FOX GLACIER — ROAD ACCESS

July 2019

ENGINEERING REVIEW

Report prepared for Department of Conservation

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1. INTRODUCTION

1.1 SCOPE

G & E Williams Consultants Ltd in conjunction with Land River Sea Consulting Ltd have been contracted by the Department of Conservation (DOC) to undertake an engineering review of the status and repair-ability of the Fox Valley Access Road (Access Road) in the Westland District of New Zealand. The location of the main access road (North) as well as the secondary access road (South) is shown on Figure 1-1 below.

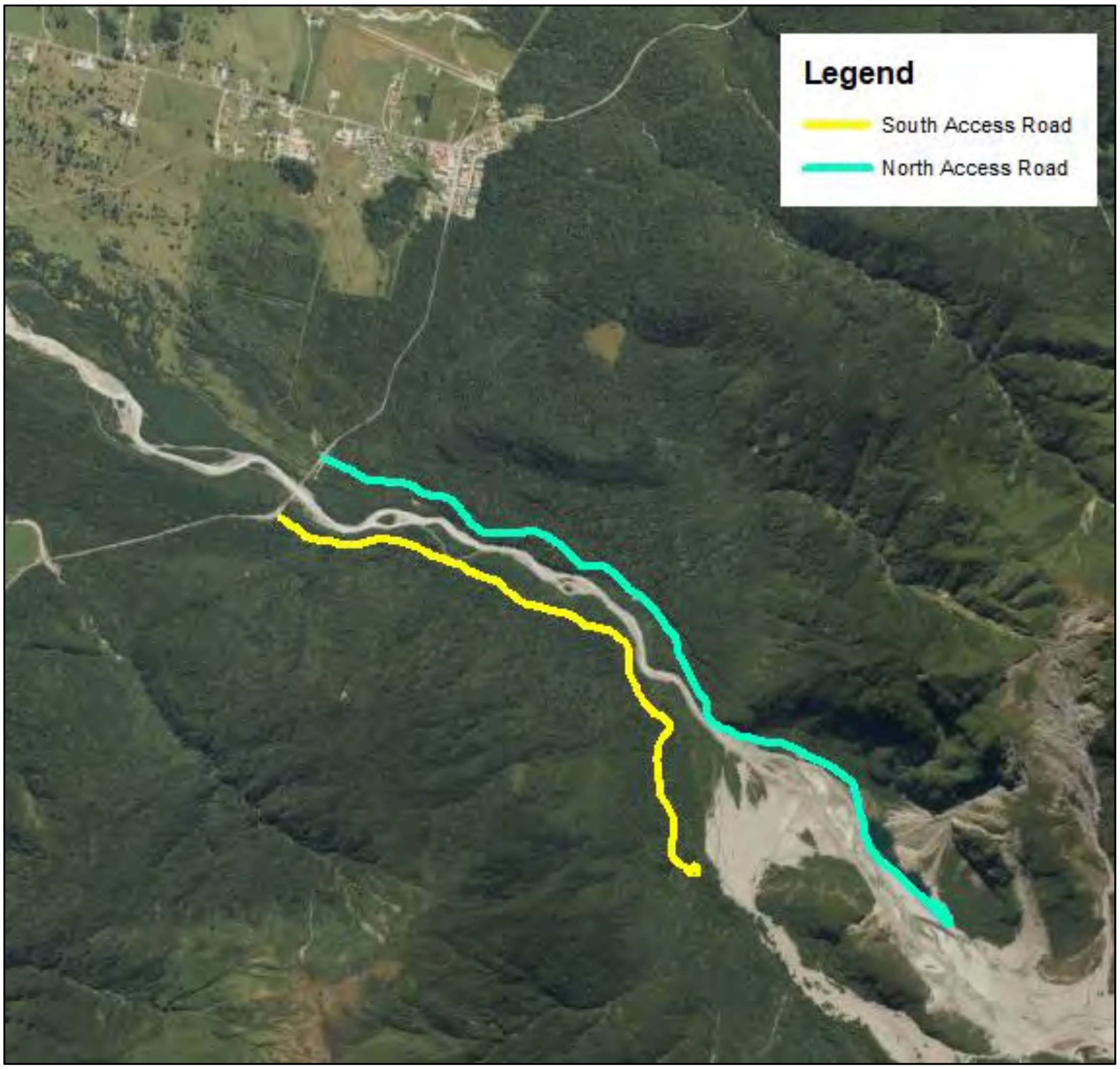

Figure 1-1 – Location of the main valley access roads

The investigation has covered a study of available reports, aerial photography and other information on valley conditions and potential hazards, an appraisal the nature of the Fox River in the valley and its dynamics, and an inspection of the road, its context and its condition, following the recent storm events.

The landscape and river conditions in the valley are now such that a reinstatement of road access up the valley is impractical, with any reinstated road being very difficult to protect, and likely to be overwhelmed by valley-wide aggradation in the short term – of years rather than decades.

This report provides an overview of the conditions in the valley, and the geomorphological and engineering evidence on which this assessment is based.

1.2 OVERVIEW

The high level of activity of the Fox River in recent storm events has given rise to large erosion embayments, as part of the scouring and deposition processes of the river, and a wider active river bed. This erosion has affected the access roads on both sides of the river, removing sections of the roads, and leaving high steep banks of loose materials beside or into the roadways.

At the same time, active debris supply from the valley sides is building large fan deposits in the upper valley, which are increasing the supply of sediments to the river. In particular, there has been a rapid increase in the size of a fan from Mills Creek, and this fan has now extended over the whole of the valley floor, and compressed the Fox River flows against the northern side, where the main access road was located. In this area, most of the roadway has been completed eroded away, with flood flows overtopping the road.

This widening of the river channel and build up of the Mills Creek fan is very clearly visible in the available satellite imagery, which has been obtained from the Sentinel 2 satellite system operated by the European Union Copernicus programme. Figure 1-2 and Figure 1-3 on the following page compare the satellite imagery taken on the 1st of February 2019 with imagery from 28 March 2019 immediately after the flood event. Figure 1-3 also highlights the location of the road washouts. Measurements of active channel width taken from the satellite imagery show that the river has approximately tripled in width for much of its length.

Images of each washout are then presented from Figure 1-4 to Figure 1-10 on the following pages. Other photographs, taken from the air and on the ground are given in Appendix A.

Figure 1-2 – Sentinel 2B Satellite Imagery taken 1 February 2019

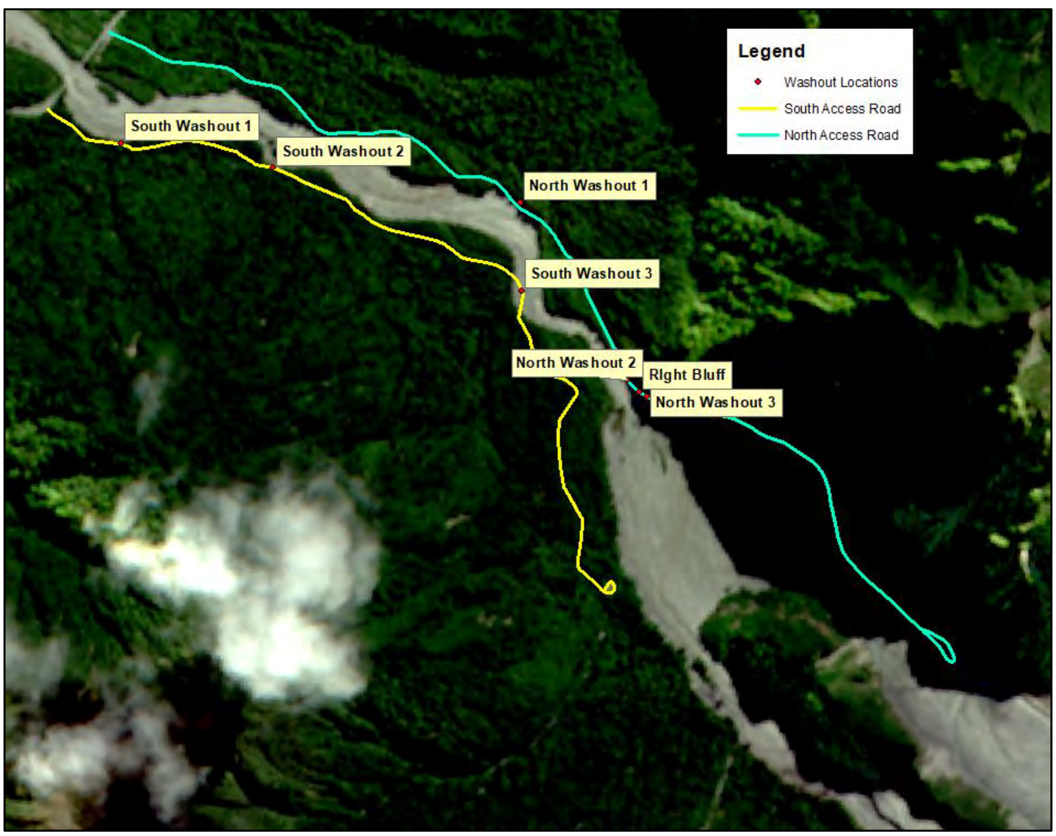

Figure 1-3 - Sentinel 2B Satellite Imagery taken 28 March 2019

North Washout 1 – This washout consists of a large erosion embayment into the road. Approximately 190 m of this section of the road has been washed away, leaving a high steep bank of loose materials, with a pronounced hook curvature along the embayment. This bank is now highly vulnerable to further erosion.

Figure 1-4 – Photos of the North Washout 1 – looking upstream & downstream

North Washout 2 – In this location flood flows have overtopped the road, causing scour behind the rock lining, which was protecting the road on the river side, and also taking out a large portion of the road.

Figure 1-5 – Photos of the North Washout 2 – looking upstream & from the fan opposite

North Washout 3 – The road went around a high bluff at this point, and the roadway has been completely removed for around 100 m. This section of the road has also been overtopped by floodwater due to fan material building up against the road and then bursting during flood flows.

Figure 1-6 – Photos of the North Washout 3 location – looking downstream

The remainder of the road upstream from this location has been largely destroyed, with a remnant of the rock-protected embankment remaining in the river bed. The main river flow is now on the north side by the Undercite fan.

Figure 1-7 – Photos of the upper section of the road, now destroyed – looking downstream

South Washout 1 – A large embayment that formed upstream of the S H Bridge eroded up to the road, leaving a very high steep bank up to the road formation. Rock lining works of NZTA are now protecting the toe of this bank.

Figure 1-8 – Photos of the South Washout 1 location – looking downstream & across

South Washout 2 – The river now has a split channel here, with erosion up to the road leaving a very high steep bank of loose materials. This bank is highly vulnerable to further erosion.

Figure 1-9 – Photos of the South Washout 2 location – looking downstream & upstream

South Washout 3 – Approximately 140 m of this section of road has been destroyed by a large embayment from the river that extends into the moraine material left behind from the 1750 glacier terminus. The active channel width of the river has about tripled in this location, leaving a very rough river bed with large boulders.

Figure 1-10 – Photos of the South Washout 3 location – looking upstream & downstream

1.3 BACKGROUND

Site inspections were carried out on 18 and 19 June, with DOC staff. This included on the ground inspections along the roads on both sides of the Fox River from the State Highway upstream to the (recently formed) large fan of the Mills Creek system. An aerial inspection covered the area of the road access and the valley up to the glacier and over the Mills Creek system up to Craig Peak.

Information on the geology and geomorphology of the Fox Valley was obtained from the studies of GNS Science (GNS) and Massey University (MU). GNS have produced a comprehensive report on the landslide hazard and loss of life risk in the Fox (and Franz Josef) valley[1]. This provided useful information on the valley geology and its landslide patterns and potential volumes of debris materials. The probability and risk analysis was, though, focused on loss of life, and not on the risks to infrastructure or assets. As well as the risk to life, there are the risks to livelihoods and the undertaking of all of life activities. Our focus, as an engineering assessment, is on the latter, and in particular the ability of people to access the area, view the glacier and undertake recreational activities.

Ian Fuller and his students from Massey University have undertaken geomorphological studies in the Fox Valley since 2010. These investigations have not been written up, but a presentation slide show was made available to us, which summarised their studies and findings. This provided a useful geomorphic overview, as well as specific information on the build up of fans in the valley and the Fox River itself.

Aerial imagery has been obtained from Google Earth, LandSat Satellites, and the Sentinel 2 satellite. Aerial imagery that was collected at the same time as the LiDAR run in June 2018 was provided under license by GNS Ltd. The aerial imagery of 2011 and 2017 was provided by WCRC. The earliest aerial imagery of the area was taken in 1953, as part of the first nation-wide aerial survey of New Zealand. Contact prints of this earliest survey were provided by WCRC.

The base data of the digital terrain models (DTM) of the 2018 Lidar survey was provided by GNS under licence, and 3-D imagery has been generated from this data.

Information on bed levels at the State Highway bridges over the Fox and Waiho rivers has been provided by WSP Opus, along with information on bed levels at the Waiho River bridge in relation to glacier advance or retreat.

The review and assessment of road access has been based on this information, and our experience on New Zealand rivers in general, and West Coast rivers in particular. We have both been involved in the assessments of the hazards and risks from the Waiho River at Franz Josef, including detailed investigations, and the development and evaluation of both protection and retreat options. Investigations in recent years on West Coast rivers have included reaches on the Grey, Ahaura, Taramakau, Hokitika, Whataroa and Cook rivers, by Gary Williams, and on Bullock Creek and Range Creek as well as on the Buller, Hokitika and Wanganui rivers by Matthew Gardner.

2. CONTEXT

2.1 GENERAL CONTEXT

New Zealand is made up of large islands on the tectonic boundary of the Pacific "ring of fire", where a segment of continental crust has been pushed and shoved, raised and sunk, over long periods of geological time. It has a mountainous backbone along the line of this boundary, with rapidly uplifted and shattered base rocks, and steep gravel-bearing rivers that have a short run from the mountains to the sea. It has a mid-latitude oceanic location in the southern Pacific Ocean, where the mountain ranges cut across the westerly circulation of anti-cyclones and depressions of these latitudes, giving rise to high intensity rainfalls.

Flood flows are generated very rapidly and give rise to sudden but brief flooding of floodplains, under natural conditions. The relatively high flood flows and steep grade of rivers in New Zealand give rise to powerful highly turbulent flows that move large amounts of sediments and debris over short periods of time. However, the short duration of these floods suddenly truncates sediment transport and channel movement, and this can leave sharp hook embayments and other channel distortions in the river bed following flood events. The steep landscape of weak fault-broken and weathered base rocks gives rise to high catchment input of sediments, even with the natural forest cover of New Zealand. As a result, the alluvial (self-forming) channels of these rivers are highly mobile and change rapidly, even over human life spans.

The oceanic climate is highly variable, with an unstable seasonal pattern, and longer-term variations from the oscillations of large global circulations, southern ocean circulations (around Antarctica) and circulations around the South Pacific. The diverse landscape and climatic regions of New Zealand are affected at different times and in different ways through the pulsating dynamic of these natural oscillations. The back and forth movement of a convergence zone of two large circulations in the Pacific Ocean gives rise to decades long variations in the New Zealand climate. This Interdecadal Pacific Oscillation (IPO) is a major driver of regional variations in storm intensity and flood flows. Thus, in a given region, there are periods of high flood intensity followed by a generally quiescent period, before a return to more and larger floods. The river systems respond to these changes, and this is reflected in changes in channel form and vegetation extent within and along river channels.

During the last glacial age, NZ was mostly covered by open grasslands and scrublands, with forests on the margins and ice fields along the higher mountain ranges. From around 15,000 years ago, there was a progressive covering and diversifying of forests, with the warmer climate and greater rainfall of the present inter-glacial period.

Earthquakes (and volcanic activity) arise from the flows of molten (magma) rock under the surface crust of the Earth. These flows have circulation patterns, with a global inter-connection, and earthquake activity would have patterns of varying activity, like those arising from the flows of water on the surface of the Earth, and air over its surface.

However, these inner Earth circulations and the resulting patterns of tectonic activity are not well understood, and there are no models of temporal earthquake activity for New Zealand. The GNS report notes that their risk assessment is based on spatially defined hazards and average probabilities of occurrence that are time independent. There is geological information on the occurrence of major movements of the South Island Alpine Fault, and this indicates a temporal pattern, with a relatively regular recurrence period (similar time intervals) of around 300+ years (Reference 1 and other GNS reports).

The last major rupture on the Alpine fault was in 1717, and this gave rise to a landscape re-set from mountainside destabilisation, landslide activity and the re-working of debris flow sediments down rivers to the alluvial floodplains. Similar landscape re-setting took place from earlier major ruptures, with a sequence of widespread gravel deposition over floodplains, slow re-foresting of the plains and then another layering of gravel sediments. Studies have demonstrated this on, for example, the Whataroa River floodplain.

2.2 LOCAL CONTEXT

The main Alpine Fault crosses the Fox River on the outer side of the mountains, dividing the mountains from the coastal plains, with their more recent glacial and alluvial deposits. From the glacier, the Fox River is confined in a glacial valley, with U-shaped steep sides, and has a wide gravel bed past Cone Rock, down to a bluff of base rock material on the right (north) side (Right Bluff), with moraine deposits on the left (south) side. From there the river has a narrower channel to below the State Highway Bridge (S H Bridge), where it progressively widens and becomes more and more braided, before entering the Cook River.

