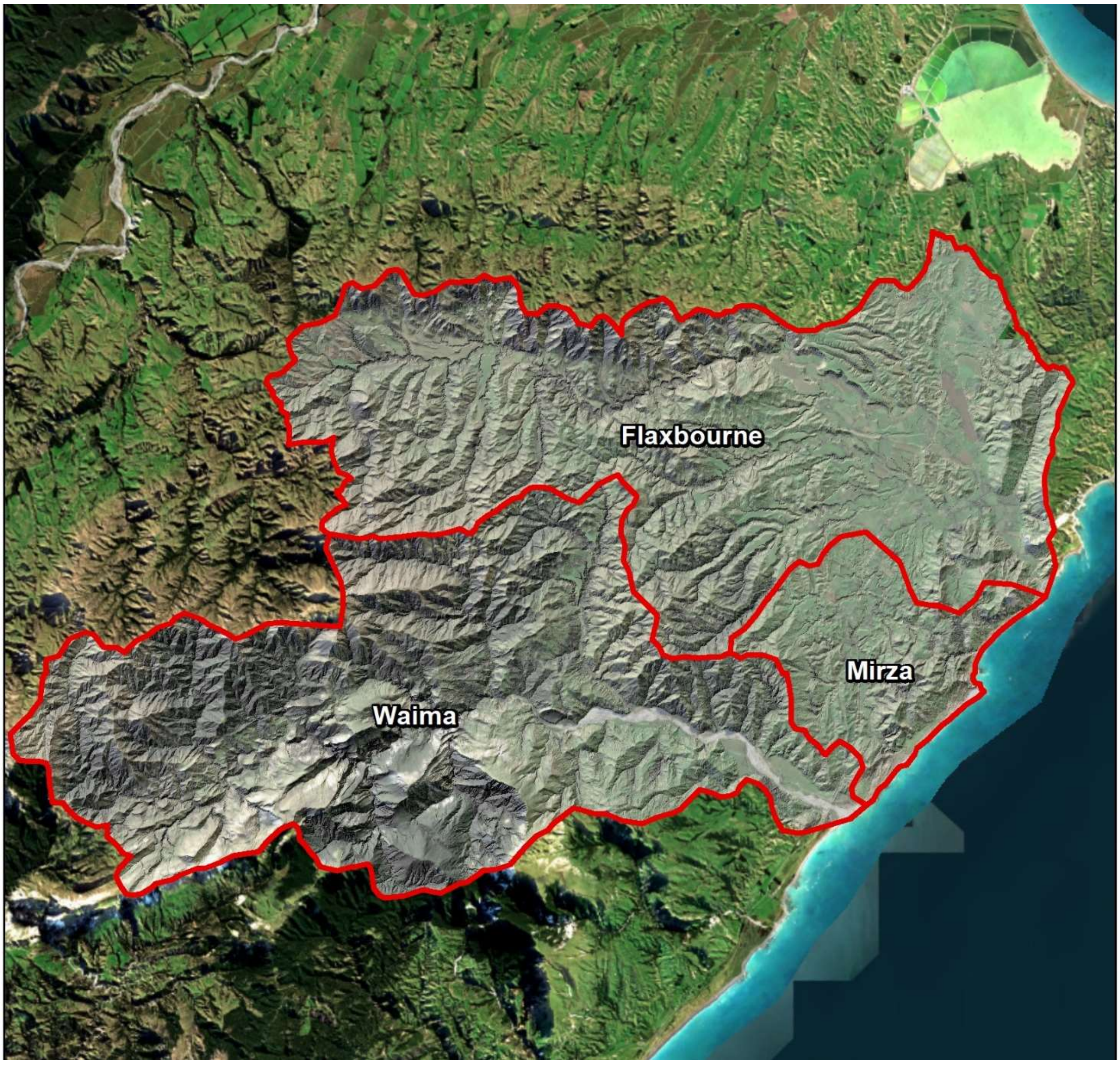
Terrain Analysis

Summary Report



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1 Introduction

WSP Opus is working with the Flaxbourne Settlers' Association, the Marlborough Research Centre, and Marlborough District Council (MDC) to identify the changes, and quantify the potential impacts, of the Kaikōura Earthquake on the water resources of the Flaxbourne, Mirza and Waima/Ure catchments.

A detailed review of all secondary information relating to the potential impacts of the Kaikōura Earthquake on the water resources of the Flaxbourne, Mirza and Waima/Ure catchments has previously been undertaken (WSP Opus, 2018). That review identified several potential risks to the water resources, and consequently to the community, within these catchments. To mitigate these risks, and support community resilience, recommendations for future work were provided. This included quantifying the changes in the local topography caused by the earthquake, and the impact of these changes on the rivers and water resources in the study area. This report presents the finding of that study.

2 Kaikōura Earthquake

The 14 November 2016 Mw 7.8 Kaikōura Earthquake occurred in the north-east of the South Island, at the boundary between the Australian and Pacific tectonic plates. It initiated near Waiau in North Canterbury at 12:03. Rupture propagated south–west to north–east and terminated offshore in Cook Strait. Surface rupture occurred on at least fourteen faults, including displacements of >10 m on the Kekerengu Fault (Clark *et al.*, 2017).

3 Methodology

There is only very limited LiDAR data available for the study area prior to the earthquake. This acts as a significant constraint on both the level and detail of analysis possible of landscape change, and its potential impacts on water resources. LiDAR data are available from two surveys following the Kaikōura Earthquake:

- Post-earthquake LiDAR data was captured within the weeks of the November 2016 earthquake. However, these data were of limited extent, and did not cover the whole of the Flaxbourne, Mirza and Waima/Ure catchments; and

- Further LiDAR data was captured approximately 18-months after the Kaikōura Earthquake, between May and July of 2018. This LiDAR was 'captured' as part of this project to ensure full coverage of the study catchments.

3.1 LiDAR

The various LiDAR data were used by MDC to derive Digital Elevation Models (DEM). Three DEMs were subsequently provided; two based on the post-earthquake LiDAR, and one from LiDAR 'captured' in 2008 i.e. pre-earthquake.

