ASSESSMENT OF INCREASED FLOOD VULNERABILITY DUE TO THE CANTERBURY EARTHQUAKE SEQUENCE

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ABSTRACT

The earthquake sequence in Canterbury from September 2010 to December 2011 caused widespread land damage to Christchurch. The earthquakes affected the flood hazard in Christchurch due to changes to ground levels and watercourses from tectonic changes, subsidence and lateral spreading. The Earthquake Commission (EQC) is responsible for compensation of land damage to residential land due to particular natural disasters. Tonkin & Taylor worked with EQC to assess potential increase in flood vulnerability for residential land due to onsite ground surface subsidence caused by the earthquake sequence. Flooding was assessed with models developed for flood hazard management in the Styx, Avon, and Heathcote catchments by Christchurch City Council. Two types of flood models were used; a river flooding model and an overland flow model (rain-on-grid approach). The flood models were used in conjunction with ground levels based on LiDAR to identify properties with potentially affected properties. This paper describes the engineering methodology and issues that have influenced the methodology.

KEYWORDS

Flooding, Earthquake, Modelling, Christchurch, Subsidence

PRESENTER PROFILE

Dr Tim Fisher is the Water Sector Leader and a Project Director at Tonkin & Taylor Ltd. He holds a PhD (Civil) from University of British Columbia in Canada and Master of Engineering (Civil) from University of Canterbury. Tim is CPEng with 19 years' experience in New Zealand, Malaysia, Philippines, Canada and UK. Tim has water engineering skills in flood management, rivers, stormwater, sediment and water quality.

1 INTRODUCTION

As a result of the earthquake sequence in Canterbury, the topography of the land has undergone significant changes. This has changed the flood vulnerability for a number of properties due to the onsite changes in ground levels (subsidence) and the offsite changes to rivers and floodplains affecting the predicted flood levels.

The Earthquake Commission (EQC) with assistance from Tonkin & Taylor (T&T) are undertaking an assessment of Increased Flood Vulnerability (IFV) to fulfill their obligations under the Earthquake Commission Act 1993 (the Act). IFV is a physical change to residential land as a result of an earthquake which adversely affects the uses and amenities that would otherwise be associated with the land by increasing the vulnerability of that land to flooding events.

The objective of T&T's IFV engineering assessment is to identify properties with potential IFV land damage by providing an assessment of the increase in flood vulnerability due to physical change on the residential land. Once the engineering process is complete, properties that have been identified as potentially having IFV are referred to EQC for EQC valuers to determine whether the increased vulnerability identified has resulting in any decrease in amenity and value to the property. This paper is limited to describing the engineering assessment within the broader EQC process.

IFV is considered for main floodplains of rivers, streams and main channels, and for overland flow paths. Overland flow paths are formed by the runoff of stormwater that exceeds the capacity of the primary (pipe) stormwater systems.

2 THE ROLE OF THE EARTHQUAKE COMMISSION

The EQC provides insurance cover for damage to residential land, residential buildings and contents caused by particular natural disasters. The scope of cover is defined by the Act.

In general terms the Act limits damage to areas that are insurable. In practice this is considered to be 8m measured from the dwelling and appurtenant structures. It also covers the primary access to the dwelling (driveway).

The EQC has received more than 460,000 claims for damage from the earthquake sequence in Canterbury, with a substantial number of these claims involving land damage.

3 CANTERBURY EARTHQUAKE SEQUENCE

3.1 MAJOR EARTHQUAKES

The Canterbury area has been affected by a large number of seismic events following a major earthquake on 4 September 2010. There have been 16 events which have caused dwelling foundation damage resulting in lodgement of EQC claims. Four significant earthquakes in the sequence caused substantial land damage around Christchurch, including the manifestation of liquefaction, lateral spreading and widespread land subsidence. The four significant earthquakes that caused measurable ground surface subsidence occurred on:

- 4 September 2010;
- 22 February 2011;
- 13 June 2011; and
- 23 December 2011.

Land damage assessment by EQC is based on the damage caused by individual earthquake events as required by the Act. Therefore, the IFV assessment needs to consider each earthquake independently to the extent possible.

As a result of the earthquakes a number of categories of land damage were developed by EQC. These categories and descriptions of damage are shown in Table 1 (EQC, 2014). The first seven forms of land damage were developed from visual inspections of residential properties following the four significant earthquakes.