The reach from this bluff, and beside the moraine material, has recently widened, now have a more meandering main channel with some island formation from channel splitting. Large erosion embayments have formed as the river has swung from side to side, with one on the left bank reaching the toe of the 1750 terminal moraine material (South Washout 3), and another on the right bank removing a long section of the main access road (North Washout 1). Further downstream this erosion process exposed the old rubbish dump, which had been placed in a side channel of the river, where there was a wider split channel at a bend – the 1953 aerial photography shows a reclamation bund across the bend. Then at the State Highway another large embayment formed on the left bank, threatening the highway bridge, and eroding up to the south access road (South Washout 1).

The main (north) Access Road originally extended up the valley to a car park, a relatively short distance from the glacier toe, by a low bluff between the Undercite and Yellow creeks. Prior to 2000, a substantial landslide from the Undercite catchment gave rise to a large and steep debris fan, which covered the road. The roadway was then re-located out onto the active bed of the Fox River. Rock protection works were used to maintain the road embankment, and the road was set back towards the fan sometime prior to 2012. This made the embankment somewhat less intrusive into the river bed, but it remained a pronounced restriction within the river. Appendix C has a series of aerial plans of the area of the roads, showing changes over time, including the recent formation and expansion of the Mills Creek fan.

Figure 2-1 – 2018 imagery, with comparison of historic road alignment (pre 2000) and existing alignment that protruded into the river bed.

A sequence of aerial imagery of the area from the State Highway (SH) to the Fox Glacier toe is shown in Appendix B, taken from available imagery. This sequence shows the changes in the extent of the glacier, the debris fans in the valley, and the side valley gully erosion and landslide features.

There was a substantial retreat of the glacier (both Fox and Franz Josef) from the 1940s through to the 1960s – 1953 imagery shows the glacier extending all the way down to Cone Rock. This retreat would have removed support along the valley sides, and pressure release would destabilise the rock faces. The debris fans from the side valleys would also extend further with a lower base level. This retreat, then, allowed material to accumulate in the valley and exposed it to re-working by the alluvial processes of flood flows. Increases in river bed levels downstream, however, appear to be more related to glacier advances, with the gravel and boulder deposits being pushed and transported downstream. This may also be because glacier advance arises from higher rainfalls and snow accumulation, which takes place during the same phase of the rainfall intensity cycle that gives rise to more intense storms and greater flood activity.

For the Waiho River of the Franz Josef Glacier system, there is some evidence of a correlation between glacier advance and rising mean bed levels at the S H Bridge, and of accumulation on the fan downstream of the bridge. When there is glacial retreat the bed levels tend to stabilise.

For the Fox River, the historic record at the S H Bridge shows progressive degradation, with bed levels lowering over time. The bridge is a constriction in the river channel, and this can give rise to a localised degradation, but in this case the trend is a long term one.

The glacial advances in the 1980s to 2000s were counter to global trends of glacial retreat, and were associated with the climatic oscillations of NZ. With some time delay, this advancing took place in the positive phase of the IPO (of more pronounced westerly flows), which was from around the mid 1970s to about 2000. Given the reversal that has now taken place, a more rapid glacier retreat would be expected, as a compensating response, and the recent rate of retreat does indicate this.

The hydrological records for southern West Coast rivers are relatively short, with the closest continuous record to the glaciers being the Whataroa River records. The Whataroa River records started in 1985, and an analysis of flood intensity (using the time above the 2 year return period flow, which is a parameter for generalised channel activity and sediment transport, does show higher intensity in the 1980s and 1990s, with a more quiescent time in the 2000s. However, some increase in flood activity takes place in the 2010s. The longer records on the northern West Coast rivers, of the Buller River (from 1963) and Grey River (from 1968), definitely show greater flood intensity over the positive phase of the IPO.

Figure 2-2 is a plot of the flood intensity (time above a 2-year return period flow), for these three West Coast rivers, showing the increased activity over the positive phase. It does also suggest that there has been a change in climatic conditions that is becoming apparent in the 2010s. This may be related to cyclonic depressions travelling down the west side of New Zealand, rather than across the North Island towards the eastern side.

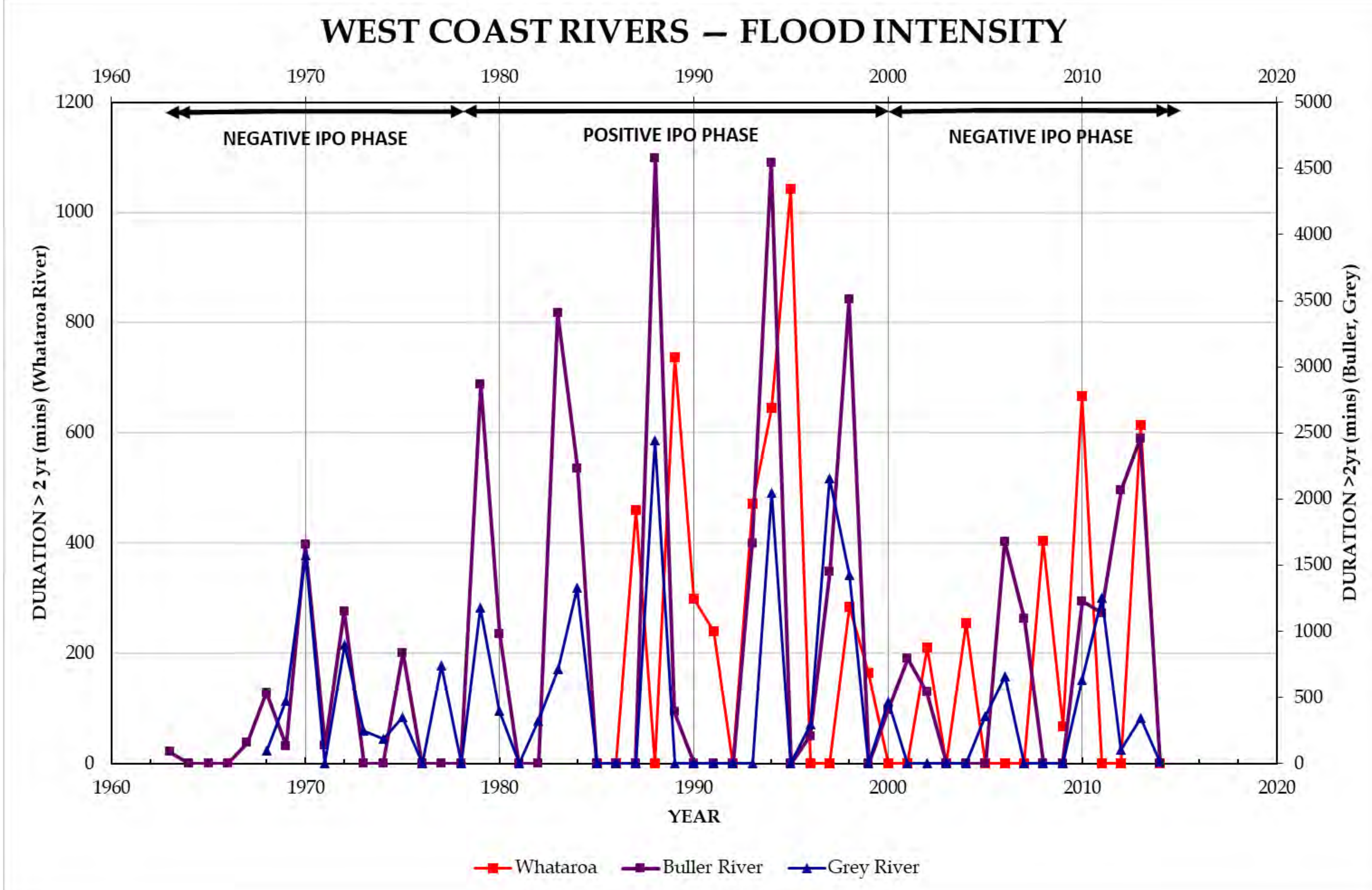

Figure 2-2 – West Coast flood intensity showing the relationship to the IPO cycle

The conditions in the Fox Valley have been profoundly altered by the recent activity in the Mills Creek system. Generally, the side valleys have a simple form, with a direct connection from debris sources down to the main valley. The Mills Creek system is unusual because of its landscape complexity, with Cone Rock deflecting the mountainside creeks and combining a number of side valleys into one waterway system. On the far upper side of this system there is a high-level debris accumulation area, of the Alpine Garden, which is relatively extensive, and where a large volume of loose material has been stored over recent decades. The Figures 2-5 to 2-7 show 3-D generated imagery from the 1953, 2014 and 2018 aerial imagery. This demonstrates the debris accumulation in the Alpine Garden area and its more recent erosion and collapsing activity, which has resulted in a large fan build up in the valley floor.

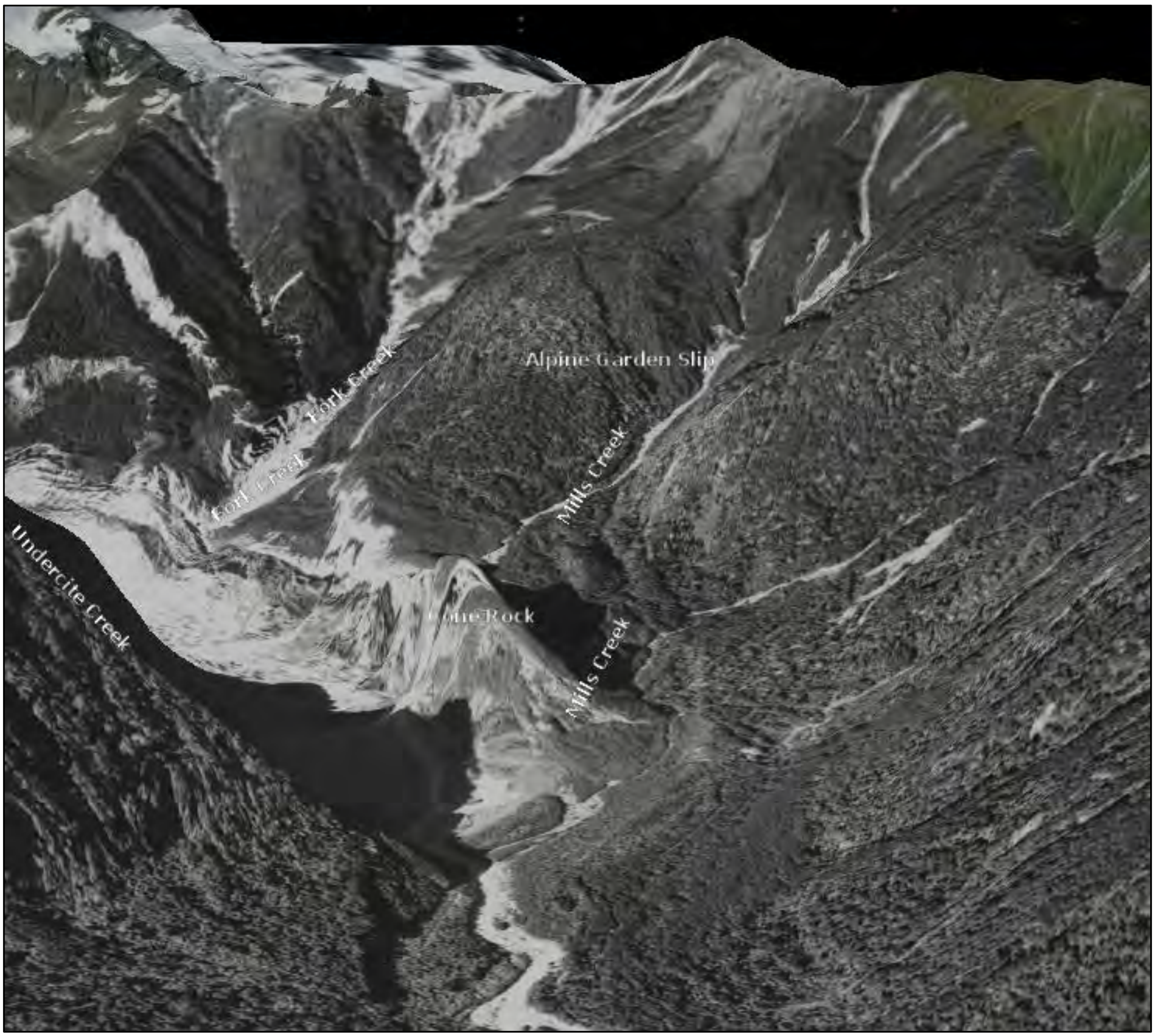

Figure 2-3 – 3D re-creation from 1953 Imagery

Figure 2-4 – 3D re-creation from 2014 Imagery

Figure 2-5 –3D re-creation from Summer 2016 / 2017 Imagery

Figure 2-6 – 3D re-creation from 2018 Imagery

In the last 2 years this high-level debris accumulation has become destabilised, with an accelerating breakdown of the mass deposits and movement of debris down Mills Creek. The recent storm events would have increased this breakdown and the supply of gravel and boulder sediments to the main valley floor. This has resulted in a large fan being formed in the main valley, covering the valley floor, and increasing in size very rapidly. This fan is very large with respect to the valley floor area, it is very mobile in flood events, and is made up of a wide range of materials up to very large boulders. The head of the fan, where it comes out from behind Cone Rock, is around 70 metres above the access road level, as shown by the 2018 LiDAR survey (see the Plan D1 with 10 and 5 metre contour lines in Appendix D).

The repeat aerial imagery since 2011 in Appendix B shows this fan build up, and the opening up of the landslide deposits that had accumulated in the Alpine Garden area. The total volume of landslide debris in the Alpine Garden area has been estimated by GNS to be at least 50 million cubic metres[1].

At the same time, there has been on-going supply of material to the valley floor and fan building from other side valleys below the present toe of the glacier. The Massey University studies have shown fan build up at the Gunbarrel and Yellow Creek fans, and a rising bed level across the Fox River channel above the large Mills Creek fan[2].

Images of the Mills Creek system, its valley fan and high-level debris accumulation, are shown in the series of photos of Figure 2-7 to Figure 2-9. Other photographs, taken from the air and on the ground are given in Appendix A.

Figure 2-7 – The Mills Creek system, from the fan on the valley floor to the Alpine Garden debris accumulation above Cone Rock, and up to Craig Peak.

Figure 2-8 – The top of the fan with the Alpine Garden above to Craig Peak

Figure 2-9 - The Alpine Garden debris accumulation below Craig Peak. Note the slip faces, cracking and active working of the material.

3. ACCESS

3.1 NORTH SIDE ROAD

The main Access Road on the north side of the valley originally extended to a car park by a low bluff between the Undercite and Yellow creeks. The sequence of aerial plans (of Appendix C) shows the changes that have taken place over time along the length of the road. Photographs of the road and river taken during the field inspections are given in Appendix A.

From the Right Bluff of exposed base rock, upstream of the walkway swing bridge (Swing Bridge), the roadway has been completely destroyed, with a remnant remaining in the middle of the river bed. The Mills Creek fan has spread from this bluff to about opposite the original car park. It now compresses the Fox River against the right (north) bank, with a very active dynamic in storm events of fan building and reworking, and the river both carving away the fan toe and being blocked by fan material.

From this bluff upstream, the roadway has been completely washed away (North Washout 3), and downstream towards the Swing Bridge the roadway has been severely damaged, with scouring alongside the protective rock lining, and by the concrete water table drain (North Washout 2). The temporary blocking of the river by the fan movement has raised water levels sufficiently for flood flows to pass down the road formation, causing the scouring and leaving debris deposits.

The Swing Bridge is at the downstream edge of the present Mills Creek fan and the main flow of the Fox River is against the right bank. The large erosion embayments that have formed downstream have affected the roads on both sides, with a large section of the main Access Road being removed by erosion that has left a high vertical bank in the alluvial materials of the valley (North Washout 1). Then as the river has swung back to the right side a further large embayment has eroded close to the road.

3.2 SOUTH SIDE ROAD

The south side road parallels the river, the same as the north side road, but then climbs up the moraine deposits on this side of the valley, to a carpark close to the Mills Creek fan. This road alignment is also shown on the sequence of aerial plans (Appendix C). Photographs of the road and river taken during the field inspections are given in Appendix A.

Downstream of the Swing Bridge a large erosion embayment on the left side has removed a long section of the road, where the road went around the end of the 1750 moraine (South Washout 3). The reworked channel area is now very rough and uneven, with many large boulders, making it a very difficult terrain for any road reinstatement.

Further downstream there is another area of bank erosion, with a high raw vertical bank, which has not progressed up to the road. Closer to the State Highway erosion has cut a very high bank up to the road edge (South Washout 2). The large embayment upstream of the S H Bridge also came up to the road formation, with an exceptionally high raw bank (South Washout 1). However, the NZTA works, which involve a long rock lining around the curvature of the erosion embayment upstream of the bridge, have been constructed in front of this area, and hence give protection to the road at this point.

3.3 SWING BRIDGE

The river has widened with a very rough boulder channel at the bridge. The mass of boulders on the left side would provide some deflection and hence protection to the left side bridge tower. The confining of river flows to the right side does, however, increase the erosion hazard on this side, and the present bank is right at the outer side of the tower footings.

The tower footings are simple concrete blocks, with no apparent under-piles. The right side tower is, thus, likely to fail from underscoring by the river. The height of the bank, its closeness to the bridge towers, the loose bank material and the boulders in the river bed, all add up to a very difficult site for any protection works.

The bridge is also at risk from debris materials coming down the Mills Creek fan, which is likely to spill into the area behind the bridge on the left side as the fan builds.

Images of bridge area are shown in Figure 3-1 and Figure 3-2 below. Other photographs, taken from the air and on the ground are given in Appendix A.