LiDAR data covering the lower ends of each catchment was 'captured' during a survey of SH1, the rail line, and associated infrastructure immediately following the earthquake (i.e. 2016 DEM). The DEM derived from these data was then meshed with that derived from more recent LiDAR data 'captured' in 2018 (i.e. 2018 DEM).

The 2018 DEM provided by MDC is based on LiDAR data 'captured' by AAM(NZ) Ltd from 26th May to 29th of July 2018. This data has a vertical accuracy of ±0.1m.

Both post-earthquake LiDAR surveys had the houses and vegetation removed from the topographic data, are in NZVD2016 datum, and the DEMs have a 1m cell size. Little manipulation was therefore needed when meshing the various DEMs.

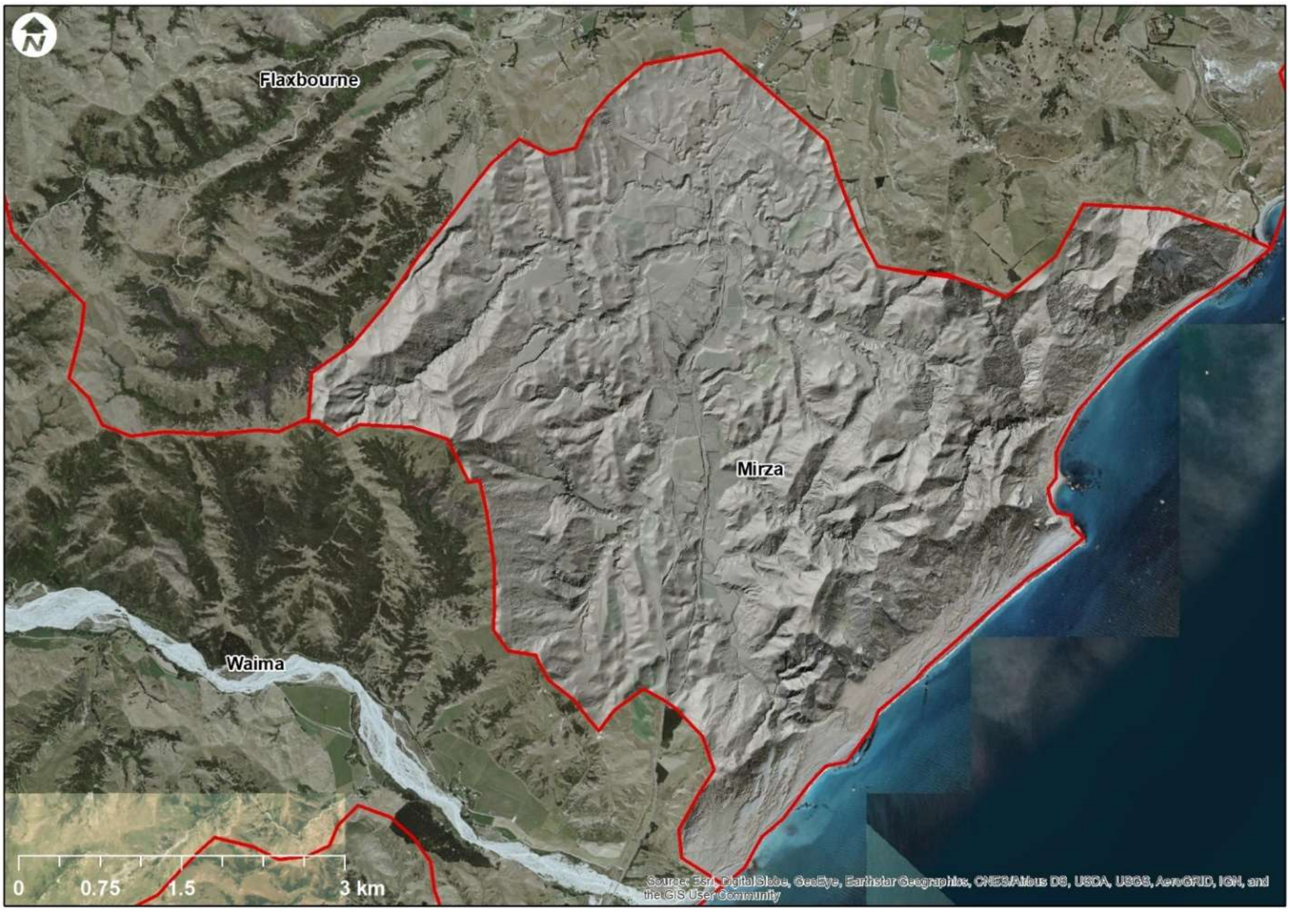
The final DEM available is of a small (i.e. 3.5km^2) area at the mouth of the Waima/Ure River. This DEM is based on LiDAR data 'captured' in 2008. This DEM has a 0.5m cell size and is in the Lyttelton 1937 datum. When converted to the NZVD2016 datum, this DEM shows some areas of where there have been significant apparent changes to the topography i.e. apparent vertical and horizontal shifts in the landscape because of the Kaikōura Earthquake. This is further discussed is section 3.3.1.

As this DEM covers such a small area, and the process of its generation unknown, there is some uncertainty inherent in its use for detailed analysis of topographic changes.

3.2 DEMs

The DEMs derived from the post-earthquake LiDAR, and used in the analysis of topographic changes and their potential impact on the water resources of the Flaxbourne, Mirza and Waima/Ure catchments, are shown in Figure 3.1 through Figure 3.3.

These DEMs will be used in future stages of this study to investigate the impact of the Kaikōura Earthquake and the flood hazard, channel stability, and sediment transport.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 3.1: Mirza catchment DEM based on post-Kaikōura Earthquake LiDAR.