The last two forms of land damage, Increased Vulnerability to Liquefaction and IFV, cannot be readily identified from visual observations. Both vulnerability forms of land damage require extensive investigations and modelling to identify areas and properties at greater risk of damage from liquefaction or flooding post-earthquake. T&T on behalf of EQC has developed the methodologies by which properties can be identified, which potentially have these forms of land damage. The ultimate aim for EQC is to compensate property owners for these forms of land damage.

Table 1: Flat land damage categories

Damage that can be seen	
Category	**Description**
Land cracking caused by lateral spreading	Lateral spreading is the sideways movement of land, typically toward watercourses. Blocks of the earth crust (the surface soils above groundwater) move sideways over liquefied soils toward a lower area. Surface damage can include minor or major cracks in the land and tilting of ground crust blocks.
Land cracking caused by oscillation movements	Cracks to land can result from both lateral spreading (see above) and oscillation (backwards and forwards ground movement during earthquake shaking). Cracks resulting from oscillation are typically minor and isolated.
Undulating land	Undulating land is caused by the uneven settlement of the ground surface as a result of the ejection of sand and silt, and, to a lesser extent, the uneven settlement of liquefied soils below ground.
Local ponding	Local settlement or lowering of the land resulting in water forming ponds on the ground surface for extended periods in locations where it did not pond before the earthquake.
Local settlement causing drainage issues	In some areas residential land has settled more than the adjacent land beneath which public services are located (and vice-versa). This results in drains now flowing the opposite way.
Groundwater springs	New groundwater springs have emerged and are now flowing over the ground surface where this was not happening before the earthquake. The spring usually occurs at a specific location on residential land.
Inundation by ejected sand and silt	Sand and silt is ejected to the ground surface from the zone below the water table through cracks in the crust. The ejected sand and silt may be deposited in isolated mounds, under houses, or over large areas.
Damage involving an increased vulnerability	
Increased liquefaction vulnerability	In some areas the ground surface has subsided and the groundwater table has typically remained at a constant level. Therefore the ground surface is closer to the water table than prior to the earthquake. This generally reduces the non-liquefying ground crust thickness. As a result there has been an increase in the future vulnerability to the liquefaction hazard of some sites.
Increased flooding vulnerability	In some areas, the ground surface has subsided. As a result, there has been an increase in the future vulnerability to flooding of some sites situated near waterways. Refer Section 5 for more details.

3.2 LAND SUBSIDENCE

The land in Christchurch has settled as a result of the Canterbury earthquake sequence. Local effects resulting in subsidence include ground densification, lateral spreading, liquefaction and tectonic settlements. The effects are particularly pronounced adjacent to the rivers and streams where lateral spreading has occurred, a consequence of this is increased flood depths and extents. An indication of the severity and extent is shown in Figure 1.