Figure 3-1 – Erosion embayment at and downstream of bridge


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Figure 3-2 – True right bridge abutment protected by boulders. Left abutment exposed and vulnerable

3.4 ACCESS ALTERNATIVES

During fine weather the safest place to be is in the middle of the valley, that is, in the middle of the river. An alternative route could then be a 4-wheel drive gravel road graded into the river bed material. This, however, requires conditions where the low flow channel can be easily crossed, and forming the access is relatively straightforward, and maintainable without constant reinstatement.

In this case an access by the south side and then across the Mills Creek fan may have looked possible. However, the main problem is the nature of the fan. In essence, it is too large, too active and too full of large boulders (see Figure 3-3). Given the damage to the south side road as well, there is no practical route for an in-river 4-wheel drive access way.

The only road options are along one or other of the banks or in-river.

Figure 3-3 - Photo showing the wide extent of the Mills Creek fan and highlighting the size and type of rock material. Fox Glacier to the left of Cone Rock, Alpine Garden and Craig Peak to the right

4. COMMENTS

The Fox Valley, upstream of the State Highway, is in a mountainous environment, formed by glacial and alluvial action. There are high rates of hillside erosion, valley scouring, landslides and rockfalls, which produce loose colluvial materials on the valley sides and large fan deposits into the valley floor. The mountains are being uplifted by tectonic plate movements, with the main movement concentrated in a single very active fault of the Alpine Fault. This fault is subject to severe earthquakes at relatively short and regular intervals.

The combination of earthquakes and intense rainfall gives rise to very steep slopes of fault ruptured and broken rock that produces high sediment loads to the mountain waterways. The periodicity of both earthquake activity and storm intensity does, though, gives rise to relatively quiescent periods, when human access and infrastructure is more easily established and maintained. A shift to a high intensity of earthquake or storm activity then has a major adverse impact on the security and maintenance costs of our infrastructure and assets, as well as the risks to life and limb.

Past records would indicate that the West Coast is in a relatively quiet period in terms of storm and flood intensity. On the other hand, the periodicity of major fault ruptures on the Alpine Fault would suggest that there is a limited time span before a profound resetting of the sediment supply, transport and deposition dynamic of the West Coast environment. This will alter the character and activity dynamic of waterways in this region, and give rise to wide spread sediment deposition along the river valleys and floodplains.

Consideration of infrastructure maintenance and protection options should take cognisance of this limited time span.

The storm and flood dynamic is also being affected by global climate changes, and the regional responses to this in New Zealand. This alters, and in a progressively increasing way, the driving forces of storm events, and hence the likelihood of flood events that have a significant impact on sediment transport and channel form and migration.

There is no longer a (dynamically) stable population of flood events on which to base statistical analyses and frequency of recurrence probabilities.

The high hazard environment of the Fox Glacier valley roads means that they have a high maintenance cost, and emergency and damage prevention maintenance costs over the 10 years from 2008 to 2018 were just under $3½ million. The repair costs in 2008/9 were over $½ million, and in 2017/18 nearly $1 million. These are high costs for such short lengths of road. Repairing and protecting the roads from the recent damage would be many millions of dollars, while they would remain vulnerable to both overwhelming by sediment flows and undermining from high energy scour and erosion.

It is not clear what has triggered the destabilising of the Alpine Garden deposits. There is, though, likely to be a cycle of deposition build up to an overloaded condition, and then a release of material following some destabilising tipping point. The landslide materials accumulate above a valley throttle and transport restriction, high up on the mountainside, giving rise to a storage and release dynamic.

The proportion of the stored material that is released in a collapsing phase would vary from episode to episode, depending on the degree of overload and the transporting drivers of each episode. From the studies that have been undertaken and the visual condition of the debris field, the present episode is likely to result in a large proportion of the stored material being released. The breakup of the field has extended across the whole width of the deposits, and there is a very active breakup of the whole field taking place.

While the storm intensity pattern may be in a relatively low-level phase regionally, large flood events can still occur, as demonstrated by the recent events. The trends with climate change will be for larger weather systems, with an increase in the frequency of storms over the whole spectrum of storm intensities. This will change the dynamics of waterway processes and hence the character of rivers in terms of channel type and width and sediment transport capacity. In general, the result will be greater volumes of sediment being transported within a wider and more braided channel, with increased erosion and deposition activity.

It is very unusual for intense depressions from tropical cyclones to go down the west side of NZ as far as the mid-latitudes of the West Coast. If this continues, with the Tasman Sea becoming warmer, then the weather patterns on the West Coast will be significantly altered from past patterns.

The large supply of sediment being delivered to the Fox River by the Mills Creek system will alter the transport dynamics and hence character of the river, with increased erosion activity and deposition within and alongside the river channel. Increasing storm intensities from climate change will heighten this trend.

The Fox Valley from the Mills Creek fan upstream will continue to rise because of the supply to this fan. The potential volumes are much larger than the other valley side fan, such as the Undercite fan, and could be up to two orders of magnitude greater, that is, 100 times larger. Along what is, at present, a transport reach, from the Right Bluff on right side, and with the moraine deposits on the left side, sluicing material through to the downstream floodplain, the degradation trend is likely to reverse to an aggrading waterway.

The transport processes will become more variable and dynamic, with the river bed rising and erosion pressures along its margins increasing.

Downstream of the State Highway, where the river already has a wide braiding form, sediment deposition rates will increase, with the active channel becoming wider. This will result in more channel splitting around islands in the river and breakouts into side flood channels.

A reversal of these trends is unlikely in the short to medium term. For a re-establishment of the road access of the past, a pre-condition would be for the debris supply activity of the Mills Creek system to die down, and the Fox River channel start to revert to a narrower and more single channel form.

5. CONCLUSIONS

The road access on both sides of the valley has been severely damage by river erosion in the recent flood events. A major contributing factor is the rapid increase in the supply of material from the Mills Creek system, with the formation of a large and active fan across the whole of the valley floor of the Fox Valley. This is a recent feature that has arisen because of the activation of a large high-level debris accumulation in the relatively complex Mills Creek system, with its restricted outlet behind Cone Rock.

The Fox River below this fan has widened, with large erosion embayments, which leave very high vertical banks of loose alluvial materials. The supply of material from the Mills Creek system is likely to reverse a long-term trend of channel degradation along its transport reach to below the State Highway, and maintain erosion pressure against the channel sides. An increase in channel braiding is likely along the downstream plains, with channel widening and increased deposition.

The reinstatement of the main (north side) Access Road would be very difficult because of the existing river bed and bank conditions, and hence very expensive. Given the Mills Creek fan will continue to rise, any reinstated road would be subject to severe erosion pressures along the fan reach, and in time would be overwhelmed by the rising valley bed levels.

The present fan covers the whole valley floor, and its height and extent means it is a severe restriction on the Fox River in flood events. The erosion and collapse activity of the Alpine Garden debris accumulation has increased in recent years, and the trend is one of accelerating collapse, not declining. The fan build up and pressures on the north side will thus continue to increase.

If the south side road is to be maintained, and used as a walking/biking access, then some work at the erosion areas close to the State Highway should be undertaken, to lower the overall bank height and protect the bank toe. At the South Washout 1 a length of roadway could be lowered to achieve a wider platform and reduce the upper steep face of the bank collapse, with some toe support above the NZTA works. At the South Washout 2 there is active river erosion from a side channel, and bank protection works would be required here. At the same time, the roadway could be lowered to reduce the height of the erosion face, with the road having an incline in this area. At the main washout, of South Washout 3, by the 1750 moraine, a new route over the moraine would have to be developed. Given the terrain, this would be a significant work, even for 4-wheeler maintenance access. Reinstatement around the end of the moraine over the river bed would be very problematic and expensive, and remain highly exposed to future erosion pressures.

A continuing rise in the Mills Creek fan will threaten this south access, as sediments could flow down to the car park and then down the moraine deposits on which the road is formed.

The Swing Bridge is threatened by sediment flows from the Mills Creek fan on the left side, and the right side is likely to fail through bank erosion undermining of the bridge tower on this side.

Given the activity of the Mills Creek system, and the quantities of debris material that could be transported to the valley floor, a cautious approach should be taken with any access improvements. The rate of fan supply and build up will depend on the pattern and intensity of storm/flood events, but even minor storm events are activating the system, and significant changes are likely in the near term, of one to two years. The narrow supply channel to the top of the fan means that scour and deposition activity can take place along any alignment over the width of the fan. The fan does, though, have a wider spread downstream, and more activity and fan enlargement is likely on this downstream side of the fan, lengthening the active face of the fan that confines the Fox River flood flows.

The general regional trend, from past records, is for the West Coast to be in a relatively quiet climatic period. However, recent storm events suggest a change in the climatic regime, with climate changes having a significant effect on increased storm frequency and intensity.

Any measures to maintain access should also be evaluated on the basis of a relatively short time horizon, given the region-wide impacts and on-going landscape changes that will result from the next major rupture of the Alpine Fault.

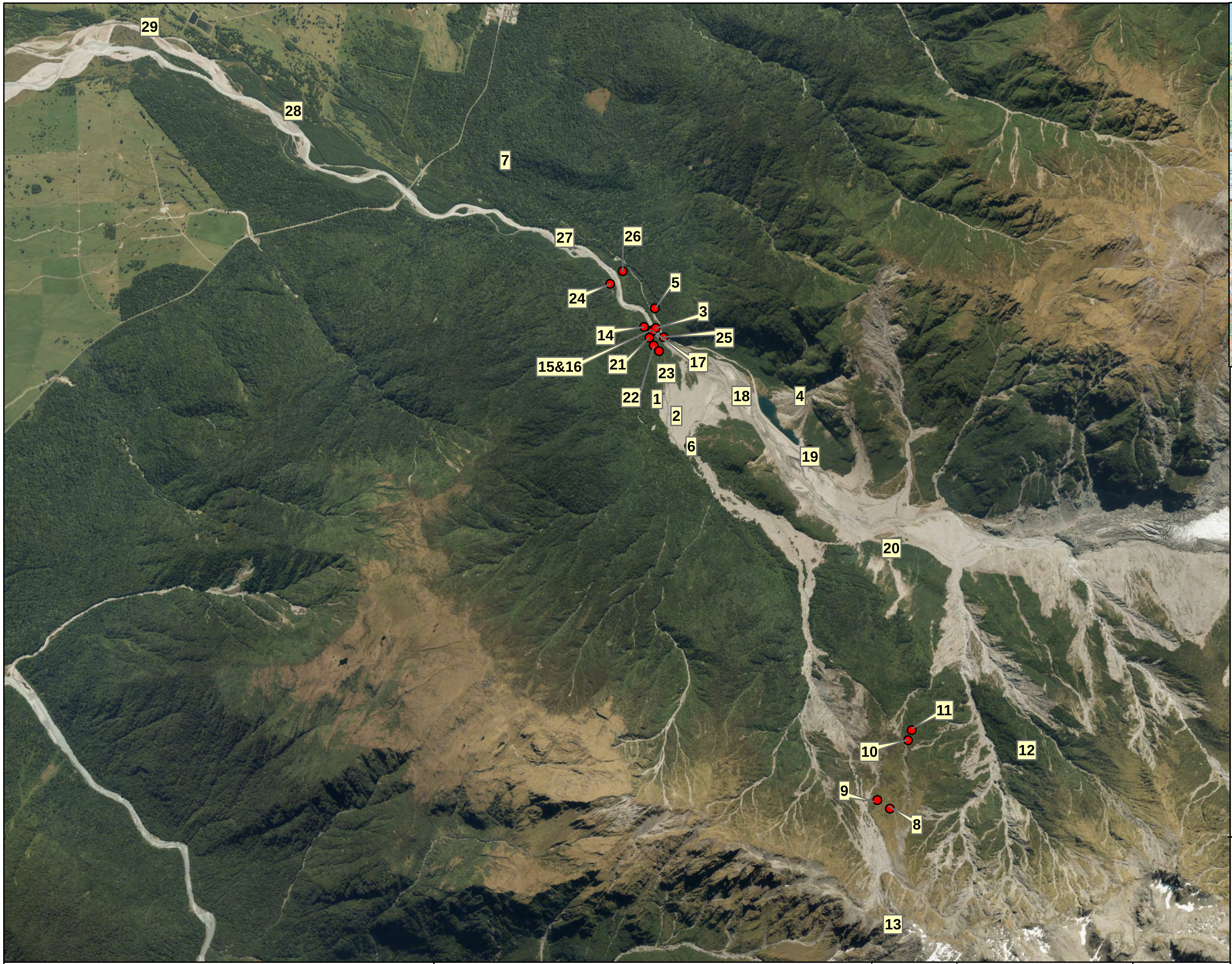
6. RECOMMENDATIONS

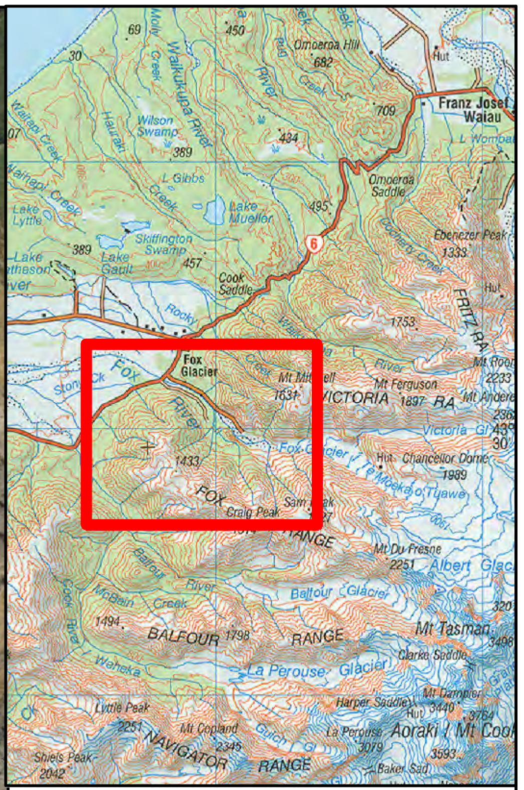
- That the north side Access Road be abandoned as impractical, given the prevailing valley and river conditions and likely future trends.
- If the south side access is to be maintained then some protection measures will be necessary, but this should not include any reinstatement at the main washout by the 1750 moraine.
- That no protection measures be undertaken at the Swing Bridge, given the likelihood of failure by bank erosion on one side, and an overwhelming by sediment flows on the other. Given these hazards the bridge should remain closed.
- That the levels of the Mills Creek fan be closely monitored, along with the consequential impacts on the Fox River, and that substantial expenditure on access ways be deferred for at least a year, or until the likely final size of the fan can be more accurately determined.

7. REFERENCES

1. C I Massey & others, 2019: "Landslide hazard and risk assessment for the Fox and Franz Josef Glacier valleys", GNS Science, Wellington. Report 2018/206.
2. I Fuller & others, 2018: "Contrasting valley response to rapid glacial retreat and implications for hazard management", Massey University, Palmerston North. ANZGG Conference presentation.

APPENDIX A – SITE PHOTOS





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Legend

● Photo Locations

PROJECT	MAP TITLE	REV	DATE	
Fox River Access Road	**APPENDIX A Photo Location Plan**	**01**	**8 July 2019**	N
		A3 SCALE **1:10,000**	AUTHOR **Matthew Gardner**	

A1 – MILLS CREEK SYSTEM

Photo 1 - Valley floor fan, with Fox Glacier to the left of Cone Rock and Alpine Garden and Craig Peak to the right. Note the size of boulders and general roughness of the fan surface.

Photo 2 - Cone Rock with the fan in front. This feature confines and deflects Mills Creek.

Photo 3 - The valley fan with Cone Rock behind and the Alpine Garden up to Craig Peak on the skyline. Taken from the Swing Bridge.

Photo 4 - Shows the extent of the fan, with Cone Rock on the left, and the road remnant in the river bed – looking downstream.

A2 – ALPINE GARDEN AREA

Photo 5 - View to the Alpine Garden, with Craig Peak above – from the road closure.

Photo 6 - Closer up zoom photo of the Alpine Garden

Photo 7 - The bottom of the Alpine Garden debris accumulation, and the start of the transport reach through to the valley floor fan.

Photo 8 - The upper end of the Alpine Garden, under Craig Peak.

Photo 9 - Looking down over the main deposits of the Alpine Garden to Cone Rock, with the Undercite, Gunbarrel and Yellow valleys to the right of Cone Rock.

Photo 10 - Shows the main deposits of the Alpine Garden, and it's very actively eroding front face on the downhill side.

Photo 11 - The upper part of the Alpine Garden, showing the slip faces, cracking and active working of the material.

Photo 12 - Looking south-west over the Alpine Garden, to the steep mountain face above, which could be destabilised in large earthquake events.

Photo 13 -The mountain crest above the Alpine Garden, showing the potential failure plane at the crest (the hollow under the snow), with the slip plane on the north-east side down to the Mills Creek system.

A3 – SWING BRIDGE (OLD FOOTBRIDGE)

Photo 14 - Looking upstream over the footbridge, showing the bottom edge of the Mills Creek fan just above it. North Washout 2 is also just above the footbridge, with the Fox River now squeezed between the fan and the roadway.

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Photo 15 - The right (north) side of the abutment, showing the eroding bank, with a large boulder in the foreground.

Photo 16 - A closer view of the right side, with the bridge tower on a concrete footing just above the raw bank that can be seen underneath the bridge.

Photo 17 - The left (south) side of the bridge, showing the large boulders that are stacked on this side of the river channel.

A4 – OTHER FANS

Photo 18 - The Undercite fan on the right (north) side, which is still active. The road was re-aligned into the river bed to go around this fan after it first formed.

Photo 19 - Looking downstream in front of the fan, with the river now flowing between the fan edge and the remains of the roadway in the river.

