of Older Volcanics from hilltop caps down to the nearest water course if LiDAR indications showed terrain consistent with Older Volcanics underlying geology.
- Landslide polygons in the landslide inventory being areas previously affected by landslide.
- Previous debris flow mapping (Coffey 1991).
- New post bushfire debris flow run out mapping produced by University of Melbourne and applied where small landslides were identified at the head of gullies and there is terrain evidence of past debris flows.

8.2 Susceptibility Map Criteria

For completeness, the criteria used to develop the recommended landslide susceptibility maps as set out in Table 1 are shown in Table 3. Note that the now redundant M0 and M1 categories which were not included in the existing EMO have been designated Low susceptibility.

Table 3: Proposed criteria to assess landslide susceptibility and include area within the EMO.

Geology	Slope Angle (Shaded boxes are the susceptibility criteria which define the proposed extent of the EMO).					
	0° to 3° (0% to 5%)	>3° to 9° (>5% to 15%)	>9° to 11° (>15% to 20%)	>11° to 22° (>20% to 40%)	>22° to 26° (>40% to 50%)	>26° (>50%)
Landslide						
Silurian and Devonian Sedimentary Rock	Not susceptible	Low	Low	Low	Medium	Medium
Devonian Granite/Granodiorite	Not susceptible	Low	Low	Low	Medium	Medium
Devonian Volcanic Rock (Dvc, Dvm, Dcl, Dvt)	Not susceptible	Low	Low	Low	Medium	Medium
Devonian Volcanic Rock (Dcd, Dvk, Dvf, Ddh, Ddr, Dcw)	Not susceptible	Low	Low	Medium	Medium	High
Oligocene Older Volcanics	Not susceptible	Low	Medium	Medium	Medium	Medium
Quaternary Colluvium/Alluvium	Not susceptible	Low	Low	Medium	Medium	Medium
Past Landslide (any geology)	High	High	High	High	High	High
Debris Flow						
High or Medium Debris Flow Risk (Coffey 1991)	Included in EMO, High or Medium align with High and Medium risk assessed by Coffey in 1991.					
University of Melbourne 2017 debris flow study debris flow run out.	Medium					

8.3 Development of Landslide Susceptibility Maps

For landslides, the spatial extents of the criteria for landslide susceptibility were combined in a GIS environment, including slope angle, mapped landslides and underlying geology. The slope angle dataset, which was generated from a LiDAR derived elevation grid with a 1 m point spacing, was converted to a 10 m point spacing with an average slope angle. Susceptibility maps using the 10 m point spacing dataset were checked against maps produced using the 1 m dataset and significant degradation in quality was not observed for the purposes of developing susceptibility maps.

Spatial areas were then assigned susceptibility levels based on the existing criteria as set out in Table 1. The result is a map with 10 m wide 'pixels' of different landslide susceptibility depending on the underlying geology and criteria in Table 4. By applying these criteria the overview map of landslide susceptibility presented in Figure 35 has been developed.

The area identified as susceptible to landslide has increased over that indicated in the current EMO, even though the susceptibility has been assessed using the same criteria that was originally used in 1999. This has occurred mainly because of the greater number of landslides identified than was previously known, but also because the digital terrain information facilitates more accurate measurement of slope angles.