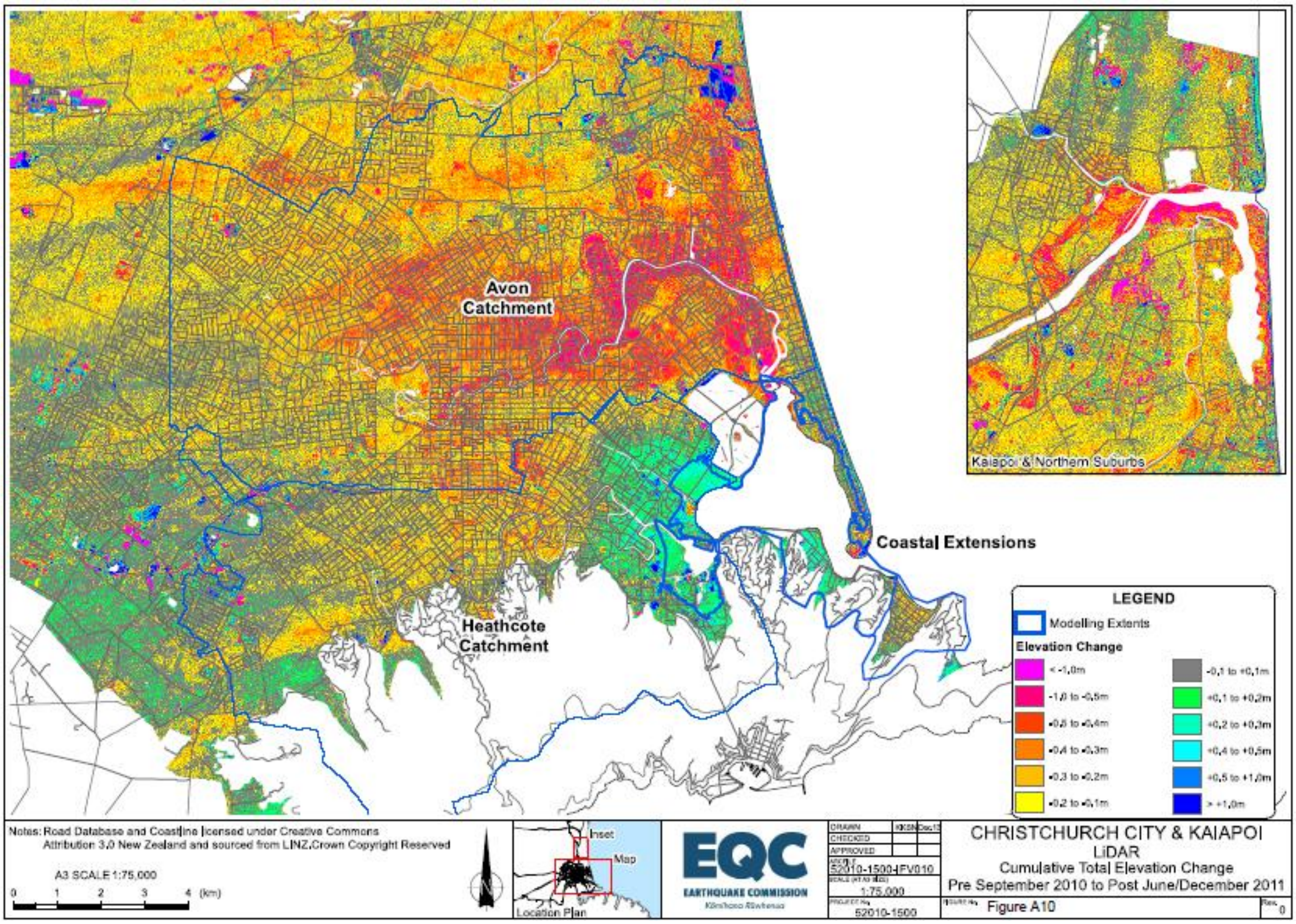

Figure 1: Cumulative earthquake subsidence Pre September 2010 to Post December 2011

4 CHRISTCHURCH RIVER CATCHMENTS

4.1 THE AVON RIVER

The Avon River catchment is located in the middle of the city. The Avon has its source in the suburb of Avonhead and runs through the suburbs of Ilam, Riccarton and Fendalton before reaching the CBD. It then passes through Avonside, Dallington, Avondale and Aranui before flowing into the Avon-Heathcote estuary.

4.2 THE HEATHCOTE RIVER

The Heathcote River catchment is located to the south of the city. The catchment starts in the west and drains to the Avon-Heathcote estuary. The catchment includes the suburbs of Yaldhurst, Wigram, Hillmorton, Hoon Hay, Spreydon, Cracroft, Cashmere, Beckenham, St Martins, Opawa, Woolston and Ferrymead. The northern slopes of the Port Hills are part of the catchment.

4.3 THE STYX RIVER

The Styx River catchment is located to the north of the city. It has two main tributaries, the Smacks Creek and Kaputone Stream, along with several other small waterways. The river originates in Harewood and flows through the suburbs of Belfast, Marshland and Spencerville before flowing into Brooklands and entering the sea at the mouth of the Waimakariri River.

There are also minor catchments draining directly to the sea or Avon-Heathcote estuary. Of particular note is the Sumner catchment comprising the suburb of Sumner and surrounding slopes of the Port Hills. It is drained by the Sumner main drain (an open channel) and piped networks.