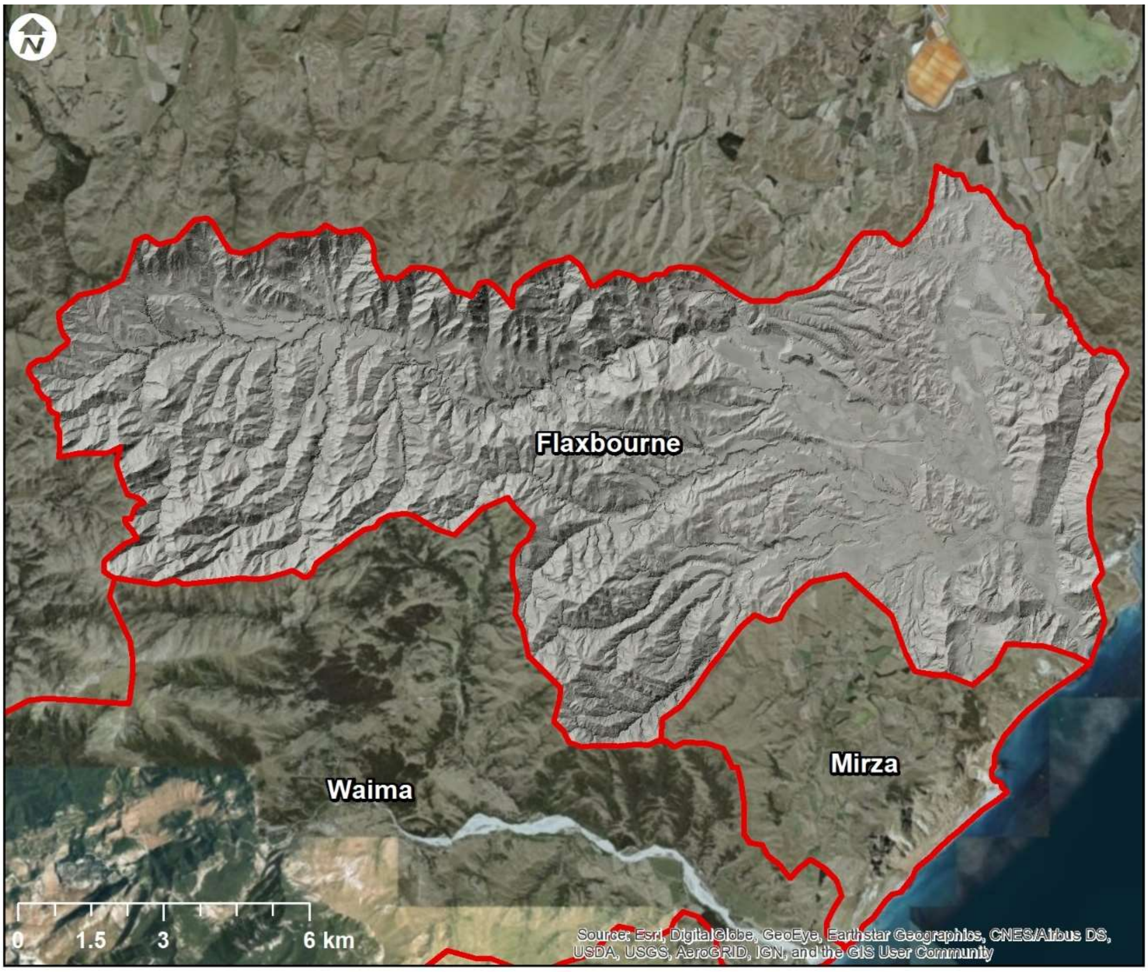


Figure 3.2: Flaxbourne catchment DEM based on post-Kaikōura Earthquake LiDAR.

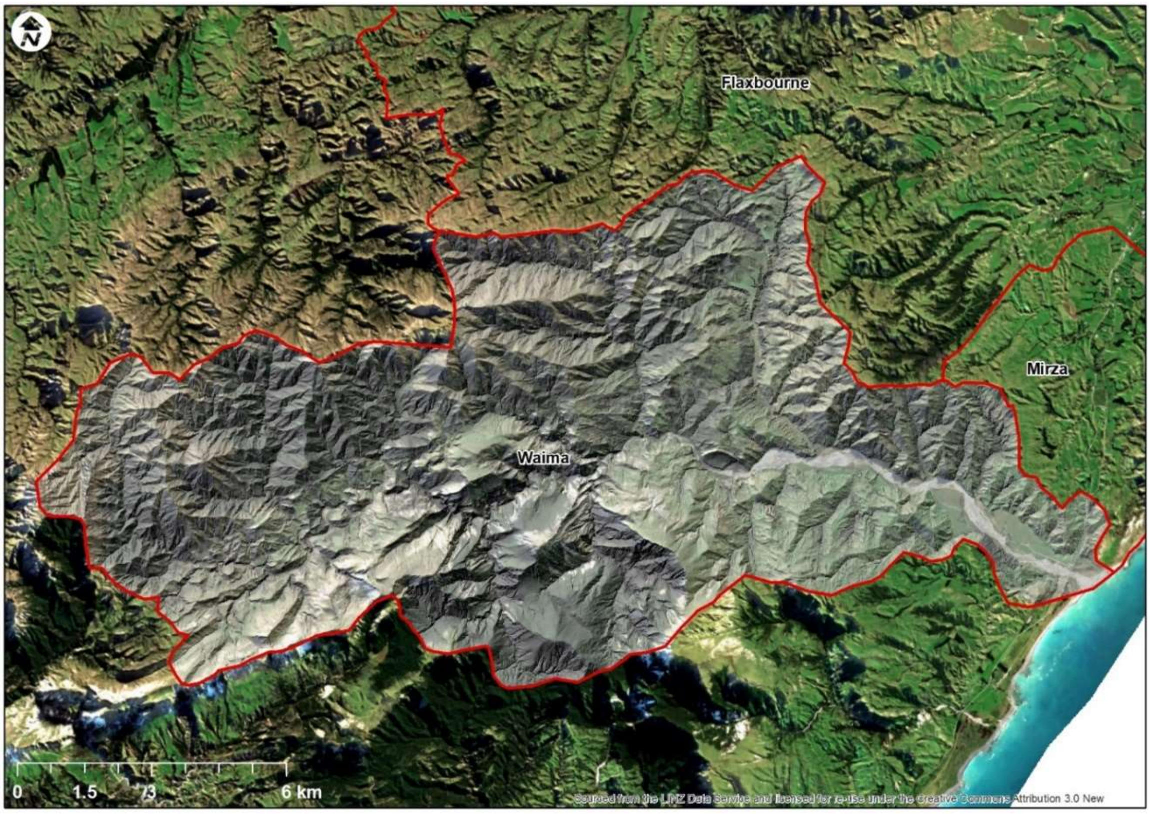


Figure 3.3: Waima/Ure catchment DEM based on post-Kaikōura Earthquake LiDAR.