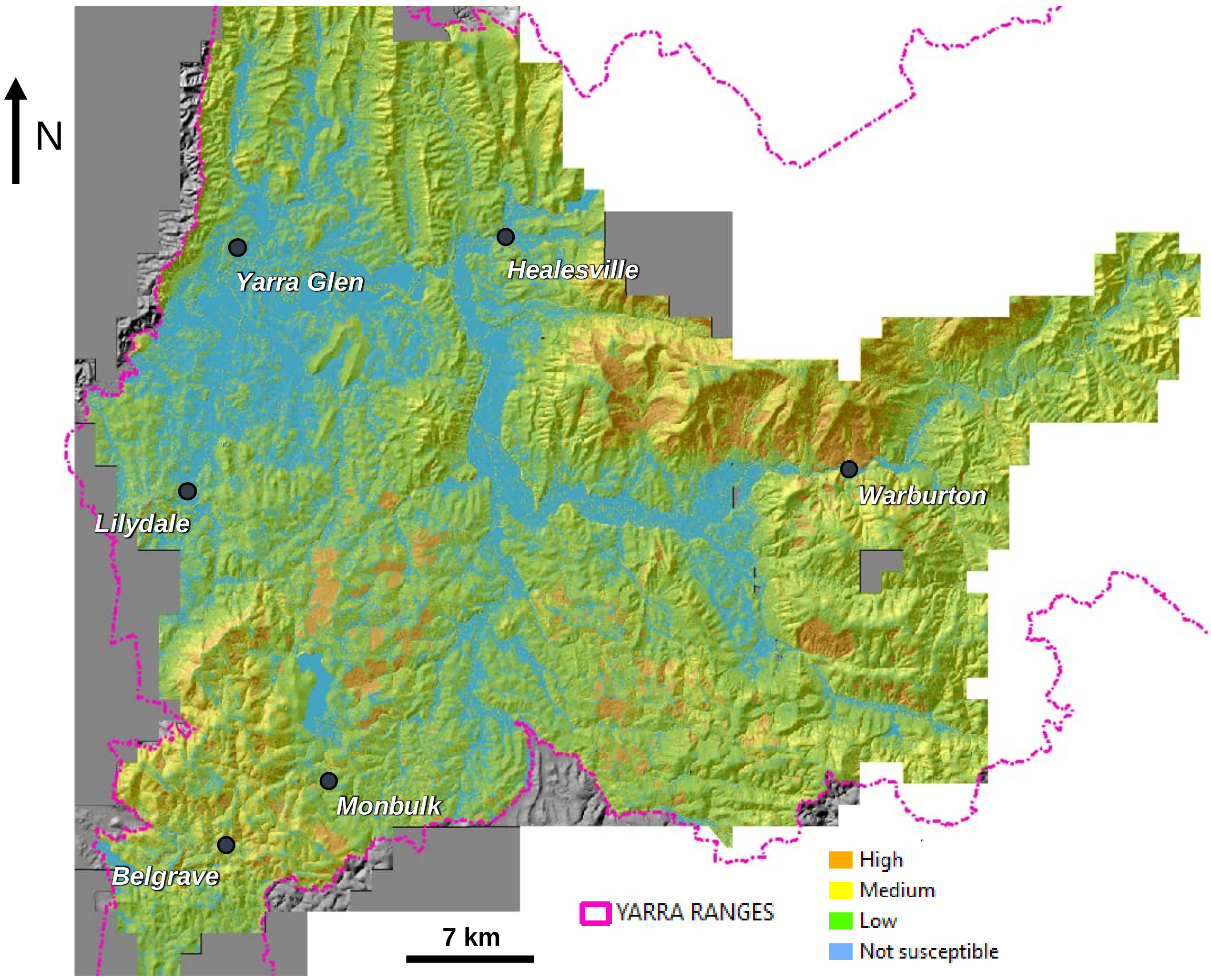

Figure 35: Overview of Yarra Ranges susceptibility mapping. Place locations are approximate.

Digital assessment of landslide susceptibility using the raster and GIS based approach described here results in susceptibility being applied to some outlying 10 m by 10 m pixels that may not be within landslide susceptible areas. Typically, this occurs where non-natural slope angles are detected, for example road cuttings, quarries and other earthworks. These can occur as isolated or non-joined separate cells within the landscape which are non-continuous and do not justify inclusion as a landslide susceptible area within an EMO planning control. An example of the pixelated areas of medium and high susceptibility at Launching Place is provided in Figure 36.

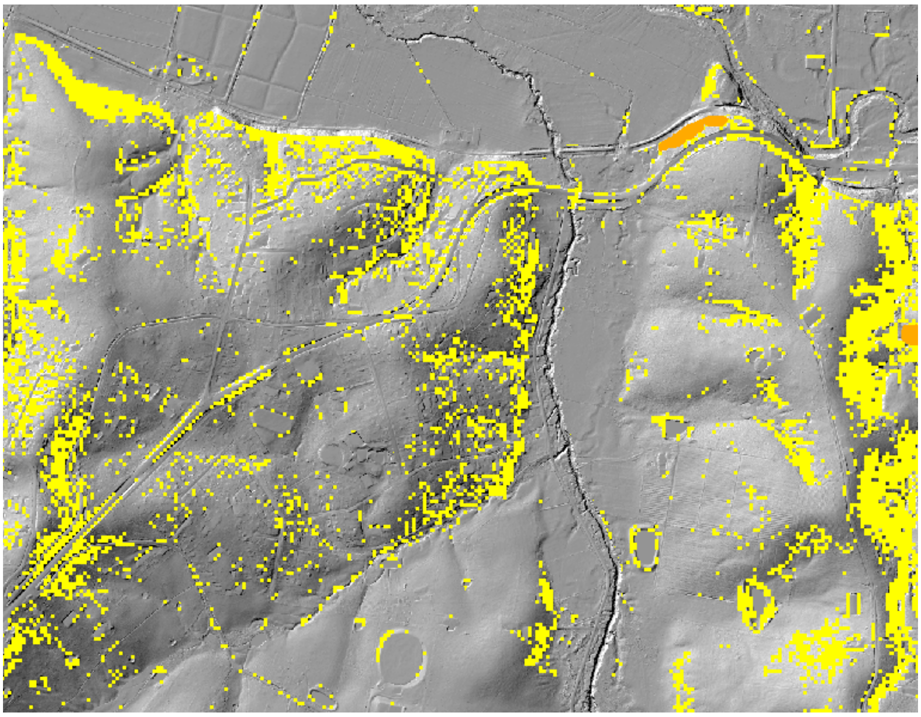

Figure 36: Example of pixelated areas of medium (yellow) and high (orange) landslide susceptibility generated by GIS using the susceptibility criteria, Launching Place.