Photo 20 - The Yellow Creek valley and fan, showing the deposition and erosion activity at the fan. The Gunbarrel valley is on the left side of the photo.

Photo 21 - North Washout 2, looking upstream.

Photo 22 - North Washout 3 looking upstream. The bluff at the outer edge of the high mountains is the point between the two washouts, where the remaining seal ends.

Photo 23 - North Washout 3 and upstream, showing the Fox River between the toe of the Mills Creek fan and the roadway along the edge of the very steep mountainsides.

Photo 24 - South Washout 3 looking upstream. The road is at the small square shadow area under the overhanging branch. Note the large boulders and very rough river bed, with much finer loose material in the river bank.

Photo 25 - From above the Swing Bridge, showing the back and forth meandering of the river bed, with large erosion embankments being formed.

Photo 26 - The erosion embayment that gave rise to the North Washout 1. Note the road on the bank crest, where there is a square shadow. Note also the fineness of the river bank material compared to the river bed.

Photo 27 - The channel splitting that has developed along the river reach. The South Washout 2 is on the left side at the point of the island where there is remaining vegetation. The old dump is on the right side, opposite where the excavator is working.

Photo 28 - Downstream of the State Highway, where the river widens and braids. Note the vegetation debris from the recent river erosion and sediment transport activity.

Photo 29 - The fully braided reach of the Fox River, before it enters the Cook River, showing the recent re-working of the river bed and vegetation debris.

APPENDIX B – AERIAL IMAGERY – FOX VALLEY AREA

Sequence of repeat aerial imagery from the State Highway to the Glacier, from the earliest imagery of 1953 to 2019.

PLAN B1 - 1953 (CONTACT PRINTS FROM WCRC)

Glacier extend to Cone Rock.

Mills Creek system quiescent, with some gully erosion in the Alpine garden area.

Fox River downstream of right side Bluff has some split channel form with islands. Area of river bed being reclaimed for the rubbish dump.

PLAN B2 – 5 APRIL 2006 (GOOGLE EARTH SATELLITE)

Glacier toe at Sam Slip. Fox River has a braided form across the valley floor down to Mills Creek and the right Bluff

Mills Creek system quiescent, with some erosion in the lower slope of the Alpine garden deposits.

Fox River downstream of Bluff has a relatively narrow active channel.

PLAN B3 - 2011 (WCRC REGIONAL IMAGERY)

Shows just the lower area of the Mills Creek system to the State Highway.

PLAN B4 – 18 OCTOBER 2012 (GOOGLE EARTH SATELLITE)

Shows main (north) Access Road to car park.

Mills Creek system has a mostly vegetated fan area, with a relatively small active area.

Fox River has a wide braided form across the valley floor.

PLAN B5 – 13 APRIL 2013 (GOOGLE EARTH SATELLITE)

Very similar to 2012.

PLAN B6 – 1 MAY 2015 (DECEMBER) (LANDSAT SATELLITE 15M RESOLUTION)

Glacier retreating to Paschendale Slip.

Some enlargement of erosion on the lower slopes of the Alpine Garden, and some upper slop activity.

Active deposition extending over the Mills Creek fan area. Deposition behind Cone Rock and build up to the level of the rock lip where the creek is deflected.

Fox River has a main low flow channel and relatively quiescent conditions.

PLAN B7 – 6 SEPTEMBER 2015 (LANDSAT SATELLITE 15M RESOLUTION)

Increase in gravel material in Mills Creek area

PLAN B8 – 27 DECEMBER 2015 (LANDSAT SATELLITE 15M RESOLUTION)

Further increase in gravel material in Mills Creek area and increased erosion visible in alpine gardens area.

PLAN B9 – DECEMBER TO MARCH 2016/2017 (WCRC REGIONAL IMAGERY)

Further enlargement of the eroding area on lower slopes of Alpine Garden and generally to the upper slopes.

The Mills Creek fan now mostly covered by actively worked gravel deposits, and starting to extend into the valley floor.

Fans on the north side (Undercite, Gunbarrel, Yellow) remain generally the same as 2012 imagery.

PLAN B10 - 2018 AERIAL IMAGERY (FROM GNS)

Further enlargement of the eroding area on lower slopes of Alpine Garden, with major collapses of the accumulated deposits, and break-up activity over the full extent of the high valley deposits.

The Mills Creek fan now extends over the full width of the valley floor, with very actively re-worked deposits.

Main (north) Access Road remains intact, but the Mills Creek fan has now compressed the Fox River up against the road (and north side slopes).

PLAN B11 – FEBRUARY 2019 - (SENTINEL 2B SATELLITE – 10M RESOLUTION)

2019 (May) Landsat (low resoultion)

Further collapsing of the Alpine Garden deposits and removal of material down slope.

Mills Creek fan building up with some downstream enlargement of the active area.

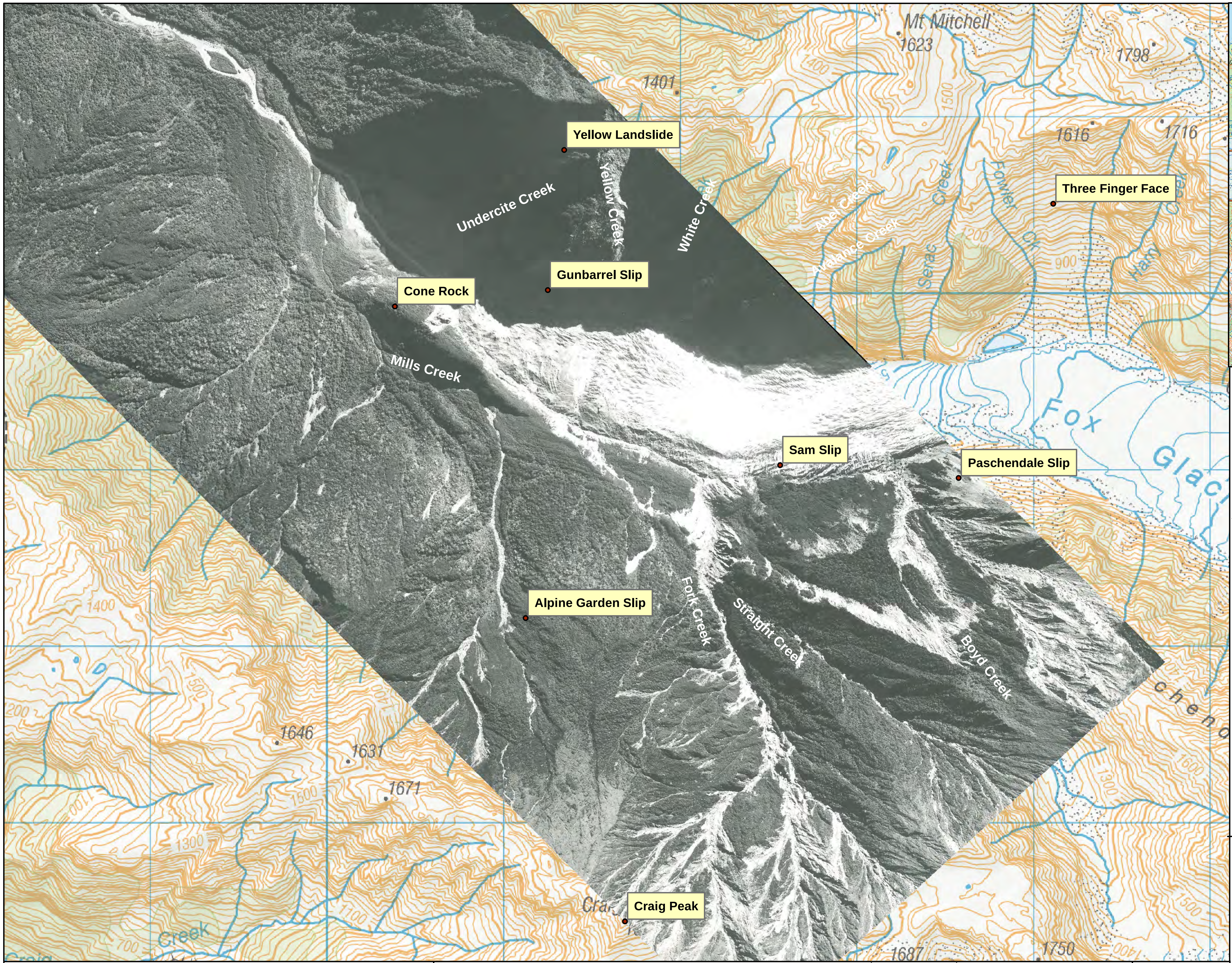
Fox River actively eroding the fan toe, and erosion widening of the channel below the fan (and right Bluff), with large hook embayments being formed from side to side along the river channel.

PLAN B12 – MARCH 2019 – (SENTINEL 2B SATELLITE – 10M RESOLUTION)

Significant widening of Fox river active channel visible. Large erosion embayments visible. (Upstream road obscured by shadows)

PLAN B13 – MAY 2019 – (LANDSAT SATELLITE 15M RESOLUTION)

Upstream road erosion visible in this image and change in river alignment



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1953 Imaging provided by WCRC.
Images are not perfectly aligned.

PROJECT	MAP TITLE		REV	DATE	
Fox River Access Road	Plan B1	**Aerial Imagery 3 April 1953**	**01**	**27 June 2019**	N
			A3 SCALE **1:20,000**	AUTHOR **Matthew Gardner**	

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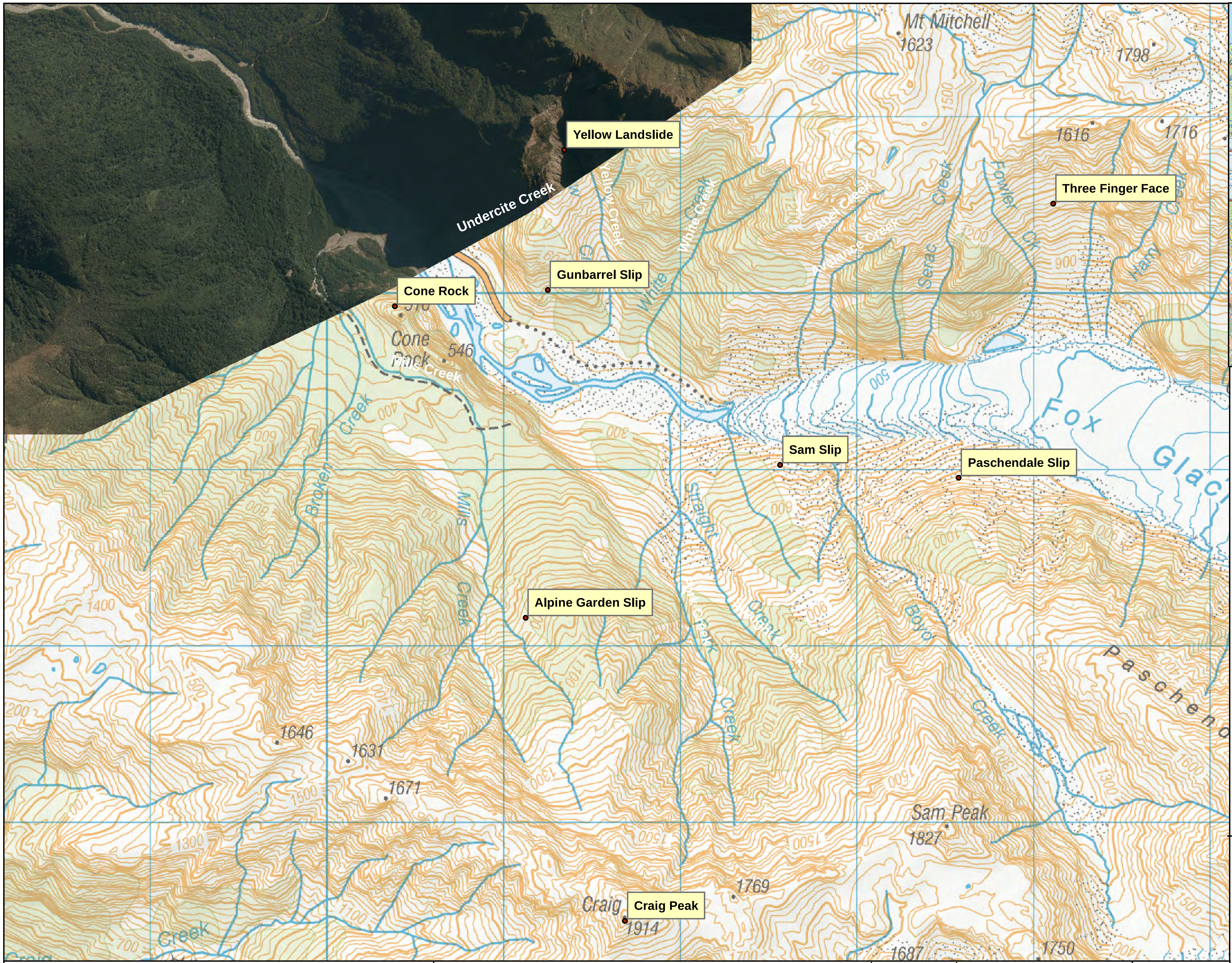
PROJECT	MAP TITLE		REV	DATE	
Fox River Access Road	Plan B2	**Google Earth Imagery 5 April 2006**	**01**	**27 June 2019**	N
			A3 SCALE **1:20,000**	AUTHOR **Matthew Gardner**	



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PROJECT	MAP TITLE		REV	DATE
Fox River Access Road	Plan B3	**Aerial Imagery 2011**	**01**	**27 June 2019**
			A3 SCALE **1:20,000**	AUTHOR **Matthew Gardner**

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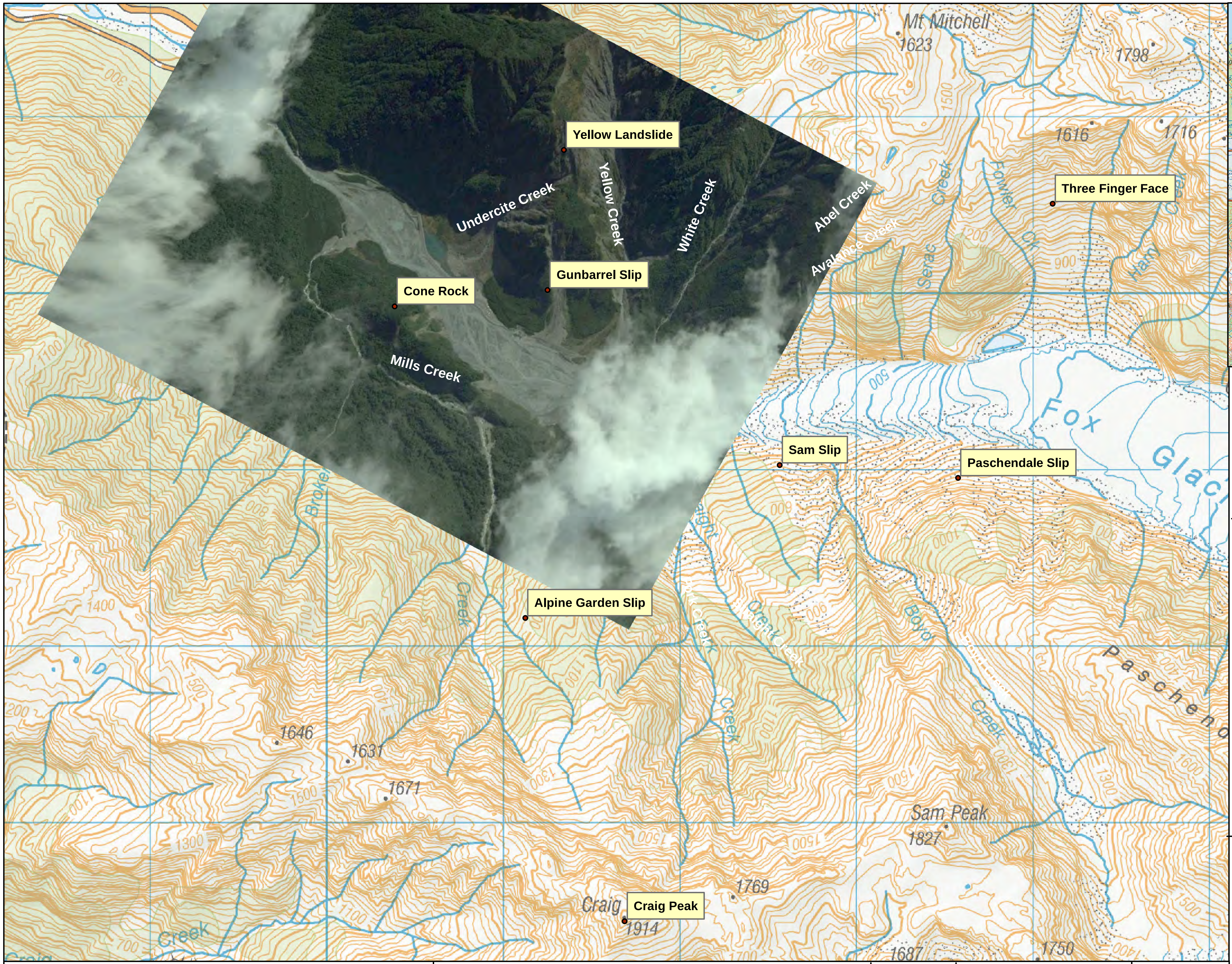