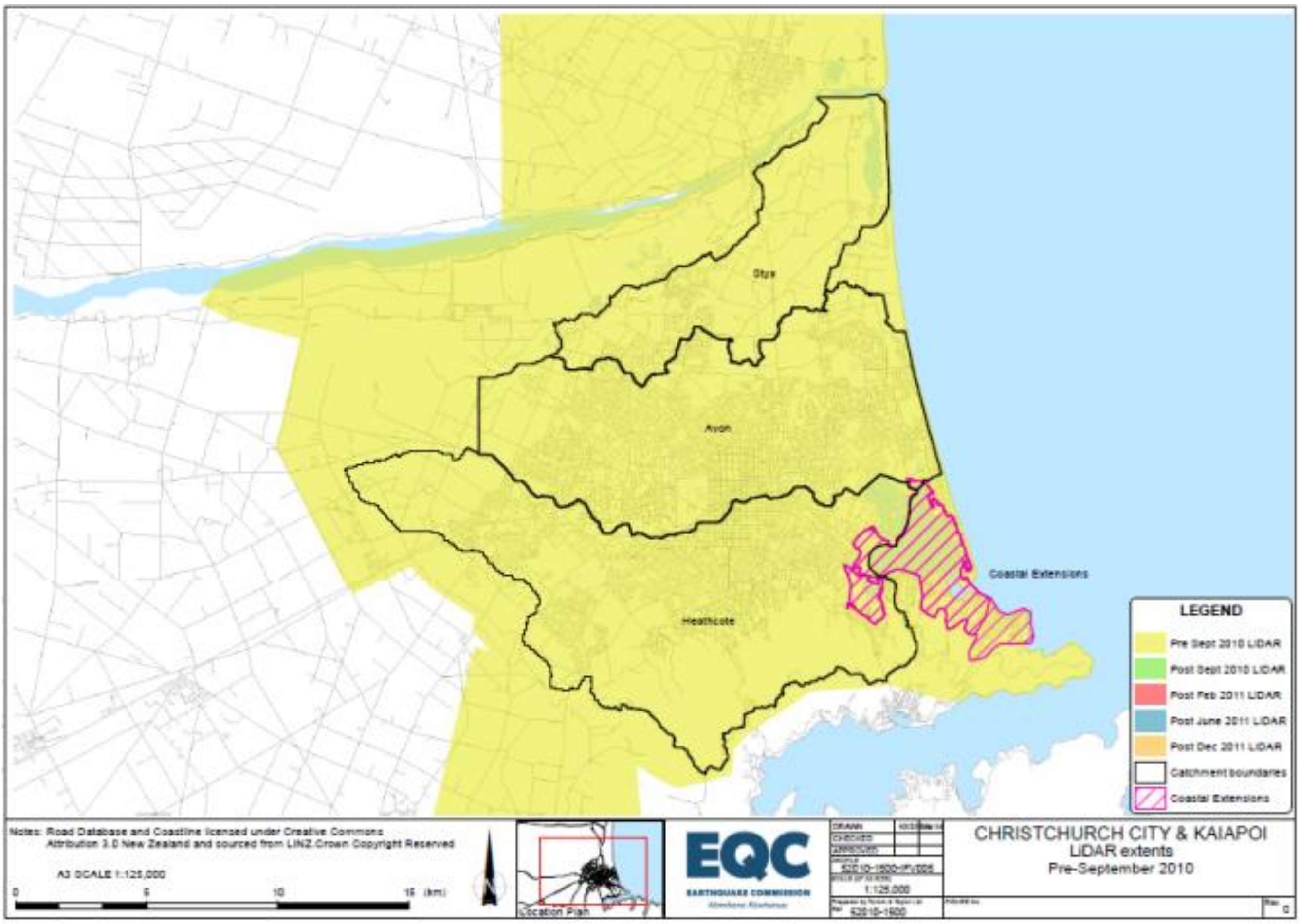

Figure 2: Overland flow model catchment boundaries including the coastal extensions

5 CHANGES TO RIVERS/DRAINAGE AND FLOODING AS A RESULT OF THE EARTHQUAKE

The earthquake sequence in Canterbury has caused changes to the topography of the land in Christchurch. This has changed the flood vulnerability for a large number of properties due to on-site changes in ground levels and the extent of the changes in ground levels are shown in Figure 1. Flood vulnerability has also changed due the off-site changes to streams/rivers and floodplains affecting the predicted flood levels.

The three flooding mechanisms that cause flooding are listed below with explanations of how the earthquake has modified these mechanisms.

- Pluvial flooding is caused by runoff that is in excess of the capacity of the stormwater systems and causes overland flow. It can be exacerbated in situations where settlement has occurred, as this settlement can change overland flow paths or reduce hydraulic gradients to stream/rivers.

- Fluvial flooding is caused by flow in streams/rivers that exceed the capacity of the channel and cause flooding of adjacent land. The earthquakes have reduced the capacity of some stream/river due to lateral spreading, which has reduced widths and increased bed levels. Ground subsidence can increase the overflow from streams/rivers onto flood prone land, and can also result in inundation of previously flood-free land.

- Tidal flooding is caused by water levels in coastal areas and lower rivers due to extreme sea levels that cause flooding of adjacent land. Land settlement can make areas more prone to tidal flooding where the land settles to a level below tide levels if not protected.