In order to adapt the susceptibility mapping to a planning overlay, the pixelated susceptibility map has been converted to a series of smoothed polygons, by using a GIS based algorithm which has been checked and amended using manual drawing where required. An example of the detailed, pixelated nature of the generated susceptibility maps at Kalorama is provided in Figure 37. The manual drawing process has removed the individual and smaller clusters of pixels that would be inconsequential to the assessment and administration of landslide risk.

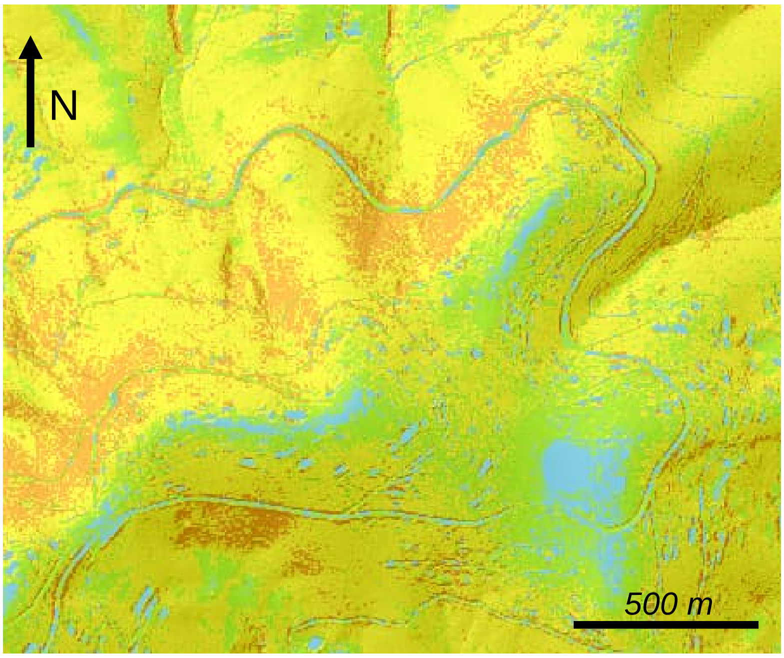

Figure 37: Example of landslide susceptibility maps generated by combining slope angle and geology on a 10 m grid, Kalorama. Existing landslides (high susceptibility) have not been added to this version of the map. High susceptibility = orange, low susceptibility = blue.

Further adjustments to refine the pixelated output of the GIS algorithm were undertaken as follows:

- Polygons were established around concentrations of grid squares classified as Medium or High. An example is provided in Figure 38. A customised script was used in the GIS software to assist in generating the consistent, smoothed polygons from the pixelated susceptibility areas.