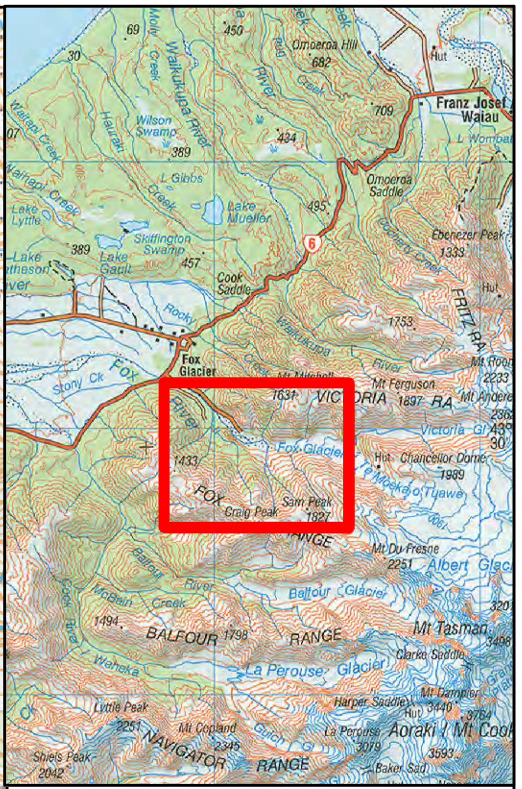

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PROJECT	MAP TITLE		REV	DATE
Fox River Access Road	Plan B4	**Google Earth Imagery 18 October 2012**	**01**	**27 June 2019**
			A3 SCALE **1:20,000**	AUTHOR **Matthew Gardner**

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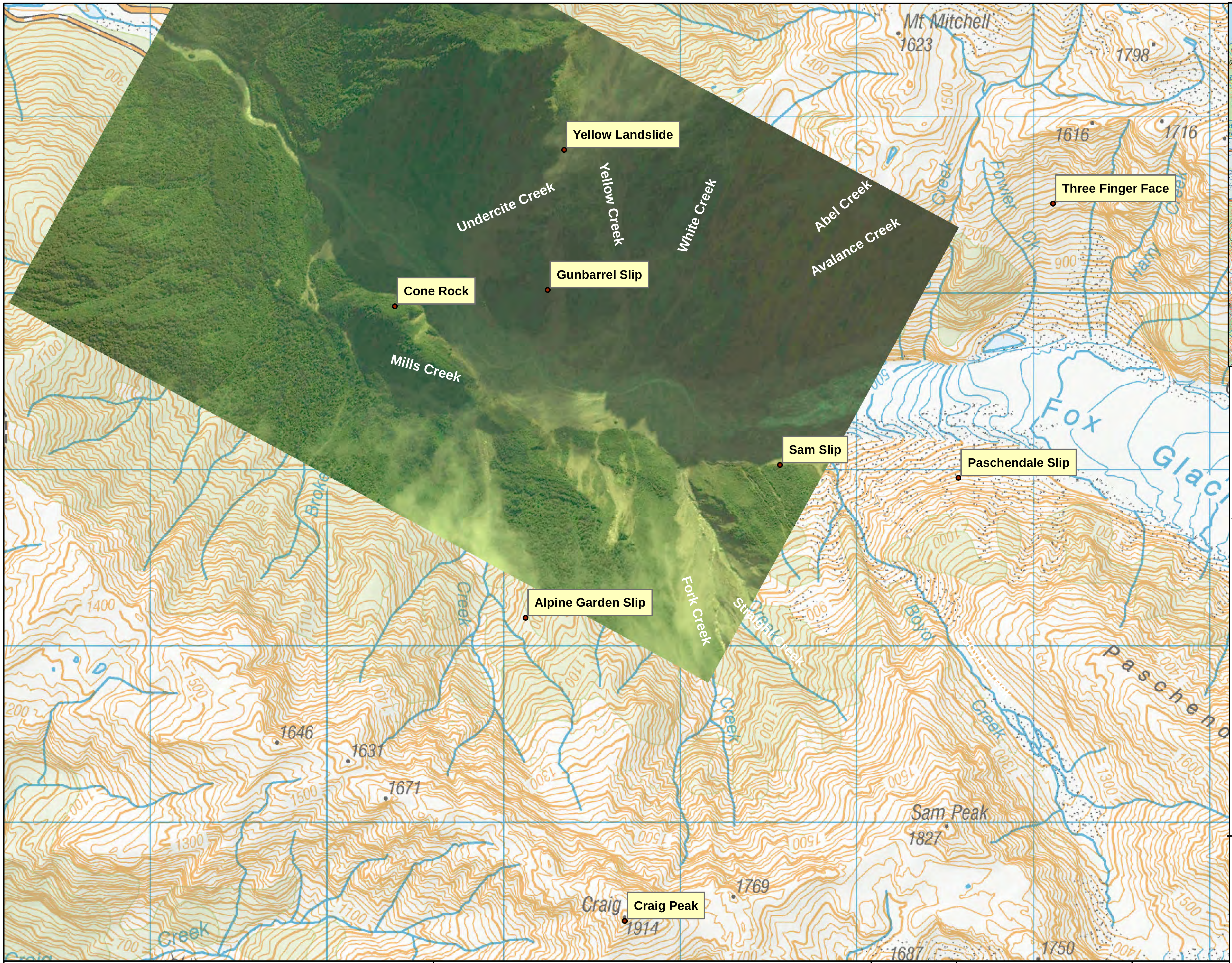

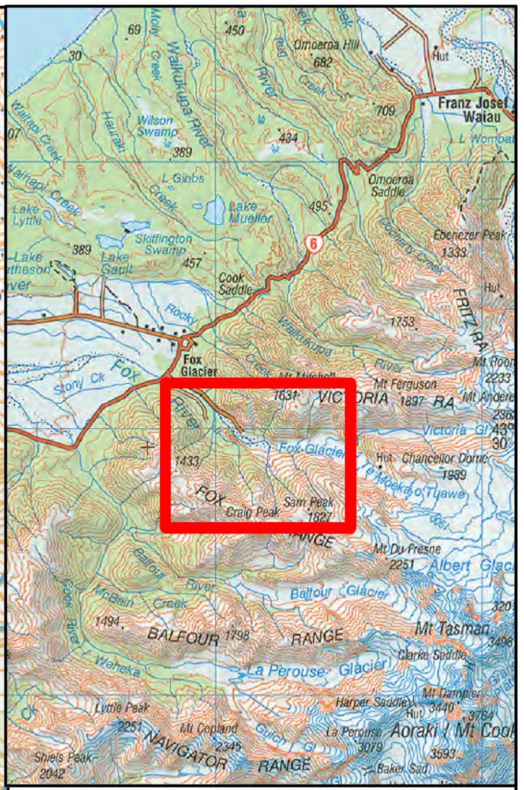

PROJECT	MAP TITLE		REV	DATE
Fox River Access Road	Plan B5	**Google Earth Imagery 13 April 2013**	**01**	**27 June 2019**
			A3 SCALE **1:20,000**	AUTHOR **Matthew Gardner**

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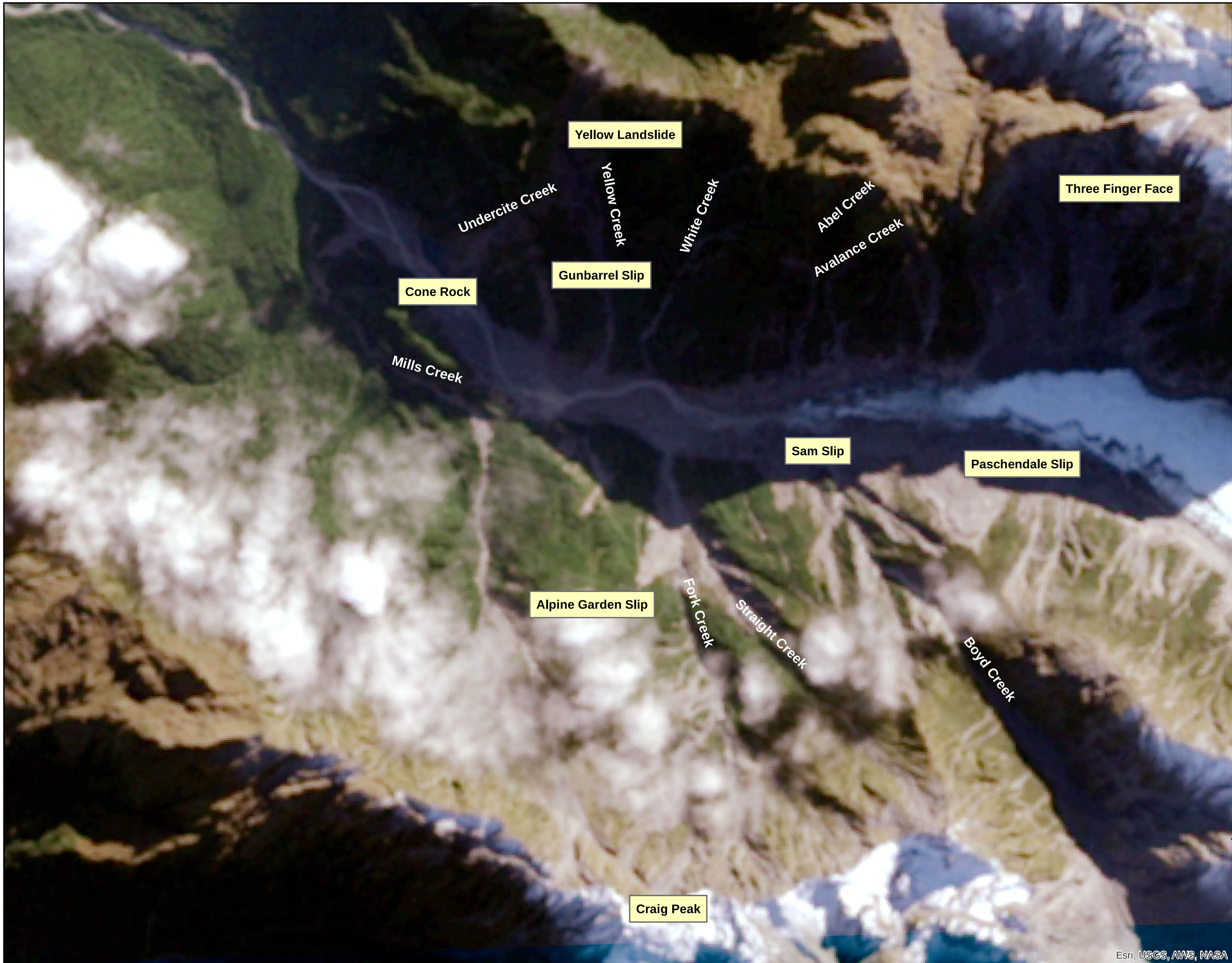

LANDRIVERSEA CONSULTING

PROJECT	MAP TITLE	REV	DATE
Fox River Access Road	Plan B6 — **Landsat8 Satellite Imagery 1/5/2015**	**01**	**27 June 2019**
		A3 SCALE **1:20,000**	AUTHOR **Matthew Gardner**

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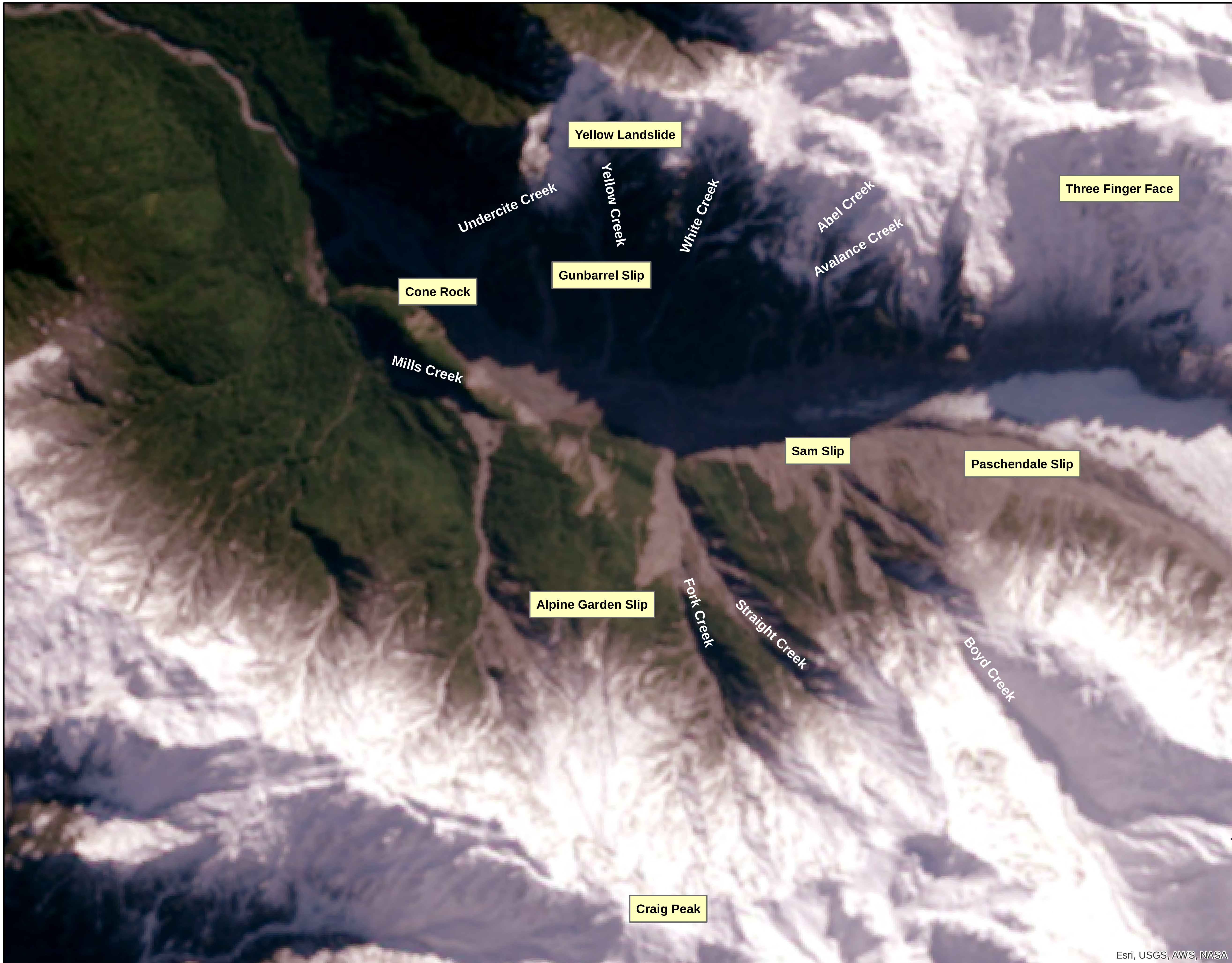

LANDRIVERSEA CONSULTING

PROJECT	MAP TITLE		REV	DATE	
Fox River Access Road	Plan B7	**Landsat8 Satellite Imagery 6/9/2015**	**01**	**27 June 2019**	N
			A3 SCALE **1:20,000**	AUTHOR **Matthew Gardner**	