3.3 Comparative analysis

Because of the limited availability of pre-earthquake LiDAR, vertical deformation across the study area had to be estimated from the differences in the elevations of pre-earthquake geodetic benchmarks and the elevations of these same points in the post-earthquake LiDAR.

There were no significant earthquakes in the study area between the most recent measurement of the geodetic benchmarks and the Kaikōura Earthquake. The Cook Strait sequence of earthquakes included the largest regional events over this period (Mw5.7, 5.8 and 6.6); however, these earthquakes produced <5mm of vertical deformation in the Kaikōura region (Clark *et al.*, 2017). No significant earthquakes have occurred in the study area since the Kaikōura Earthquake.

The geodetic benchmarks used in this study were obtained through the LINZ geodetic database. Marks were chosen within the study area with a height order of 6 or below. Orders are based on the quality of the coordinate in relation to the datum, and to other surrounding marks (LINZ, n.d.). Orders 0-8 are survey accurate, with accuracy decreasing with increasing order. Only benchmarks with orders from 0-6 were used to keep the margin of error low, and to ensure the accuracy and reliability of the heights of the benchmarks used in the analysis.

3.3.1 DEM comparison between 2008 and 2016 data

The DEM derived from pre-earthquake LiDAR (flown in 2008) did not align spatially with the post–earthquake DEM (flown in 2016-2018). Since both DEMs are in the same datum and reference system, the apparent displacement is likely to be largely the result of the Kaikōura Earthquake.

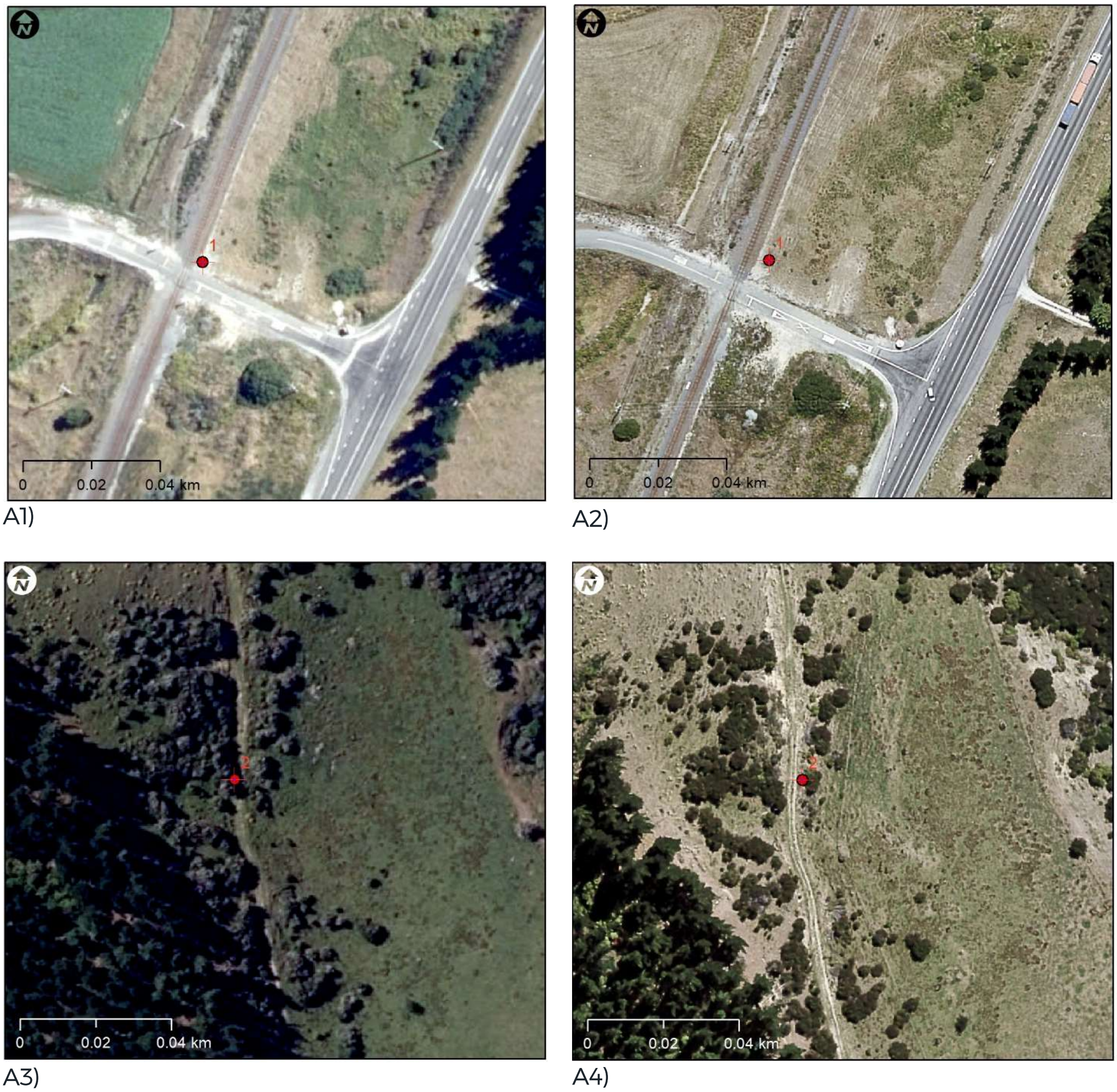
To assess the vertical displacement between the two surveys, the pre-earthquake DEM was laterally shifted to best match known points within the 2016 survey. The DEM was only shifted at two points where the location could be accurately defined; the railway crossing near the mouth of the Waima/Ure River, and another approximately 4km upstream.

At the railway crossing, the pre-earthquake DEM had to be shifted ~5m north and ~4m east to align for the post-earthquake DEM (Figure 3.4, A1 & A2). After this initial shift to the north east, the second point (within the upper catchment) had to be shifted back to the west by ~2m. This resulted in the DEM being effectively rotated about the first point.