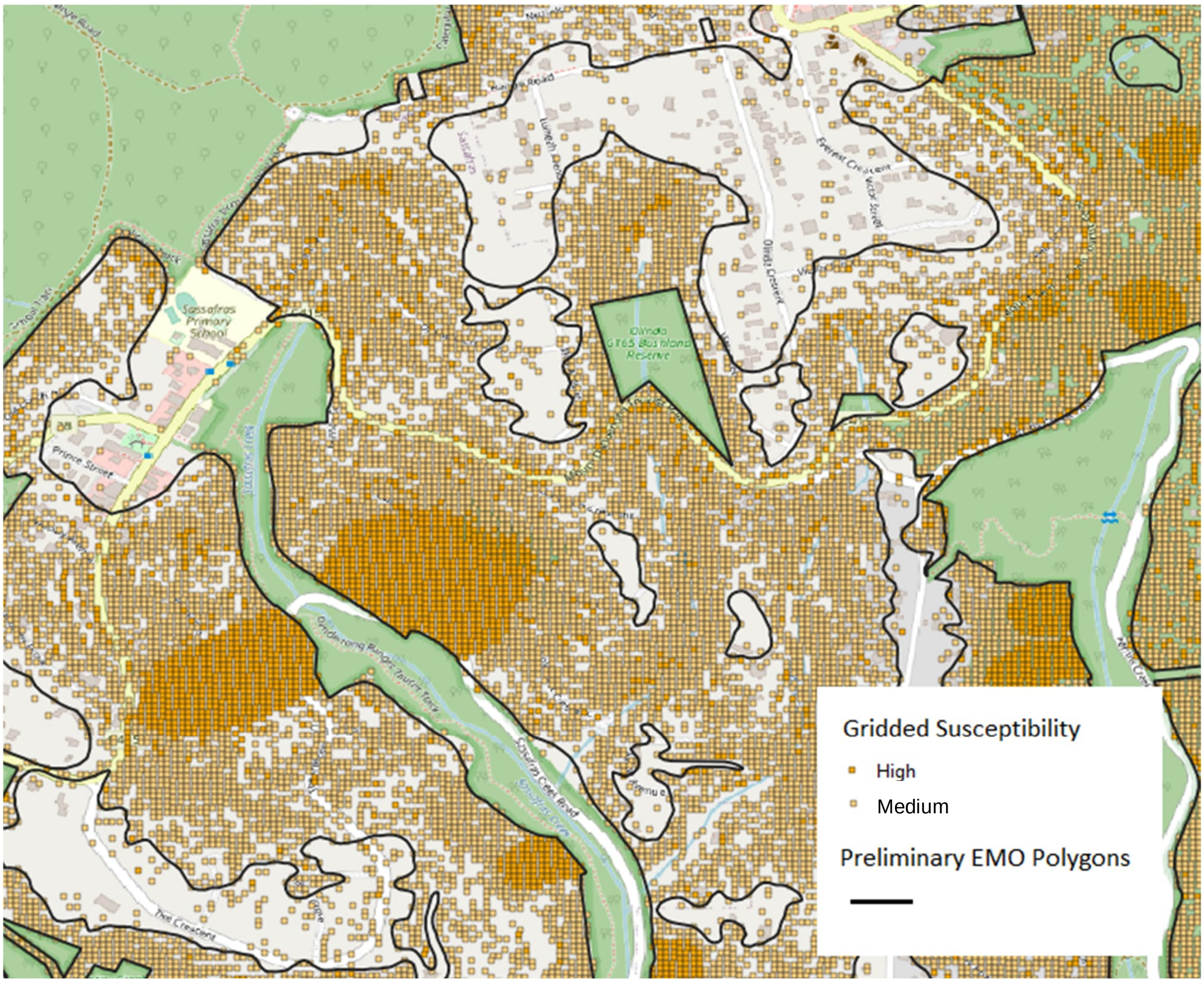

Figure 38: Example of smoothed polygons (black boundaries) generated around pixelated areas of Medium and High susceptibility

- Isolated polygons with a proportion of M2 and High pixels of less than 50% were then removed, to allow for an average slope angle within the polygon that is less than the EMO susceptibility threshold for slope angle.
- Very small polygons, smaller than the smallest observed landslide in each geology (the area smaller than than 95% of observed landslides in each geological unit) were removed. This resulted in the removal of some polygons with areas between 1084 m^2 and 6125 m^2 depending on the geological unit.
- The generated polygons were then manually checked and adjusted. This resulted in the removal of polygons that had arisen because of anthropogenic reasons, for example dam embankments, road cuttings and quarries, or other terrain features that would not be part of EMO planning controls. Polygons were also adjusted where the geological conditions inferred from the terrain features clearly differ from the publicly available large scale geological maps used in the assessment e.g. where mapped areas of

alluvium encroach on adjacent steep hillsides and where the boundary between the Oligocene Older Volcanics and Devonian Sedimentary rocks is not consistent with geological map indications.

- Land exempt to the EMO planning controls including national parks and catchment areas was then removed.

Table 4 provides a comparison between the existing and proposed extent of the EMO based on the area and properties affected.

Table 4: Summary of impact of proposed EMO mapping changes - Landslide

Source	Current EMO	Proposed EMO
Total approximate area affected (km^2)	112	136
Total approximate number of properties affected	11447	13434
Total number of properties for which removal from EMO recommended	N/A	1185 removed
Total number of properties for which addition of EMO recommended	N/A	3172 added
Net change in number of properties affected	N/A	1987 added

8.4 Development of Debris Flow Susceptibility Maps

Debris flow initiation areas were mapped in areas to the south of Warburton and to the east and south of The Basin, as well as further initiation areas which were identified on the western slopes of Mount Dandenong above Montrose. The initiation areas were mapped in a similar manner to landslides, using the digital terrain information. It should be noted that the debris flow initiation areas have been included in the landslide susceptibility areas, as the hazard to people and property in the initiation areas would be similar to a landslide i.e. generally related to ground subsidence from below. The run out paths, where people or property could be impacted by material travelling down from upslope, has been included in the debris flow susceptibility map.

Given the reasonable comparison between the debris flow run out estimate based on the Melbourne University modelling and the 1891 debris flow, run out paths of debris flows from the initiation areas identified are assumed to follow the adjacent gully channels down slope and to have run out lengths as per the indications of the University of Melbourne study. This is probably a conservative approach because post bushfire debris flows are typically more fluid and flow further than landslide induced debris flow.

The areas of medium and high susceptibility to debris flow developed by Coffey (1991) (termed risk in that report) for the Montrose area have been adopted and carried forward. Where additional initiation areas have been identified and mapped (beyond those identified by Coffey in 1991), the associated run out areas have generally been assigned a susceptibility level of ‘medium’, considering that the mapping generally identified less prominent (i.e. smaller or more subdued, and therefore likely older) initiation areas without historical evidence of occurrence and uncertainty with respect to the frequency of debris flow events.

A nominal 20 m either side of newly identified channels (40 m total width) susceptible to debris flow has been nominated as potentially susceptible. Table 5 summarises the impact to the proposed EMO of the updates to debris flow mapping.

Table 5: Summary of impact of proposed EMO mapping changes for Debris Flow

Source	Current EMO*	Proposed EMO*
Total approximate area affected (km^2)	0.5	1.1
Total number of properties affected (no.)	293	498

*Does not include debris flow source areas, which are treated as landslide areas, and does not include areas exempt from EMO.