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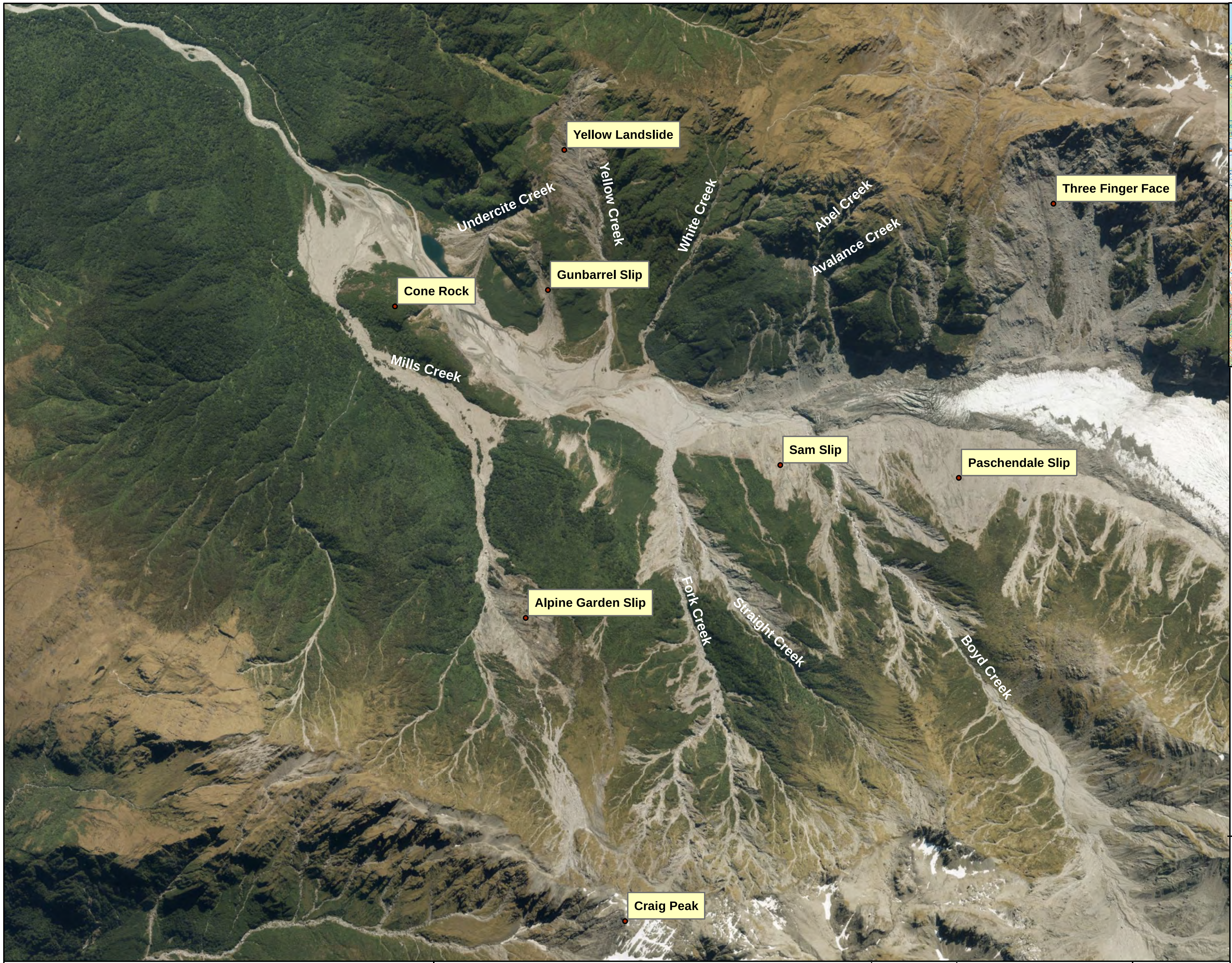
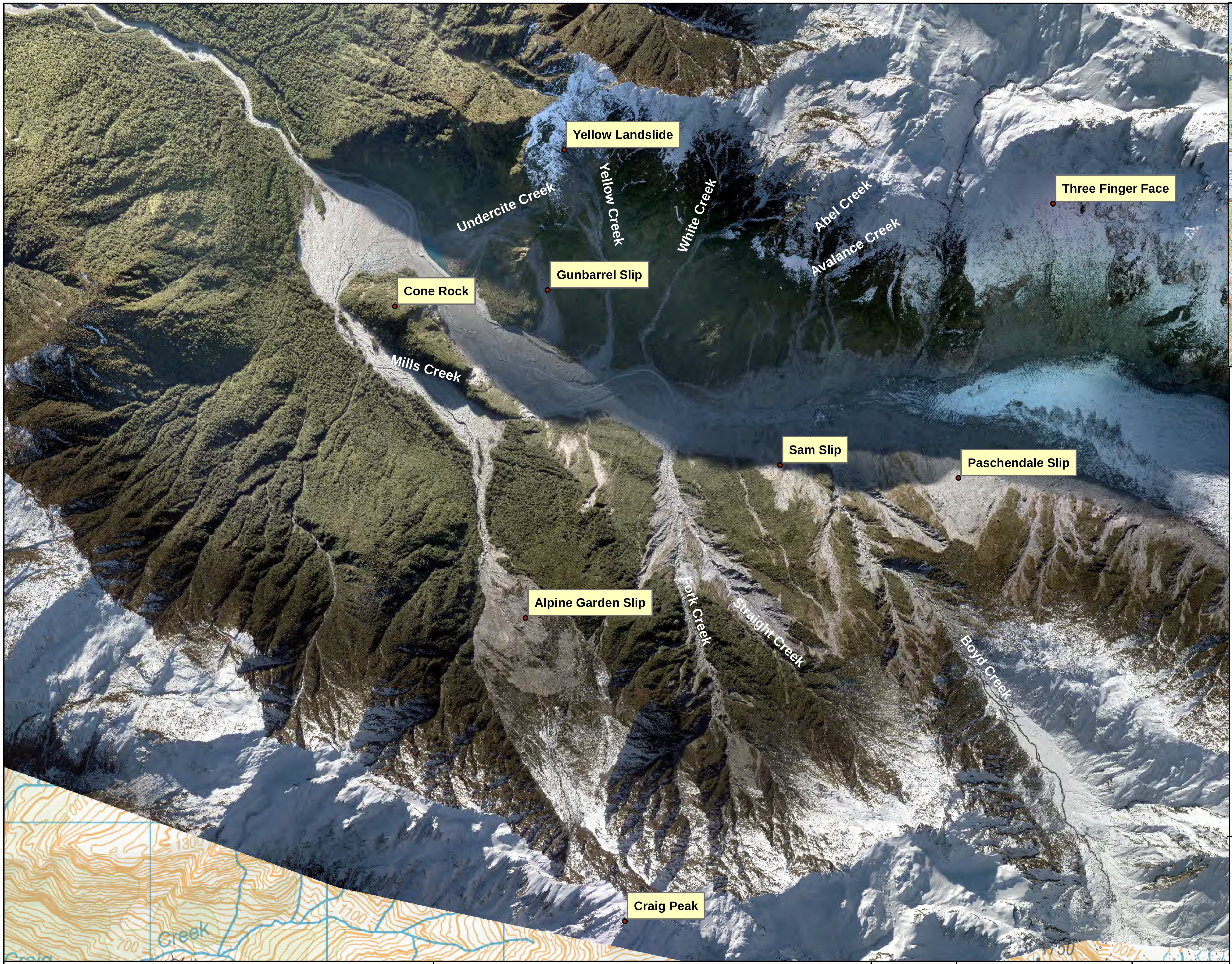
PROJECT	MAP TITLE	REV	DATE
Fox River Access Road	Plan B8 **Landsat8 Satellite Imagery 27/12/2015**	**01**	**27 June 2019**
		A3 SCALE **1:20,000**	AUTHOR **Matthew Gardner**

N



LANDRIVERSEA CONSULTING

PROJECT	MAP TITLE		REV	DATE	
Fox River Access Road	Plan B9	**Aerial Imagery Dec - March (2016-2017)**	**01**	**27 June 2019**	N
			A3 SCALE **1:20,000**	AUTHOR **Matthew Gardner**	



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Topo50 Series maps provided by Land Information NZ
2018 Aerial Imagery provided under license by GNS Ltd

PROJECT	MAP TITLE		REV	DATE	
Fox River Access Road	Plan B10	**Aerial Imagery 18/6/2018**	**01**	**27 June 2019**	N
			A3 SCALE **1:20,000**	AUTHOR **Matthew Gardner**	

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PROJECT **Fox River Access Road**	MAP TITLE Plan B11	**Sentinel 2B Satellite** **1 February 2019**	REV **01** A3 SCALE **1:20,000**	DATE **27 June 2019** AUTHOR **Matthew Gardner**

N

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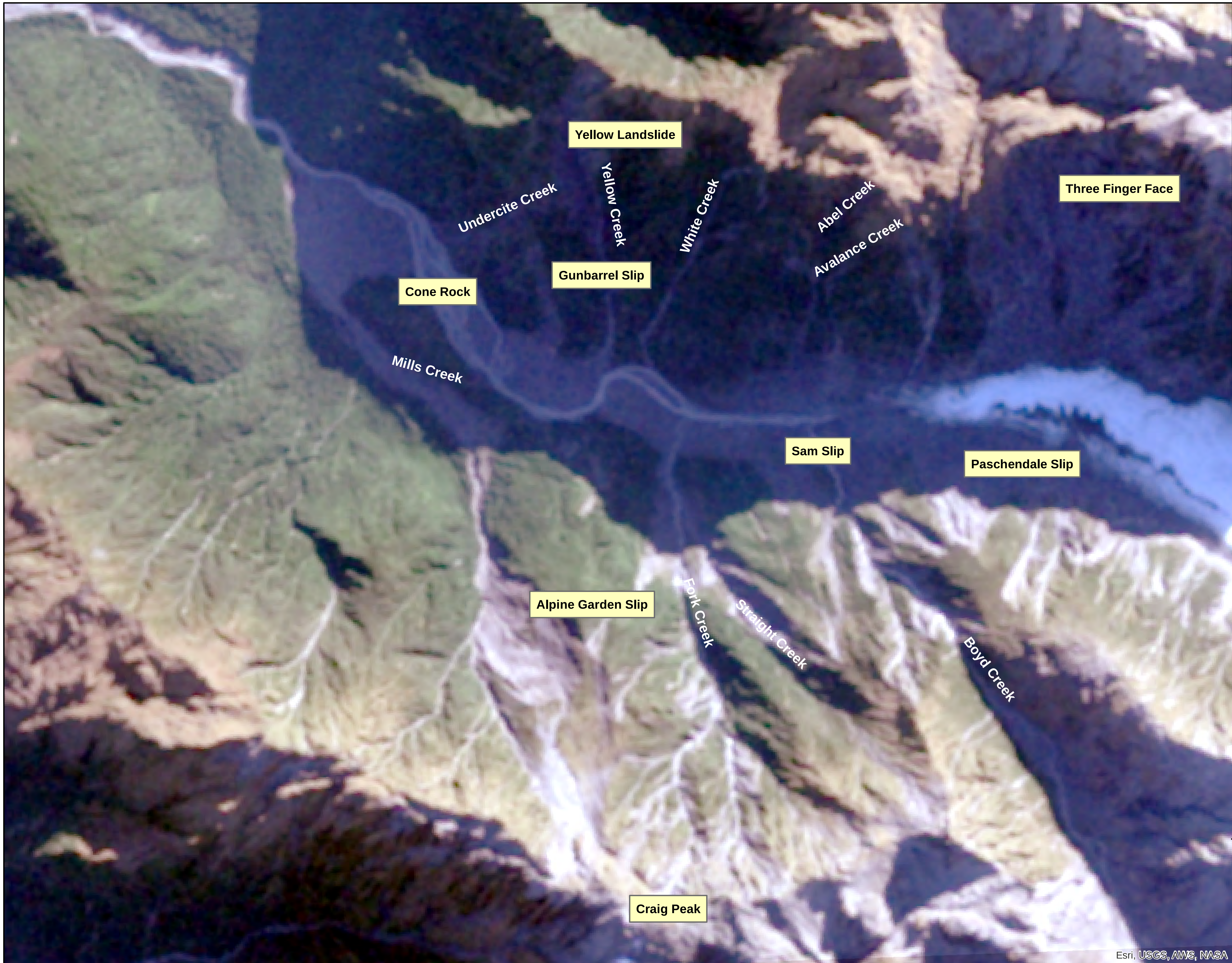
PROJECT	MAP TITLE	REV	DATE	
Fox River Access Road	**Sentinel 2B Satellite Imagery** Plan B12 **28/3/2019**	**01**	**27 June 2019**	N
		A3 SCALE **1:20,000**	AUTHOR **Matthew Gardner**	



LANDRIVERSEA CONSULTING

PROJECT	MAP TITLE	REV	DATE
Fox River Access Road	Plan B13 **Landsat8 Satellite Imagery 12/5/2019**	01	**27 June 2019**
		A3 SCALE **1:20,000**	AUTHOR **Matthew Gardner**

N

APPENDIX C - AERIAL IMAGERY (AREA OF THE ACCESS ROADS)

Sequence of repeat aerial imagery covering the valley access roads, from the State Highway to the Mills Creek fan, from the earliest imagery of 1953 to 2019.

PLAN C1 - 1953 (CONTACT PRINTS FROM WCRC)

North and south access roads to car parks.

Mills Creek fan area mostly covered by vegetation.

Fox River starts at Cone Rock, with a main low flow channel, but some channel splitting around islands.

PLAN C2 - 2006 (GOOGLE EARTH SATELLITE)

Mills Creek fan area is vegetated, with the Fox River having a relatively narrow channel, with a meandering main low flow channel.

PLAN C3 - 2018 LIDAR IMAGERY (FROM GNS)

Prior to the storms of 2019, showing the Fox River channel as not much different to that of 2006, but with the Active Mills Creek fan extending over the whole of the valley floor.

PLAN C4 – FEBRUARY 2019 - (SENTINEL 2B SATELLITE – 10M RESOLUTION)

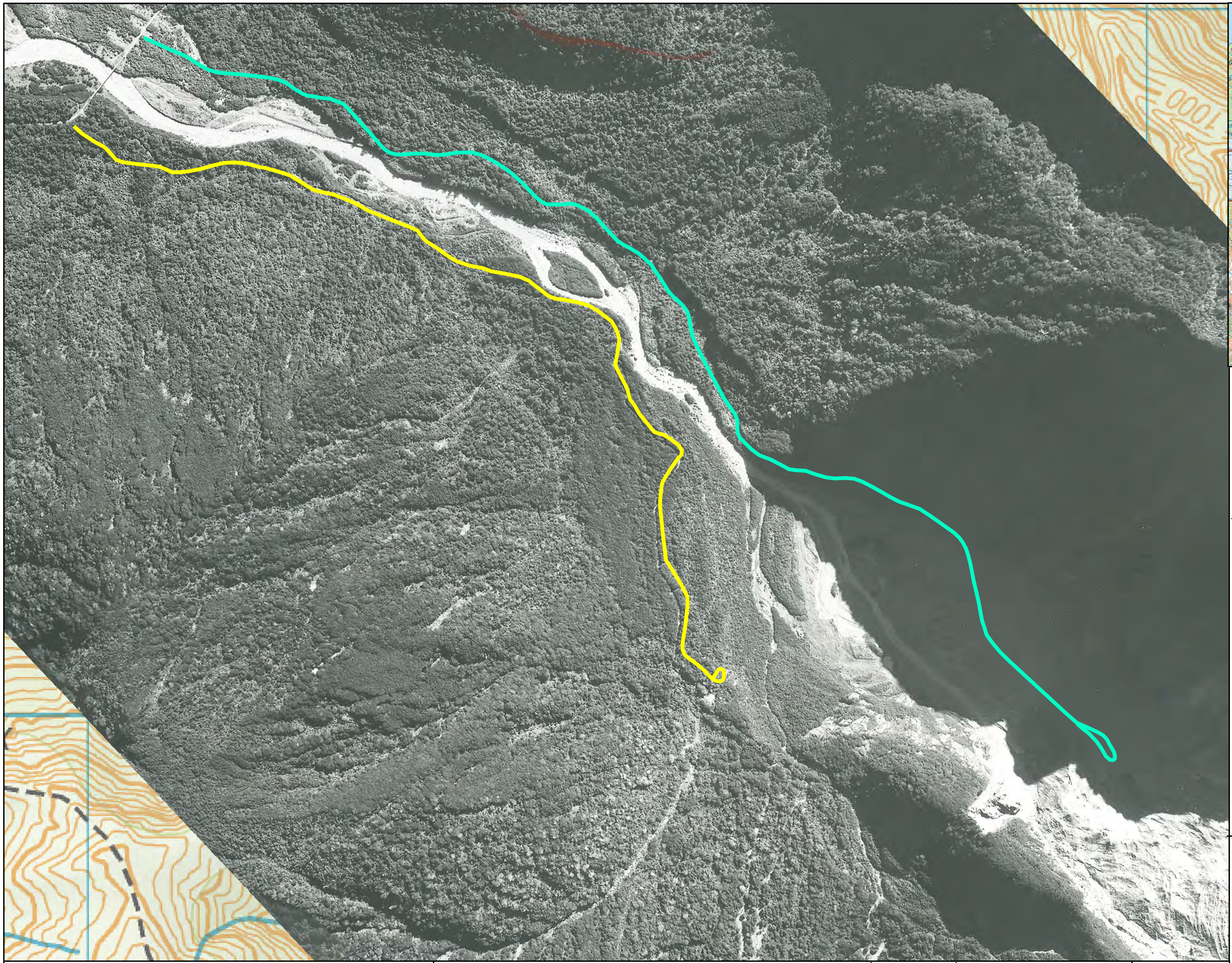
Prior to the March storm event, with the Fox River channel virtually the same as the 2018 imagery. There has been some enlargement of the Mills Creek fan on the downstream edge.

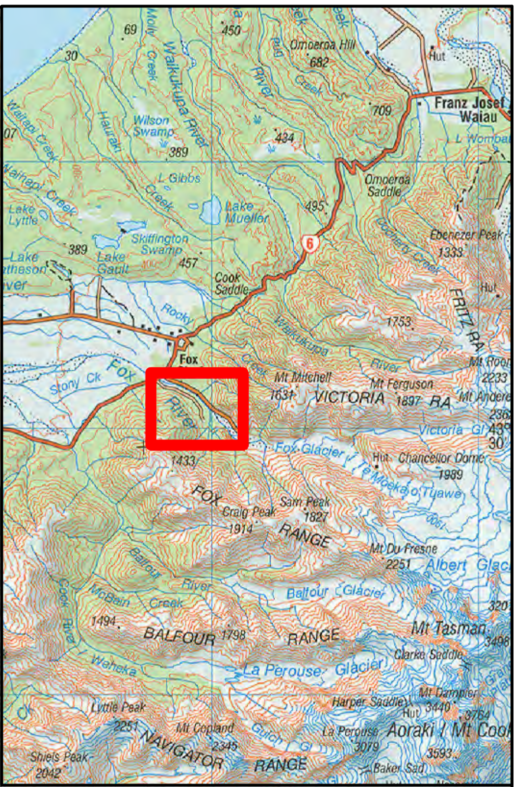
PLAN C5 – MARCH 2019 – (SENTINEL 2B SATELLITE – 10M RESOLUTION)

Shows the change in the Fox River from the storm event of March 2019. Note the increase in the active channel width. The extent of the Mills Creek fan is little changed.

PLAN C6 – MAY 2019 – (LANDSAT SATELLITE 15M RESOLUTION)

This imagery is lower quality than the previous image, however shows the river alignment more clearly upstream, showing the complete destruction of the access road.