These translations to align the DEMs is indicate that, within the upper catchment, the lateral shift was of the order of ~5m north and ~2m east (Figure 3.4, A3 & A4). Following these translations, landmarks such as roads, the railway, and major ridge lines aligned between the two DEMs.

After the DEMs were aligned, a 'difference' raster was created, by subtracting the pre- and post-earthquake DEMs, to identify changes in elevation between the 2008 and 2016 surveys (Figure 3.5). Areas represented by negative values indicate subsidence and a reduced elevation because of the earthquake, while a positive difference indicates uplift and increased elevation.

Because of the limited availability of LiDAR data, and therefore high-resolution pre-earthquake DEMs, this analysis could only be completed for the Waima/Ure catchment. For this analysis, high-resolution topographic data has a vertical accuracy of ±10cm and a horizontal accuracy of <1m.



A1) A2) A3) A4)

Figure 3.4: Locations of 'shift points' used to align the 2008 and 2016 DEMs.

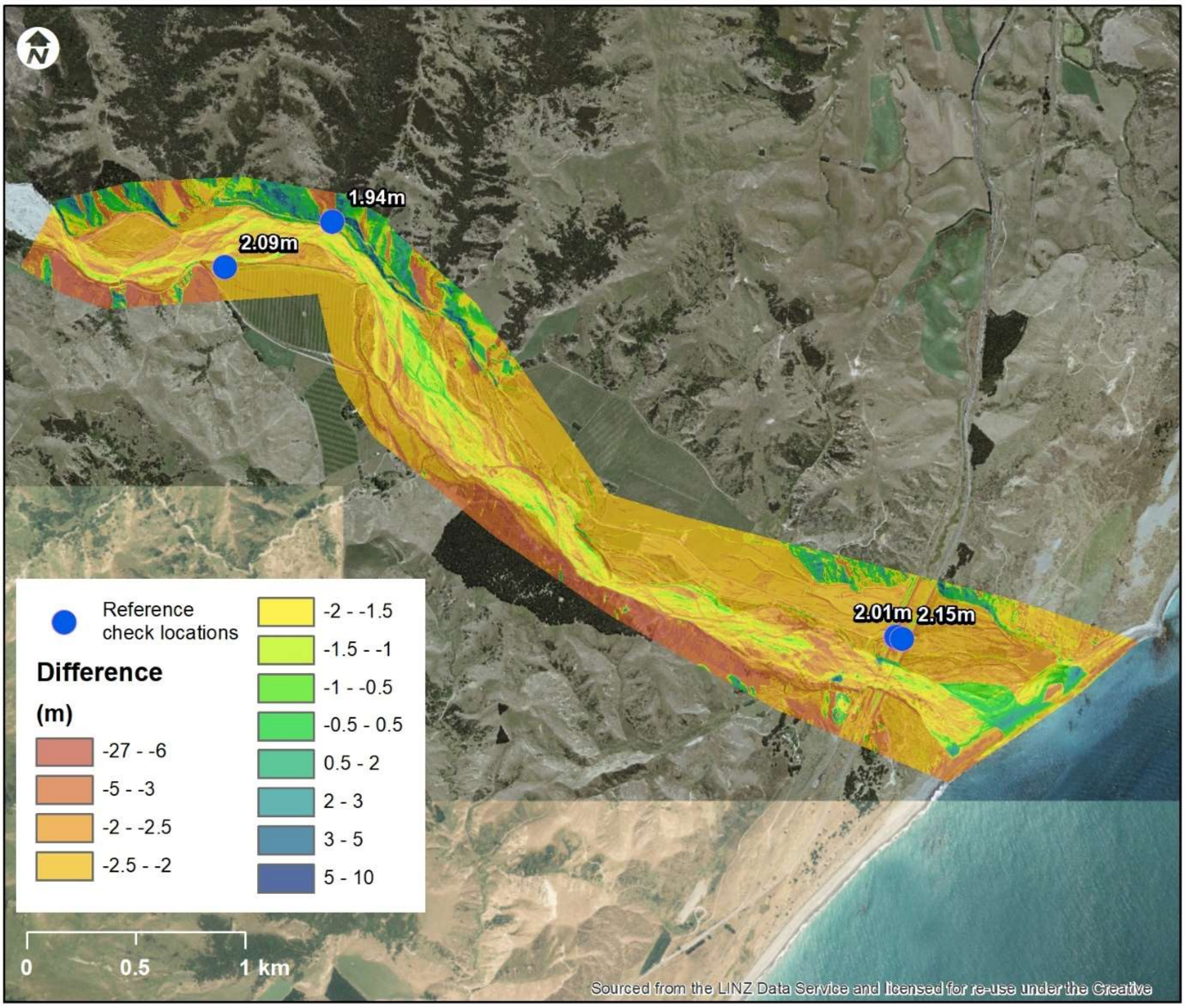


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Figure 3.5: Differences of topographic elevation between the 2008 and 2016 DEMs.

The changes in elevation for various points within the Waima/Ure catchment vary between -27 – 16m. The largest differences are within the hilly terrain bordering the Waima valley. This is because any lateral shift also affects the apparent change in elevation, which is then added to any actual change in height. These more extreme differences (of both subsidence and uplift) are therefore likely attributed to the differential lateral movement of the landscape during the earthquake.

While lateral movement occurred on a regional scale, the degree of movement is likely to have varied across the catchment. Consequently, the alignment of the pre- and post-earthquake DEMs, based on only two points, may not be accurate across the whole DEM. Where there are more extreme apparent changes in elevation (i.e. between ridge lines and gullies) any slight lateral offset in alignment will cause significant apparent vertical change.

On flatter and more event terrain, such as the valley floor and river channel, any relatively small lateral offset will not cause large apparent changes in elevation. This is shown in Figure 3.5 where the vertical elevation change within the river channel is consistently of the order of 0.5 – 2.5m.

While the variation in elevation shown in the two DEMs could be caused by 'noise' or vegetation effects this is considered unlikely. There is no evidence of extensive vegetation clearance, and any vegetation growth over 8-years would not cause the differences identified. Furthermore, various algorithms are used when processing the LiDAR signal to remove any vegetation effects.