It should be noted that no properties will be removed from the debris flow areas associated with the EMO.

8.5 Recommended Erosion Management Overlay Extents

The susceptibility mapping previously described is based on a LiDAR derived digital elevation model which represents a significant improvement on the current mapping. The LiDAR has allowed improved identification of ground affected by landslide and better application of criteria to identify areas susceptible to landslide.

Based on the study undertaken here, the criteria currently used to define the extent of the EMO are considered to largely remain valid. However, with the benefit of LiDAR information, these criteria can be reapplied. Areas assessed as having a medium or high susceptibility to landslide or debris flow as described in Table 4 are recommended for inclusion within the revised EMO mapping. Owing to the significant increase in landslides identified and included in the landslide inventory, this approach is expected to result in an increase in the area affected by the EMO.

Separate susceptibility maps have been provided for landslide and debris flow which could either be combined into a single overlay or incorporated into the planning scheme as separate overlays. Whilst areas identified as susceptible to debris flow and landslide can be combined into a single EMO and managed under a single schedule, there may be benefit in maintaining separate susceptibility maps for each hazard with a view to maintaining the option of introducing separate planning controls for each hazard type at some stage in the future.

We note that from a planning and management perspective, debris flow hazards somewhat differ from landslide hazards in a number of key aspects:

- Debris flows can travel large distances from their source – up to several kilometres. A property may be on flat ground with no indication within the proximity of the property that it might be susceptible to impact from debris flow. Where a property is susceptible to debris flow, assessment of the risk the debris flow might present to the property may need to take in areas remote from the site. In our experience this assessment may not be undertaken because the geotechnical practitioner who undertakes the assessment is informed only that the EMO applies, and not why the EMO applies in a particular area, which may assist to attain appropriate outcomes from the assessment including appropriate risk mitigation measures. Separate schedules could reduce the occurrence of these oversights.
- Debris flows which involve the rapid flow of material downslope typically present a significant risk to life. Landslides within Yarra Ranges more often involve slower movement which presents a risk to property, but less of a risk to life. There may be a basis to apply separate planning controls and management to debris flow compared to landslides due to the higher consequences and risk to life that usually arise from debris flow.

The recommended revised EMO mapped extents are provided in GIS electronic format. An overall appreciation of comparison between the existing and proposed EMO extents is presented in Figure 39.This example superimposes the existing EMO over the recommended revised EMO for comparative purposes. The new EMO areas shown include the areas with high and medium susceptibility to debris flow, as well as debris flow source areas, which are included as part of the landslide EMO. The EMO only covers council managed areas for the purposes of land development planning.

Figure 40 and Figure 41 show the existing and updated mapped areas that have medium and high susceptibility to debris flow for the Montrose and Warburton areas respectively. As noted above, debris flow source areas are included in the landslide EMO rather than the debris flow EMO, and the EMO only covers council managed areas.