LANDRIVERSEA CONSULTING

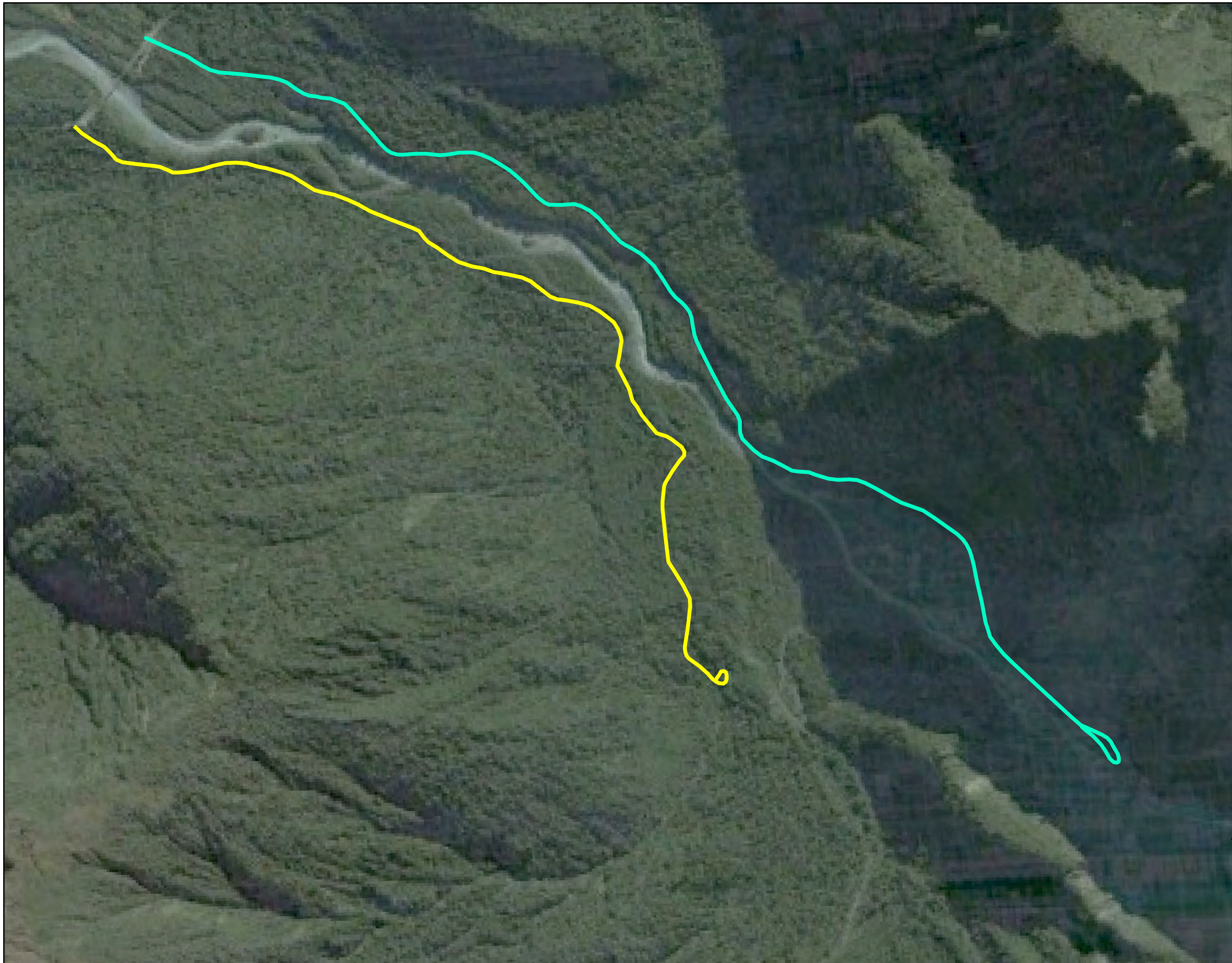
1953 Imaging provided by WCRC.
Images are not perfectly aligned.

Topo50 Series maps provided by Land Information NZ

Legend

- South Access Road
- North Access Road

PROJECT	MAP TITLE		REV	DATE	
Fox River Access Road	Plan C1	**North and South Access Roads** **3 April 1953 Imagery**	**01**	**28 June 2019**	N
			A3 SCALE **1:10,000**	AUTHOR **Matthew Gardner**	



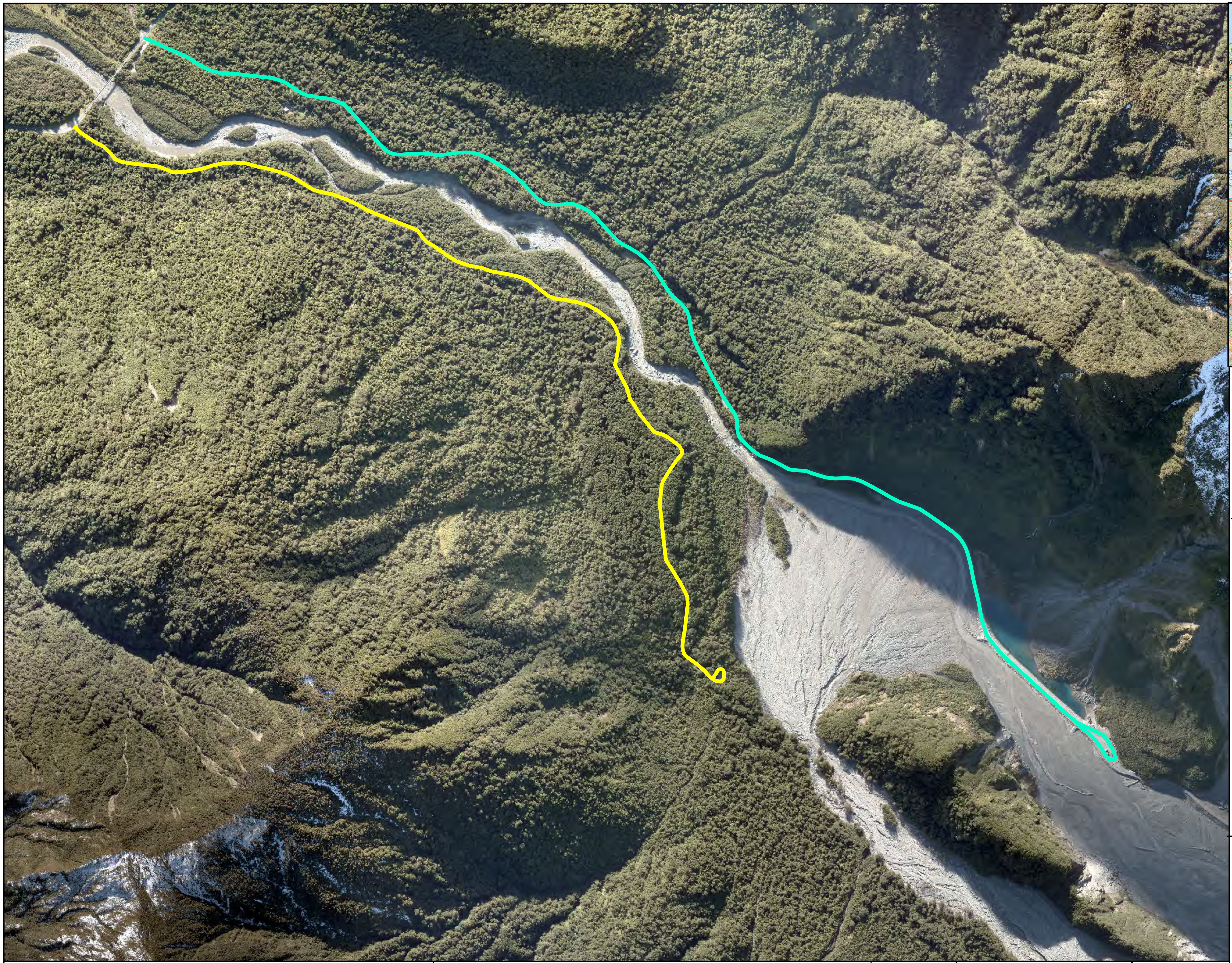
LANDRIVERSEA CONSULTING

Legend

- South Access Road
- North Access Road

PROJECT	MAP TITLE	REV	DATE
Fox River Access Road	**North and South Access Roads**	01	28 June 2019
	Plan C2 **Google Earth Imagery - 5 April 2006**	A3 SCALE	AUTHOR
		1:10,000	Matthew Gardner

N



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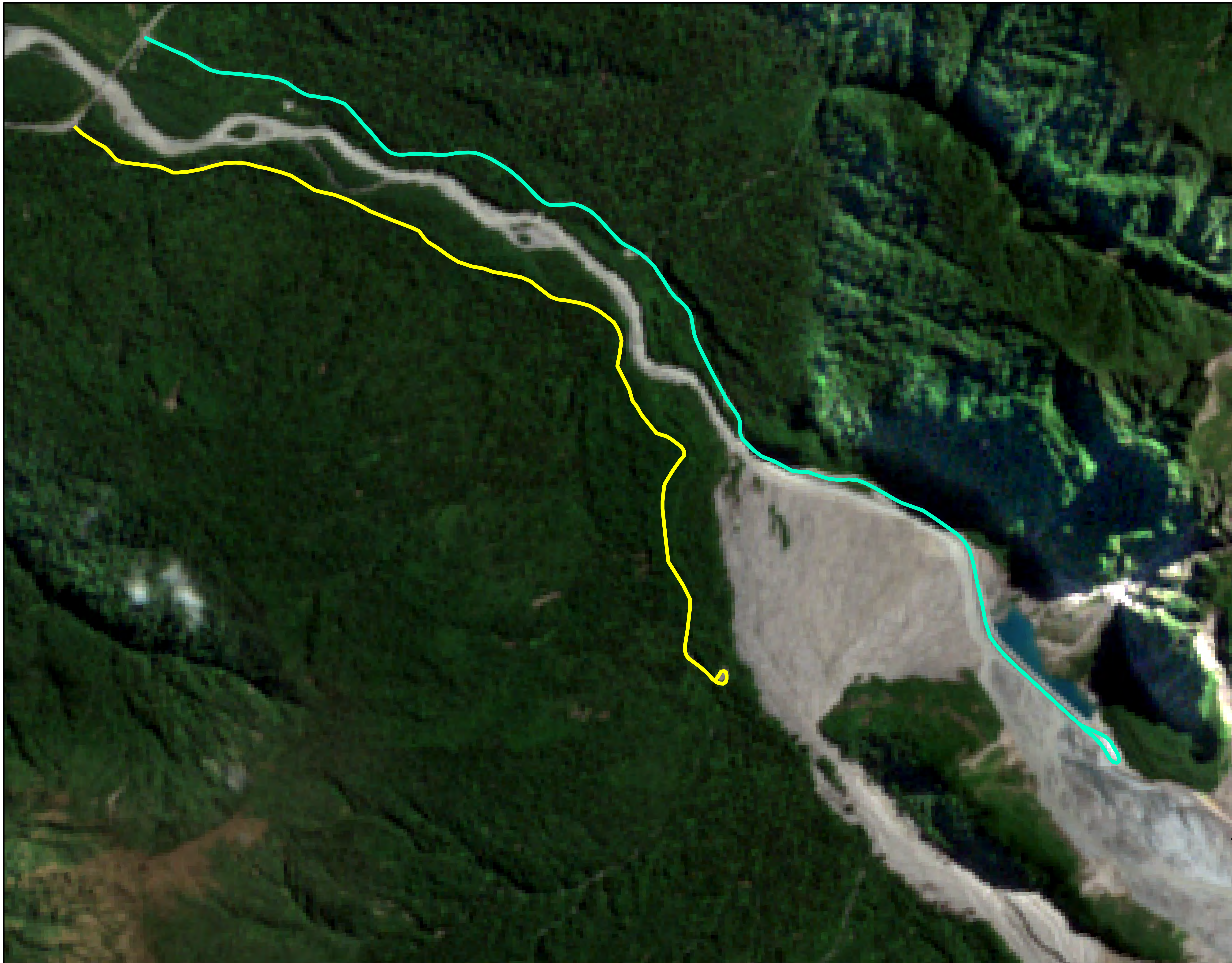
2018 Aerial Imagery provided under license by GNS Ltd

Legend

- South Access Road
- North Access Road

PROJECT	MAP TITLE	REV	DATE	
Fox River Access Road	Plan C3 **North and South Access Roads 18 June 2018 Imagery**	**01**	**28 June 2019**	N
		A3 SCALE **1:10,000**	AUTHOR **Matthew Gardner**	



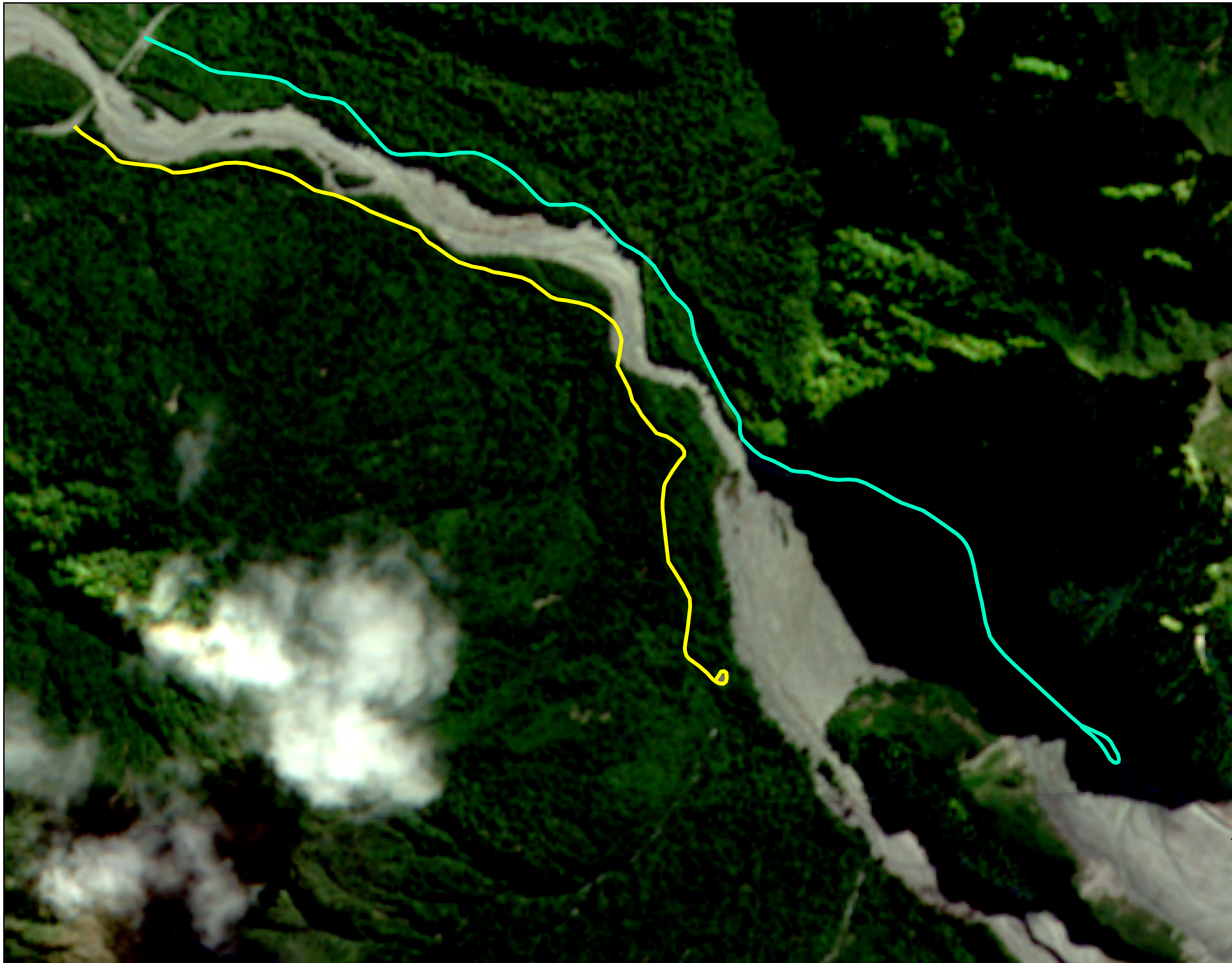
LANDRIVERSEA CONSULTING

Legend

- South Access Road
- North Access Road

PROJECT	MAP TITLE	REV	DATE
Fox River Access Road	Plan C4 — **North and South Access Roads 1 Feb 2019 Satellite Imagery**	01	28 June 2019
		A3 SCALE: 1:10,000	AUTHOR: Matthew Gardner

N



LANDRIVERSEA CONSULTING

Legend

- South Access Road
- North Access Road

PROJECT **Fox River Access Road**	MAP TITLE **North and South Access Roads** Plan C5 **28 March 2019 Satellite Imagery**	REV **01** A3 SCALE **1:10,000**	DATE **28 June 2019** AUTHOR **Matthew Gardner**