4 Topography Changes

4.1 Regional deformation trends

Extensive geodetic change occurred across the northern Canterbury and Marlborough regions during the Kaikōura Earthquake (Figure 4.1).

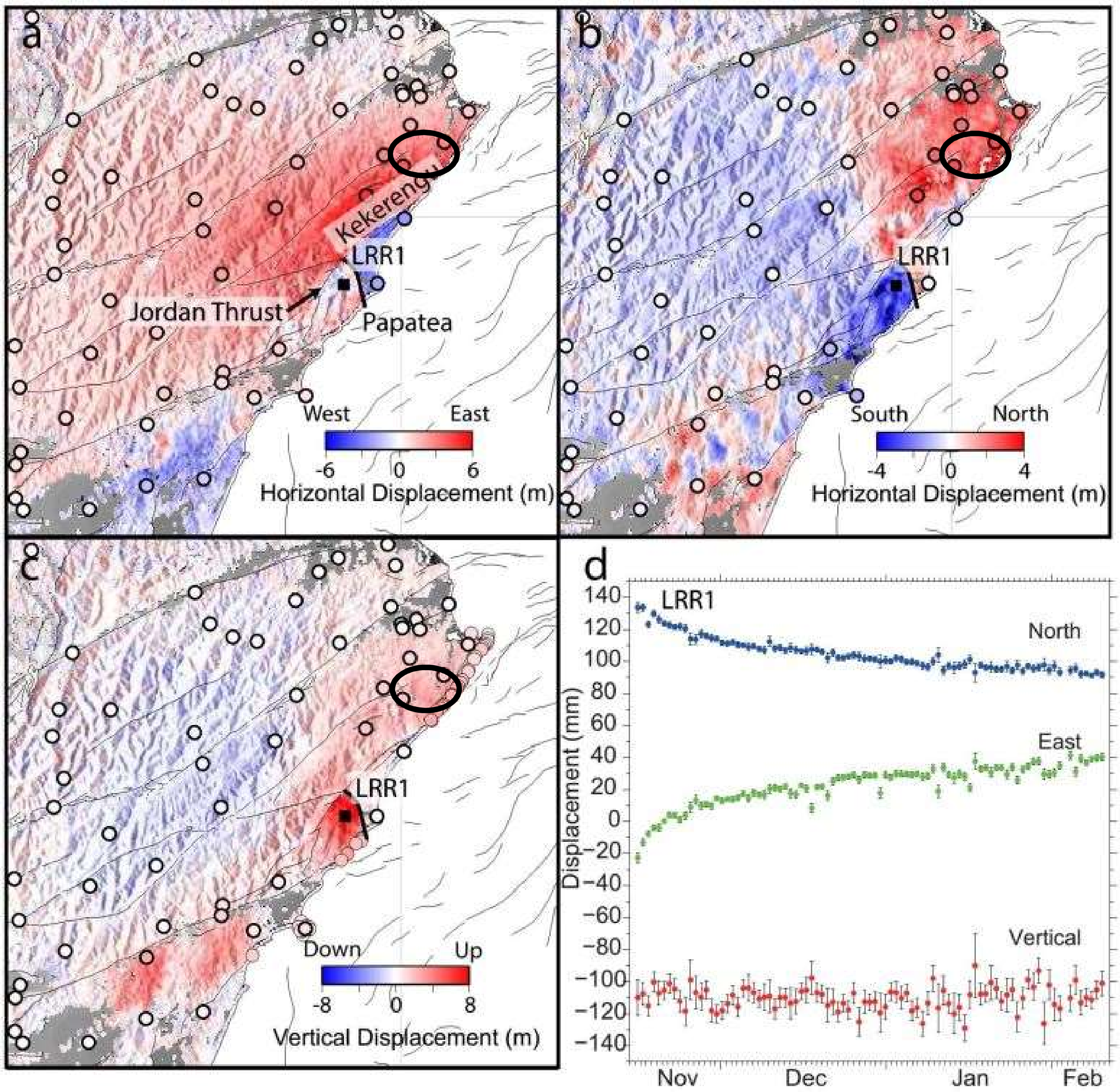


Figure 4.1: 3D displacement from the Kaikōura Earthquake with study area circled (a) east-west horizontal displacements (b) north-south displacements (c) vertical displacements and (d) post-seismic displacement time series fom semi-continuous GPS installed south-west of the Papatea Fault (Hamling et al.*, 2016).*

Much of land north of Kaikōura was shifted laterally to the east, except for a localised area north-east of the Papatea Fault. North-east of the Papatea Fault the coastal areas have also been displaced laterally to the north. South-west of the fault and inland have displaced to the south (Figure 4.1 a&b).

Coastal uplift was one of the more apparent impacts of the Kaikōura Earthquake. The stretch of coastline between the Conway River and Cape Campbell (the Kaikōura coastline) experienced varying degrees of uplift along its 170km length. The largest vertical deformation occurred between strands of the Papatea Fault, where uplift of 6.6±0.5m was identified (Figure 4.2).

The nearest known fault that ruptured near the study catchments is the offshore Needles Fault (Figure 4.3). The Needles Fault is the offshore continuation of the Kekerengu Fault, which is expressed on land approximately 8km south of the Waima/Ure River mouth. The Kekerengu Fault experienced significant dextral (i.e. right lateral) displacement of >10m, as well as localised subsidence of up to 2.5m over a width of 200-400m on both sides of the fault (Figure 4.2). However, this trend is not continuous to the north along the Needles Fault.

The Needles Fault experienced both dextral and vertical displacement, which resulted in coastal uplift of 2-3m. At the Waima/Ure River mouth, the peak coastal uplift for this section was 2.9m. North of the river mouth, there is a north-eastward decrease in coastal uplift. Uplift at Cape Campbell was 0.4m (Clark *et al.*, 2017).