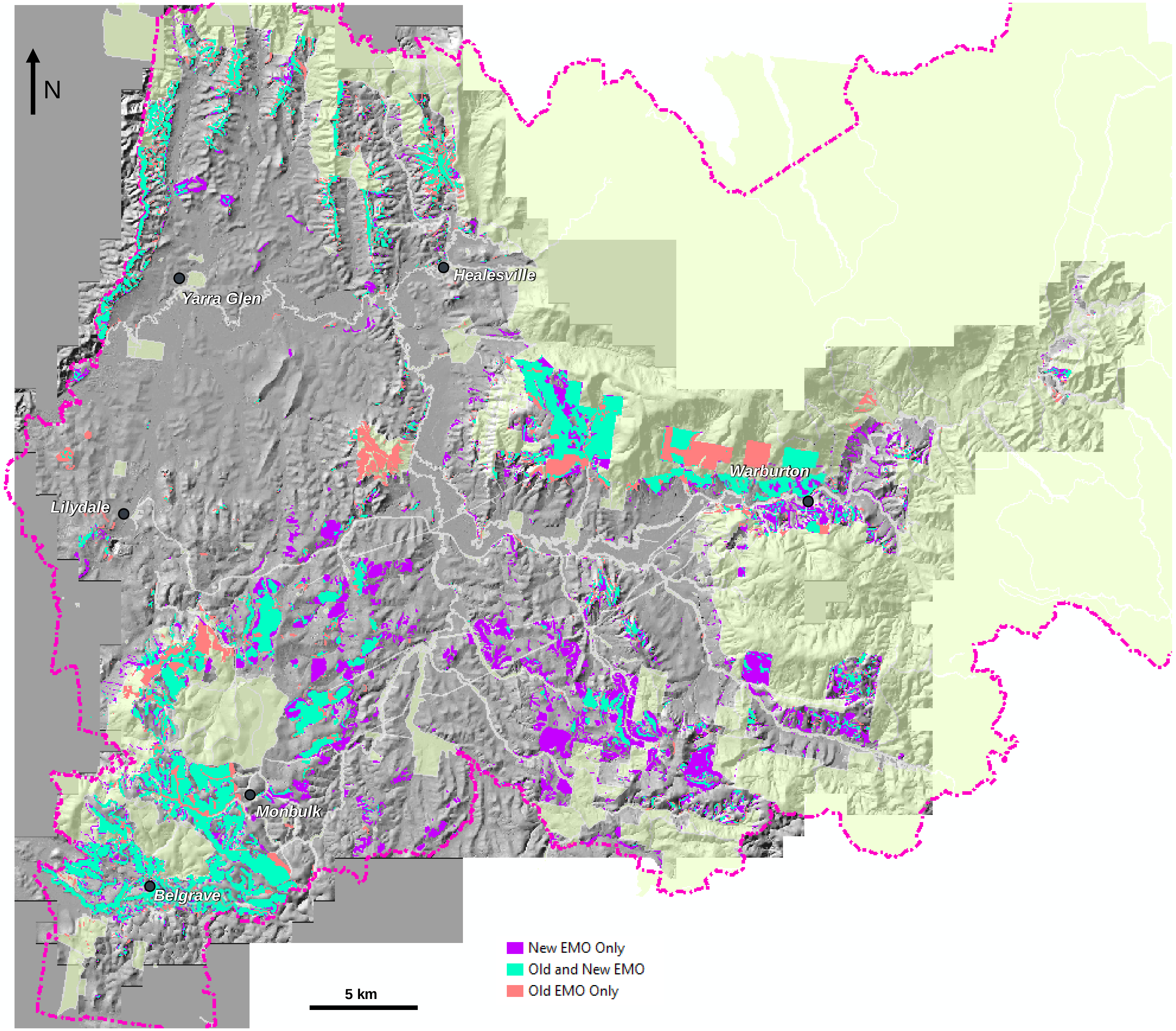

Figure 39: Comparison between existing and proposed EMO at LGA wide scale – includes both landslide and debris flow. Purple areas are proposed EMO only, Teal areas are both old and new EMO, Red areas are existing EMO only. Yellow areas are managed by entities other than YRSC.

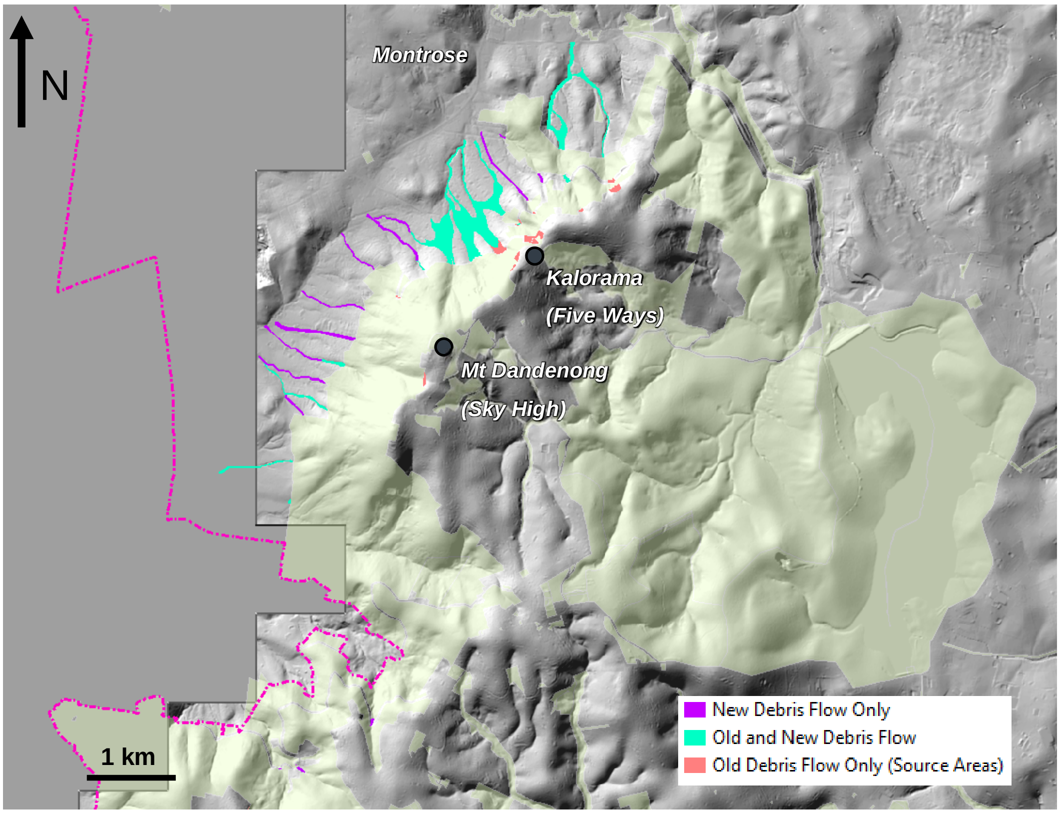

Figure 40: Previous and updated areas of medium and high debris flow susceptibility contributing to the EMO in the Montrose area. Red areas shown are mapped debris flow source areas, which are included in the landslide EMO. Yellow areas are managed by entities other than YRSC.