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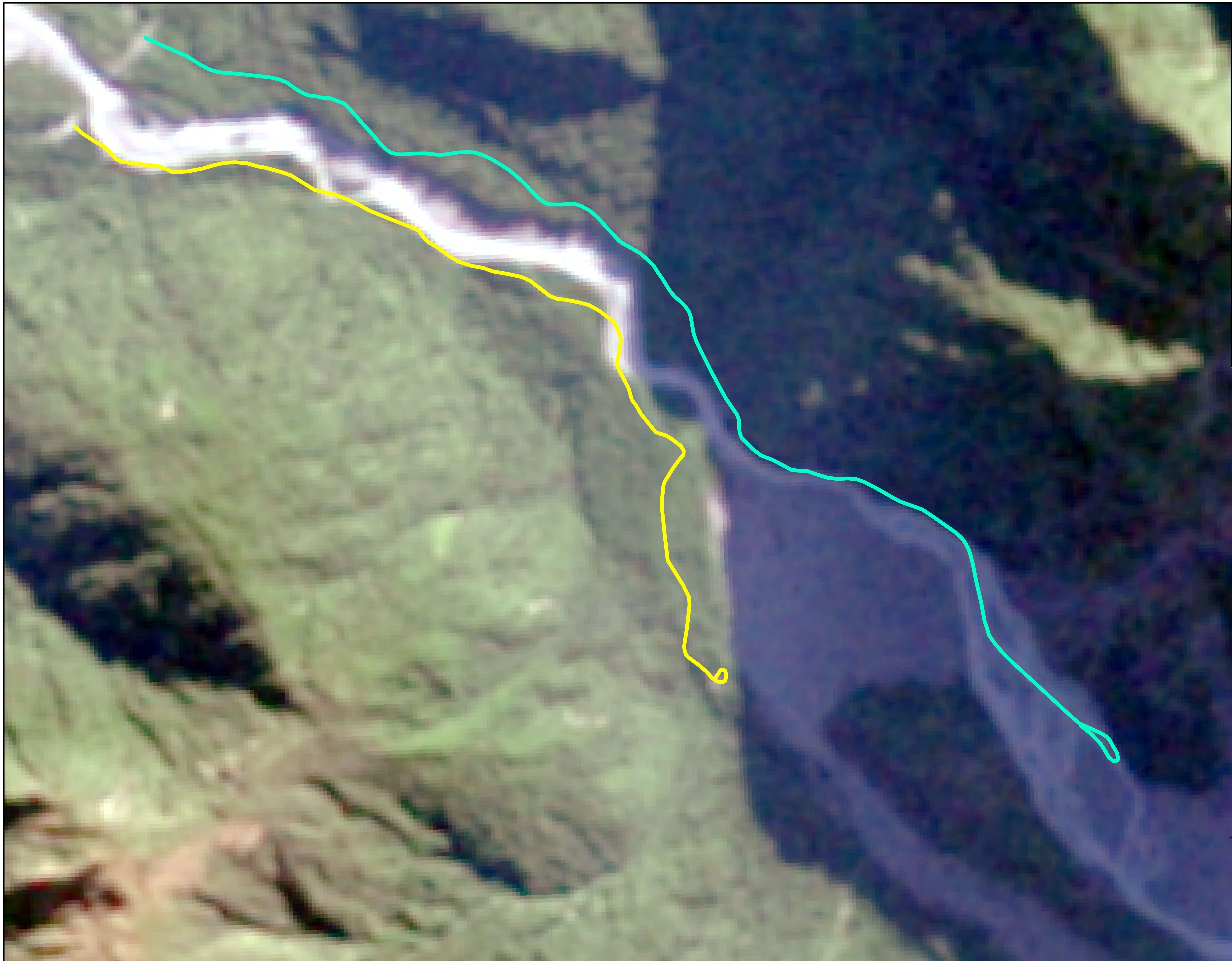


LANDRIVERSEA CONSULTING

Legend

- South Access Road
- North Access Road

PROJECT	MAP TITLE	REV	DATE
Fox River Access Road	**North and South Access Roads**	01	28 June 2019
	Plan C6 **12 May 2019 Satellite Imagery**	A3 SCALE 1:10,000	AUTHOR Matthew Gardner

N

APPENDIX D – CONTOUR MAP / COLOURED HILLSHADE

PLAN D1 – 5M AND 10M CONTOURS

LiDAR generated contour lines at 5 and 10 m intervals from 2018 survey.

Shows the height of the Mills Creek fan above the north Access Road, and the height of the top of the fan compared to the car park at the end of the south access. The top of the fan is now significantly higher than in 2018.

Also shows the steep mountainside on the north side of the valley and the bluff point (Right Bluff) that the road went around.

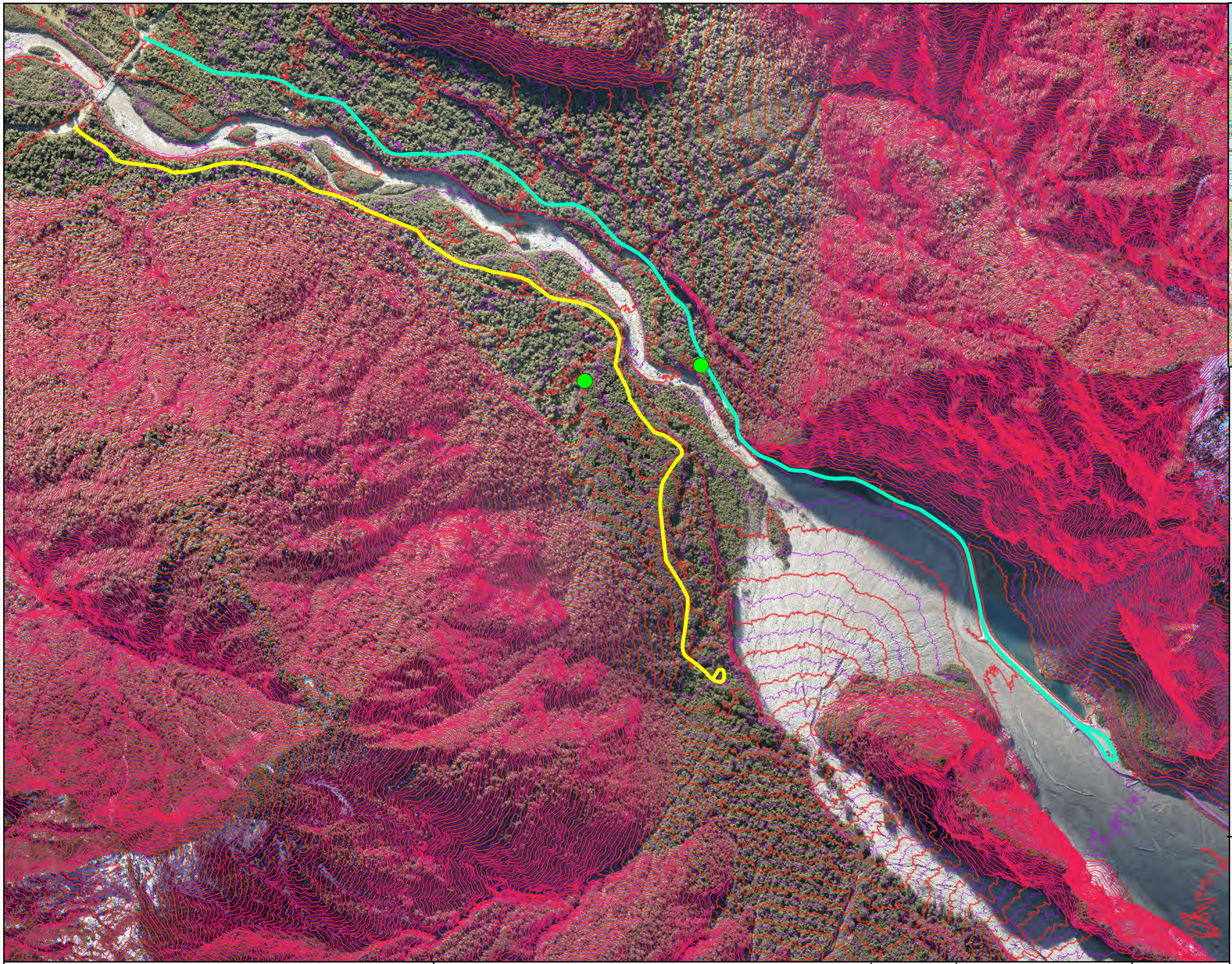
The position of the 1750 terminal moraine is indicated by the green dots.

PLAN D2 – COLOURED HILLSHADE (1:5000 SCALE)

Colour-shaded view of the topography, showing the upper part of the Mills Creek fan, and the aggrading channel area behind Cone Rock.

PLAN D3 – COLOURED HILLSHADE (1:10,000 SCALE)

Colour-shaded view of the same area as D1.



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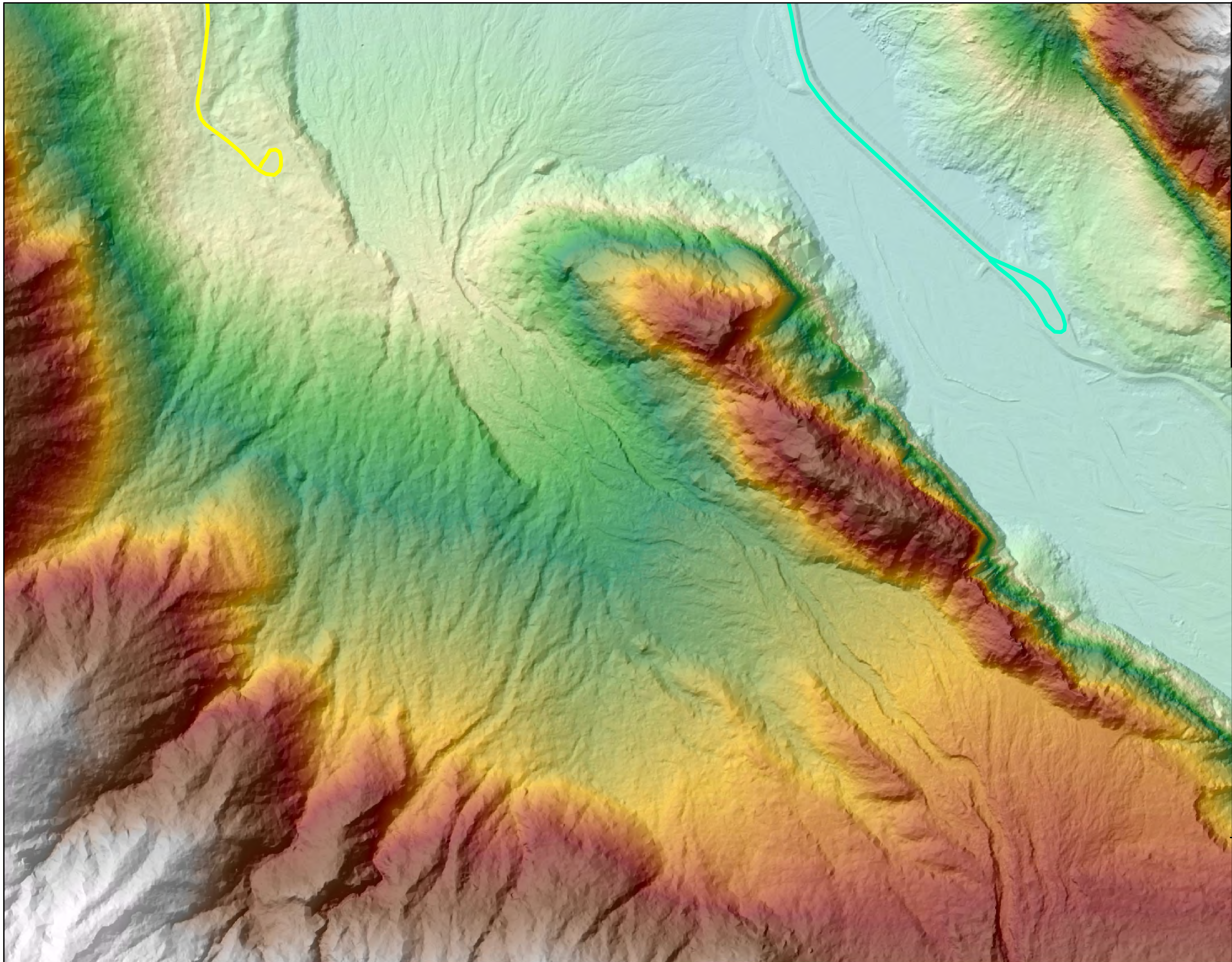
2018 DEM provided under license by GNS Ltd

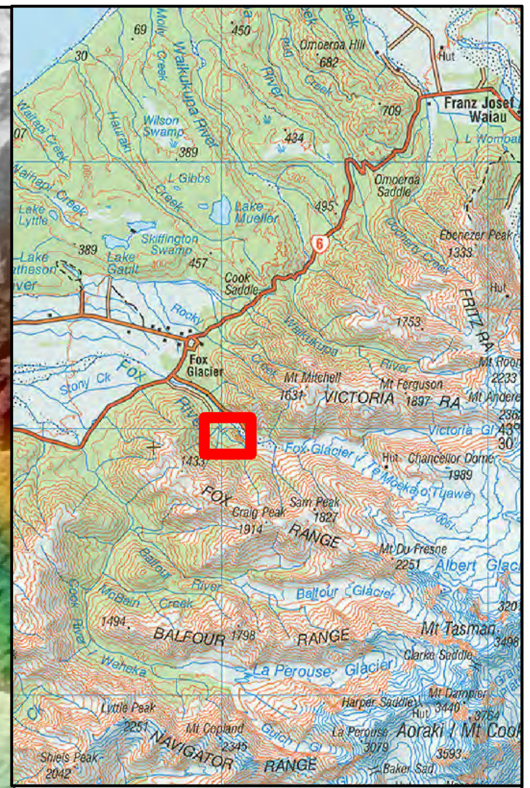
Legend

- Glacier Terminal 1750
- South Access Road
- North Access Road
- 10m Contours
- 5m Contours

PROJECT	MAP TITLE	REV	DATE
Fox River Access Road	**North and South Access Roads**	**01**	**28 June 2019**
	Plan D1 **5m Contours based on June 2018 LiDAR**	A3 SCALE **1:10,000**	AUTHOR **Matthew Gardner**

N





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2018 DEM provided under license by GNS Ltd

Legend

South Access Road

North Access Road

2018 Digital Elevation Model

High : 730 m

Low : 227 m

PROJECT **Fox River Access Road**	MAP TITLE **North and South Access Roads** Plan D2 **Coloured hillshade visualisation of LiDAR**	REV **01**	DATE **28 June 2019**
		A3 SCALE **1:5,000**	AUTHOR **Matthew Gardner**

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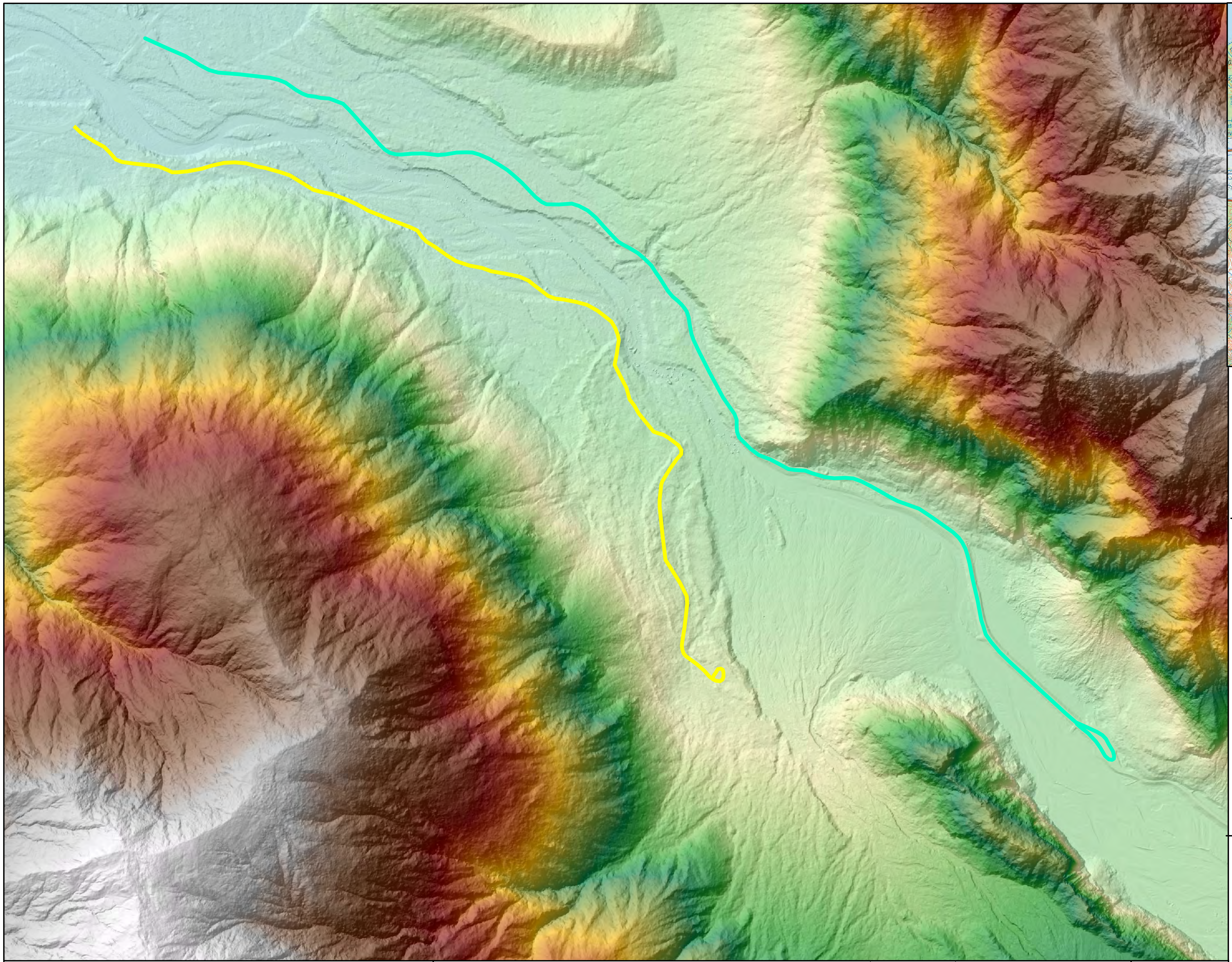

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Legend

- South Access Road
- North Access Road

2018 Digital Elevation Model

High : 1250 m

Low : 154 m

PROJECT	MAP TITLE	REV	DATE
Fox River Access Road	**North and South Access Roads**	**01**	**28 June 2019**
	Plan D3 **Coloured hillshade visualisation of LiDAR**	A3 SCALE **1:10,000**	AUTHOR **Matthew Gardner**

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