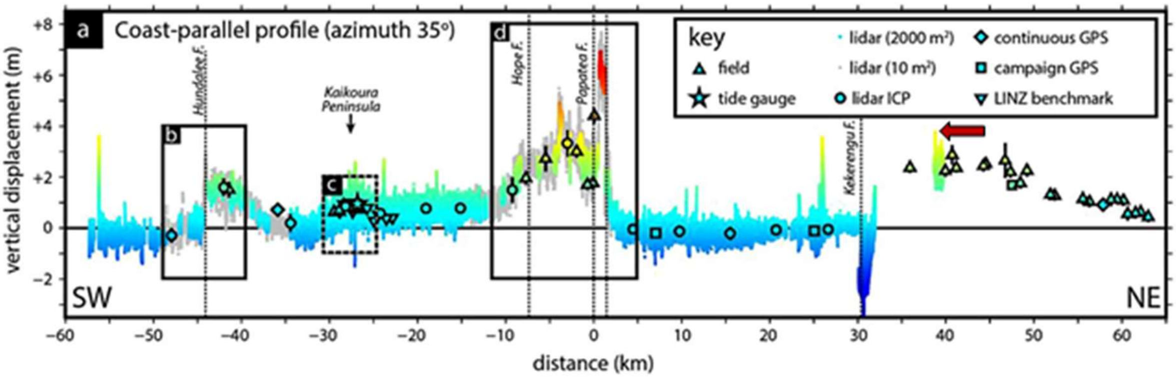


Figure 4.2: *Field, LiDAR and geodetic measurements of co-seismic vertical deformation of Kaikōura coastline (Clark* et al.*, 2017). Red arrow shows approximate location of Waima/Ure River mouth.*

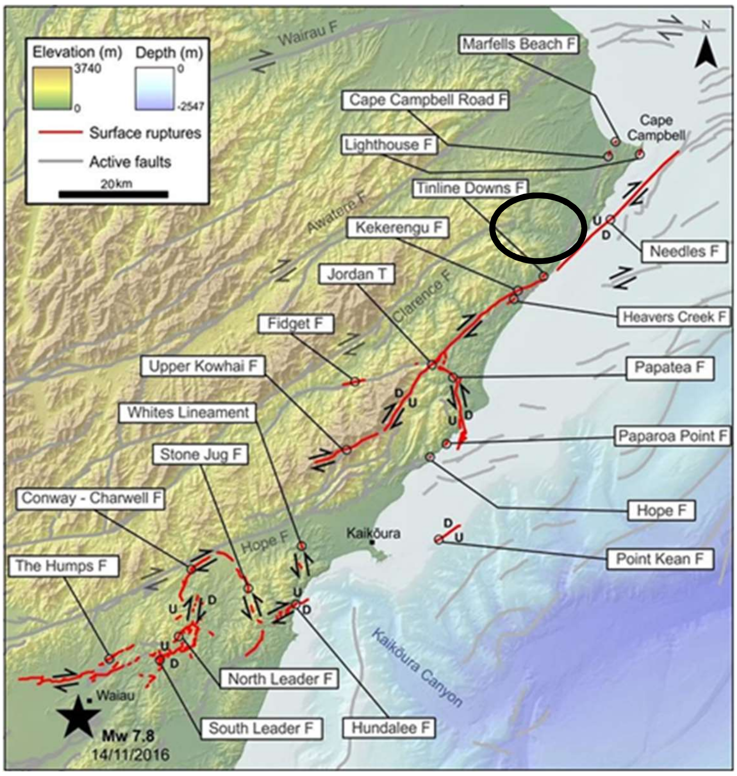


Figure 4.3: *Surface fault ruptures of the 2016 Kaikōura Earthquake, with study catchments circled (Stirling* et al.*, 2017).*

4.2 Flaxbourne, Mirza and Waima/Ure catchments

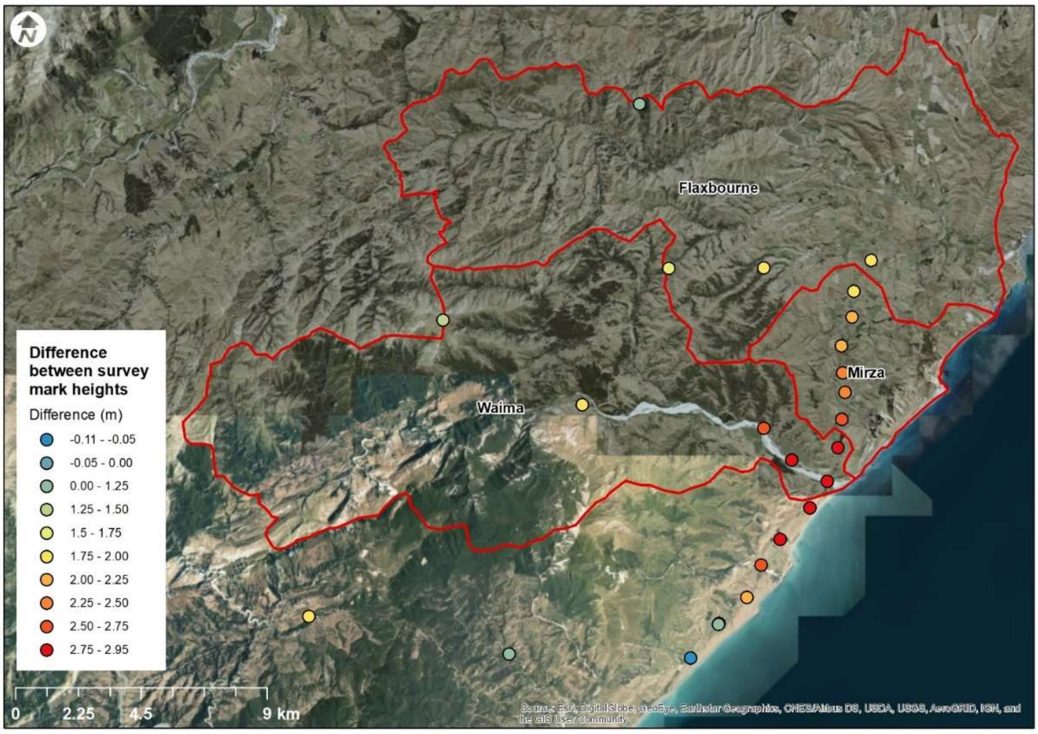
Lateral displacement of the wider Marlborough Region has occurred to the north-east, with a maximum of ~6m around Cape Campbell (Hamling *et al.*, 2017). High-level analysis of GPS data indicates that the extent of lateral movement is relatively consistent across the wider area, and unlikely to vary significantly locally within the study catchments. Comparison of pre- and post-earthquake DEMs generated from LiDAR data within the Waima catchment suggests that there is a general north-east trend of movement within the catchment (Figure 3.4). Near the mouth of the Waima River, displacement caused by the earthquake was ~5m north and ~4m east. In the upper catchment, lateral movement is of the order of ~5m north and ~2m east.