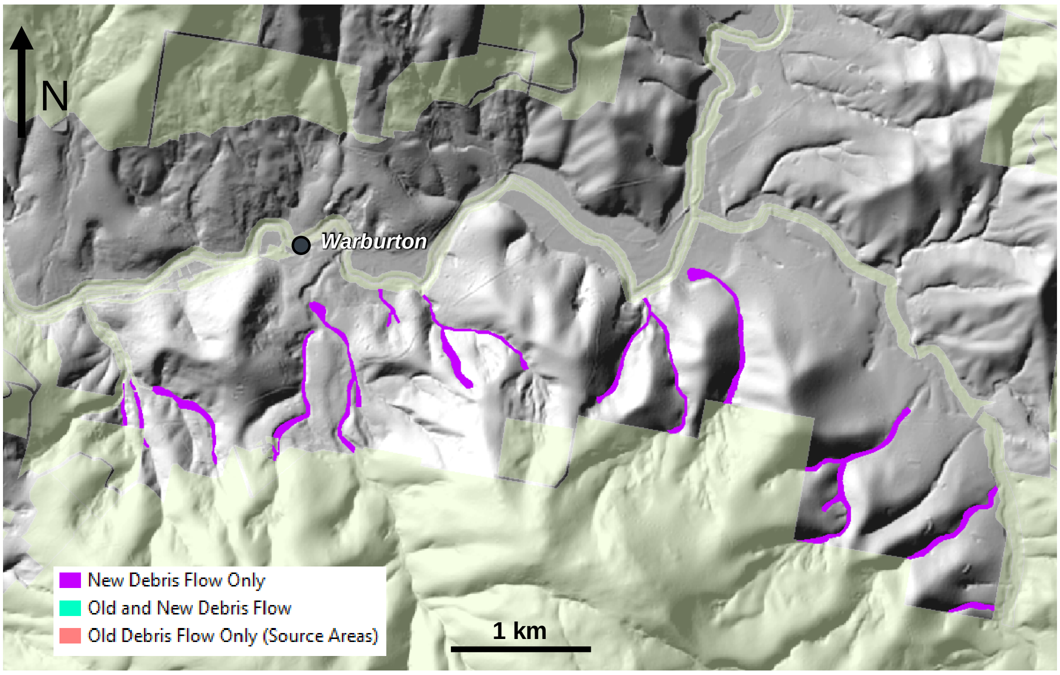

Figure 41: Previous and updated areas of medium and high debris flow susceptibility contributing to the EMO in the Warburton area. Red areas shown are mapped debris flow source areas, which are included in the landslide EMO. Yellow areas are managed by entities other than YRSC.

9.0 REFERENCES

Cited references

Australian Geomechanics Society (AGS 2007), Landslide Risk Management, Journal and News of the Australian Geomechanics Society, Vol 42, March 2007.

Coffey and Partners (1988), *Upper Yarra Valley and Dandenong Ranges Authority, Landslip and Subsidence Risk Study*, Unpublished report to the Upper Yarra Valley and Dandenong Ranges Authority.

Coffey Partners International Pty. Ltd. (1991), *Study of Risk of Debris Flows and Other Landslips, Montrose, Victoria, Vol 1 – 3.* Unpublished report to Shire of Lillydale.

Coffey Partners International Pty. Ltd. (1992), *Study of Risk of Debris Flows and Other Landslips, Montrose, Victoria, Vol 4, Supplementary Information*. Unpublished report to Shire of Lillydale.

Coffey Partners International Pty. Ltd. (1999), *Landslip Zoning of the Shire of Yarra Ranges*, Unpublished report to Shire of Yarra Ranges.

Fell, R. (1992) *Some landslide risk zoning schemes in use in Eastern Australia and their application*, Proceedings of the 6th Australia – New Zealand Conference on Geomechanics, Christchurch, 1992.

Heine, W. (1992) *Risk of Debris Flow and Other Landslips in the Montrose Area, A report to Councillors of the Shire of Lillydale, by Warwick Heine, Chief Executive Officer, October 1992.*

Nyman. P. Post-fire debris flows in southeast Australia: initiation, magnitude and landscape controls, PhD thesis, University of Melbourne, 2013.

Nyman, P, Rutherford, I.D., Lane, P.N.J., Sheridan, J., Debris flows in southeast Australia linked to drought, wildfire and the El Nino-southern oscillation, Journal of the Geological Society of America, Volume 47, No. 5, 2019.

Soil Conservation Authority (1981), *Land Constraints to Urban Development in the Upper Yarra Valley and Dandenong Ranges Region*, Unpublished report to the Upper Yarra Valley and Dandenong Ranges Authority.

Soil Conservation Authority (1981), *Land Constraints to Urban Development in the Upper Yarra Valley and Dandenong Ranges Region, Landscape Living Policy Area*, Unpublished report to the Upper Yarra Valley and Dandenong Ranges Authority.

Other non-cited references

Anutech Pty. Ltd. (1988) *An Archaeological Survey of the Upper Yarra Valley and Dandenong Ranges*, Unpublished report to the Victoria Archaeological Survey.

Moon, A.T., Olds, R.J., Wilson, R.A., Burman, B.C. (1992), *Debris Flow Risk Zoning at Montrose, Victoria,* Proceedings of the Sixth International Symposium on Landslides, Christchurch, Volume 2, pp 1015 to 1022, Balkema, 1992.

Ritchie, L., Hunt, G., (2001) *Landslips – a moving story (a Municipality's Perspective)*, Australian Journal of Emergency Management, pp. 28-32, Summer 2001.

Unisearch Limited (1991), *Review of Coffey Partners Report "Study of the Risk of Debris Flows and Other Landslips, Montrose, Victoria*, Unpublished report to Shire of Lillydale.

Wilson, R. A. (2002), *The Shire of Lillydale – Yarra Ranges Landslide Zoning Scheme*, Australian Geomechanics, Vol 37, No. 5, December 2002.

10.0 IMPORTANT INFORMATION

Your attention is drawn to the document titled “Important Information Relating to this Report” which is included in Appendix B of this report. The statements presented in that document are intended to advise you of what your realistic expectations of this report should be. This document is not intended to reduce the level of responsibility accepted by WSP Golder, but rather to ensure all parties who rely on this report are aware of the responsibilities each assumes in so doing. We would be pleased to answer any questions the reader may have regarding this document.

Signature Page

Golder Associates Pty Ltd

Darren Paul
Technical Director - Engineering Geology

ABN 64 006 107 857

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APPENDIX A

Inventory of digital GIS information accompanying this report

Layer	Description
Factual Information	
Geology	***Geological Units 250k*** 1:250,000 geological maps showing mapped geology at the ground surface according to publicly available geological maps produced by the Geological Survey of Victoria. (Shapefile: GSV_Geological_Units_250K_YRSC) ***Geological Units 250k simplified*** The 1:250,000 geological maps above simplified and grouped to include the relevant geologies for this study as set out in Section 4.3 (Shapefile: GSV_Geological_Units_250K_YRSC_Simplified)
LiDAR Elevation Information	Digital Elevation Models for the LGA, derived from LiDAR data acquired in 2015 to 2017 and provided by DELWP. The maps presented have a pixel size/resolution of 10 m for functionality purposes. Note, the 1 m resolution versions of these maps were used during landslide mapping. ***LiDAR extents*** Boundaries showing the extents over which LiDAR information is available. (TIF file: DELWP_YRSC_2015_2017_LiDAR_Extents) ***DEM*** Digital elevation model based on LiDAR data. (TIF file: DELWP_YRSC_2015_2017_LiDAR_DEM_10m) ***Hillshade*** LiDAR derivatives highlighting terrain morphology. (TIF file: DELWP_YRSC_2015_2017_Hillshade_10m) ***Slope Angle*** LiDAR derivative classifying terrain based on slope angle. (TIF file: DELWP_YRSC_2015_2017_Slope_10m)
Landslide Information	
Interpreted Geology	***Interpreted Older Volcanics Influence Areas*** Areas interpreted to be underlain by in situ or transported materials derived from Older Volcanics. (Shapefile: YRSC_EMO_Older_Volc_Influence_Area)
Landslide Inventory	Mapped landslides including information about location, date of occurrence (if known) and type of landslide. A point file and a polygon file are provided. (Shapefiles: YRSC_EMO_Landslide_Inventory_Poly_AUG2024; YRSC_EMO_Landslide_Inventory_Point_AUG2024)
Susceptibility Maps	The susceptibility maps have a pixel size/resolution of 10 metres. Maps including and excluding areas managed by others within the council boundaries are provided (filenames including 'InclExempt' and 'ExclExempt' respectively).

Layer	Description
	Landslide Susceptibility to landslide with high, medium, low, and not susceptible classes. (Shapefiles: YRSC_Landslide_Susceptibility_Map_InclExempt_AUG2024; YRSC_Landslide_Susceptibility_Map_ExclExempt_AUG2024) ***Debris Flow*** Susceptibility to debris flow with high, medium, low, and not susceptible classes. The map incorporates the 1991 Coffey debris flow susceptibility mapping for the Montrose area and other areas identified in the study as susceptible to debris flow. (Shapefiles: YRSC_Debrisflow_Susceptibility_Map_InclExempt_AUG2024; YRSC_Debrisflow_Susceptibility_Map_ExclExempt_AUG2024)
Proposed Erosion Management Overlay	Proposed EMO being areas assessed as having medium or high susceptibility to landslide or debris flow. (Shapefile: YRSC_Landslide_DebrisFlow_Proposed_EMO_AUG2024)

APPENDIX B

Important Information

Limitation Statement

This Report is provided by WSP Australia Pty Limited (*WSP*) for the Shire of Yarra Ranges (*Client*) in response to specific instructions from the Client and in accordance with Contract CQ7025 between WSP Australia Pty Limited and Shire of Yarra Ranges dated 20 September 2022 (*Agreement*).

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