There is no high-resolution topographic data (i.e. a vertical accuracy of ±10cm and a horizontal accuracy of <1m). from before the earthquake available for the Flaxbourne and Mirza catchments. Consequently, any detailed analysis of lateral and vertical deformation is only possible for the Waima/Ure catchment.

As described in Section 3, the elevation of geodetic markers measured before the Kaikōura Earthquake have been compared to the heights of the same locations after the earthquake to derive an estimate of the vertical displacement within the Flaxbourne, Mirza and Waima/Ure catchments (Figure 4.4).

The horizontal displacement has not been assessed using the geodetic benchmarks. However, as discussed above, regional scale data indicate that lateral movement, while extensive, is not likely to be variable at an individual catchment scale.

Analysis of geodetic markers within the study catchments are consistent with regional deformation trends. In general, all the study catchments have uplifted by >1m. Less uplift is observed in the upper reaches of the catchments, with uplift decreasing with distance from the coast i.e. the Needles Fault (Figure 4.3). Maximum uplift of >2.75m is measured at the mouth of the Waima/Ure River.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 4.4: Comparison of the elevations of pre-earthquake geodetic benchmarks and post-earthquake LiDAR.

Vertical displacement within the Waima/Ure River valley has also been assessed though the comparison of 2008 and 2016 LiDAR surveys (Figure 3.5). As previously discussed, the lateral movement during the earthquake has constrained vertical comparison of the catchment within the hill country. However, within the river valley, vertical displacement along the river valley is of the order ~2m.

5 Potential impact on water resources

The topographical changes experienced in the Flaxbourne, Mirza and Waima/Ure catchments from the 2016 Kaikōura earthquake are both locally and regionally extensive.

Analysis indicates that while there is a general trend of vertical uplift, the extent of uplift ranges from 1-3m. More significant uplift has occurred along the coastal sections of the catchments. This aligns with movement along the offshore Needles Fault. Increased relative uplift experienced at the coast has reduced the channel gradient in the lower reaches of each catchment. The lowered gradient over these reaches has the potential to:

- Change the existing dynamics of the saline interface at the coast. While the uplift may have increased the depth to the interface, the reduced gradient could lead to any saltwater intrusion extending further inland, affecting water quality. It is important that the dynamics of the saline interface, following the Kaikōura Earthquake, be defined accurately. This will allow any risk to groundwater quality to be quantified, and the implications of this to water resources in the lower valleys be resolved.

- Change the dynamics of any groundwater system. The lateral movement of the landscape identified from the LiDAR survey has the potential to alter the location and permeability of recharge zones, particularly the boundaries between surface water and groundwater. A change in hydraulic gradient, caused by the general 'flattening' of the lower valleys identified in the LiDAR, has the potential to affect subsurface flow within any water bearing units. This also has the potential to affect the dynamics, location and sensitivity of the saline interface.

- Increased sedimentation. The increased gradient of the upper catchments, combined with the general 'flattening' of the lower valleys, identified in the LiDAR will affect the supply, transport and deposition of sediment. The aerial photographs obtained during the LiDAR survey, shows a large volume of material which has been (and has the potential to be) mobilised in the upper catchments of these three river systems. The information collected during the LiDAR survey will allow the source, area, volume and connectivity of this material to the drainage network to be quantified.

  This debris will be transported downstream over time. The reduced channel gradient will reduce the energy of any flow. This will lead to increased aggradation, increased bed levels, and reduced channel cross-sectional area. The changes to the landscape, and their changes over time will be able to be quantified using the LiDAR data as the current environmental baseline. The DEMs, when combined with the flood regimes of these rivers, will allow those areas prone to sediment deposition and bed aggradation to be identified. This will allow proactive management of sediment to help mitigate potential problems.

  The DEM of the current riverscape will also allow, when combined with subsurface investigations, the volume of gravel within the mid to lower valleys to be quantified. This will provide information on the shallow unconfined aquifer, and the potential volume of water that may be available from this source.

The deposition of sediment will impact on the capacity of the channel to contain larger flood events. It is likely that overbank flows will occur more often, inundation will be to a greater depth, and any flooding will persist for longer. The DEMs will be a critical input to the development of flood models of the extent and depth of inundation during a range of design events. Areas prone to flooding, and the nature of any flooding, will be able to be identified and quantified during design events.

- Increased sedimentation and reduced channel gradients are likely to lead to an increase in the water table; and saturation of the ground occurring more frequently, and for longer. The high-resolution DEMs will allow those areas at greatest risk to be identified. Increased groundwater levels and ground saturation could impact on the most productive, versatile, and valuable land in these catchments i.e. the floodplains adjacent to the channels. This may also affect water quality.

6 Conclusion

The Kaikōura Earthquake led to both lateral and vertical deformation across the Flaxbourne, Mirza and Waima/Ure catchments. The available topographic data does not allow detailed quantification of differential lateral movement. However, regional scale data indicate that lateral movement, while extensive, is not likely to be variable at the individual catchment scale.

Analysis indicates that while there is a general trend of vertical uplift, the extent of uplift ranges from 1-3m. More significant uplift has occurred along the coastal sections of the catchments. This aligns with movement along the offshore Needles Fault. Increased relative uplift experienced at the coast has reduced the channel gradient in the lower reaches of each catchment.

The lowered gradient over these reaches has the potential to: change the existing dynamics of the saline interface at the coast; change the dynamics of any groundwater system, including recharge, hydraulic conductivity, transmissivity and storativity; increase sedimentation, bed aggradation, reduced channel capacity; increase the frequency, magnitude and duration of overbank flooding; and increase the elevation of the water table leading to saturation of the soil occurring more frequently and for longer.

The Kaikōura Earthquake therefore has caused, and will exacerbate, a number of existing water resource issues in the Flaxbourne, Mirza and Waima/Ure catchments.

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