What this means at a property level is that some individual residential properties that previously were not exposed to flooding now have the potential to flood, whereas properties which had some existing flood vulnerability may have an increased area with potential to flood, or an increased flood depth due to this subsidence.

6 FLOOD MODELS USED IN DETERMINING IFV

The IFV methodology (refer Section 7) uses the maximum flood depths. Three types of flood model have been used to determine flood depths. In summary these are:

1. **River flood models**: The river flood models are computer models developed by Christchurch City Council (CCC). They are used for flood hazard assessment by CCC. These have been developed using DHI's MIKE FLOOD suite of software. There is a river flood model for each of the Avon, Heathcote and Styx river catchments developed by DHI, NIWA and GHD, respectively. The river flood models are used to assess "fluvial and tidal" flooding in the main floodplains in close proximity to rivers, stream and main drains. The models for the Avon-Heathcote Estuary coastal areas also consider extreme tide levels when assessing flood hazard.

2. **Overland flow models**: The overland flow models are developed using the 2D software package TUFLOW GPU. These models simulate the flow of runoff across land using the Rain on Grid method, although the TUFLOW model has hydrological losses. There is an overland flow model for each of the Avon, Heathcote and Styx catchments. The overland flow models are used to assess "pluvial" flooding outside the main floodplains that is not assessed by the river flood models.

3. **Coastal extensions**: This model was developed for areas that are not covered by either the river models or the overland flow models. The coastal areas around Southshore, Ferrymead, Bromley and South New Brighton are at additional risk to flooding due to high sea levels. A study by Goring (2011) found that the maximum 1% AEP tide level is 10.894 m above the Christchurch Drainage Datum. This is equivalent to 1.851 m above the Lyttleton Vertical Datum. For the Sumner area, the level from Goring (2011) is 10.856 m above the Christchurch Drainage Datum (1.813 m LVD). In some places, the coastal extensions overlap the Avon

and Heathcote models. Where this is the case, the maximum flood depth of the two overlapping points is adopted.

The models are run for pre and post each of the four significant earthquake. The five scenarios are pre-September 2010, post-September 2010, post-February 2011, post-June 2011 and post-December 2011.

7 INCREASED FLOODING VULNERABILITY

The process for making the engineering assessment as to whether a property has potential IFV is described in the following text.

1. The **flood depth** is the maximum flood depth for the 1% annual exceedance probability (AEP) rainfall event for each scenario. The change in flood depth is determined overall across the earthquake sequence and for each of the four significant earthquakes.

2. The **exacerbated flood depth** is defined as the increase in flood depth due to onsite land subsidence. The increase in flood depth due to onsite land subsidence is the portion of the increase in flood depth that is caused directly by the ground surface subsiding. In some cases, the increase in flood depth is greater than the ground surface subsidence, due to off-site issues causing the flood level to rise. In this case, the exacerbated flood depth is the depth of ground surface subsidence. In other cases, the increase in flood depth is less than the ground surface subsidence, due to the flood level dropping. In this case, the exacerbated flood depth is the limited to the increase in flood depth. Thus, in all cases, the exacerbated flood depth is the minimum of the increase in flood depth, or the depth of ground surface subsidence.

3. **Potential IFV properties** are those with exacerbated flooding in areas with observed land damage.

4. **Onsite assessment** is the final part of the engineering assessment for IFV to check that the flood mapping used to determine the IFV is providing sensible outcomes. The onsite assessment includes checking that no barriers exist which may block flow, or that there are any other reasons why the flood mapping may not reflect reality.

After the engineering assessment of properties is complete, the properties with potential IFV are passed to the EQC valuers who undertake their own valuation assessment in order to confirm that a property should be recognised as damaged due to IFV.

8 ISSUES IN DETERMINING IFV

8.1 LIDAR

The primary data source used in the assessment is the LiDAR. The LiDAR is used as the basis for Digital Elevation Model (DEM) that are used for each scenario modelled using river flood models and overland flow path models.

The LiDAR was commissioned by various agencies at different times and for different purposes. Extensive verification by T&T and SCIRT has been undertaken to understand the limitations of its use.

A key limitation was the differing extents for each LiDAR run. The LiDAR coverage is shown for three scenarios in Figures 3-5. Where LiDAR coverage was not available a composite DEM was developed substituting data from earlier LiDAR runs. A second limitation is that the pre-earthquake LiDAR was of a lower quality than more recent LiDAR surveys.

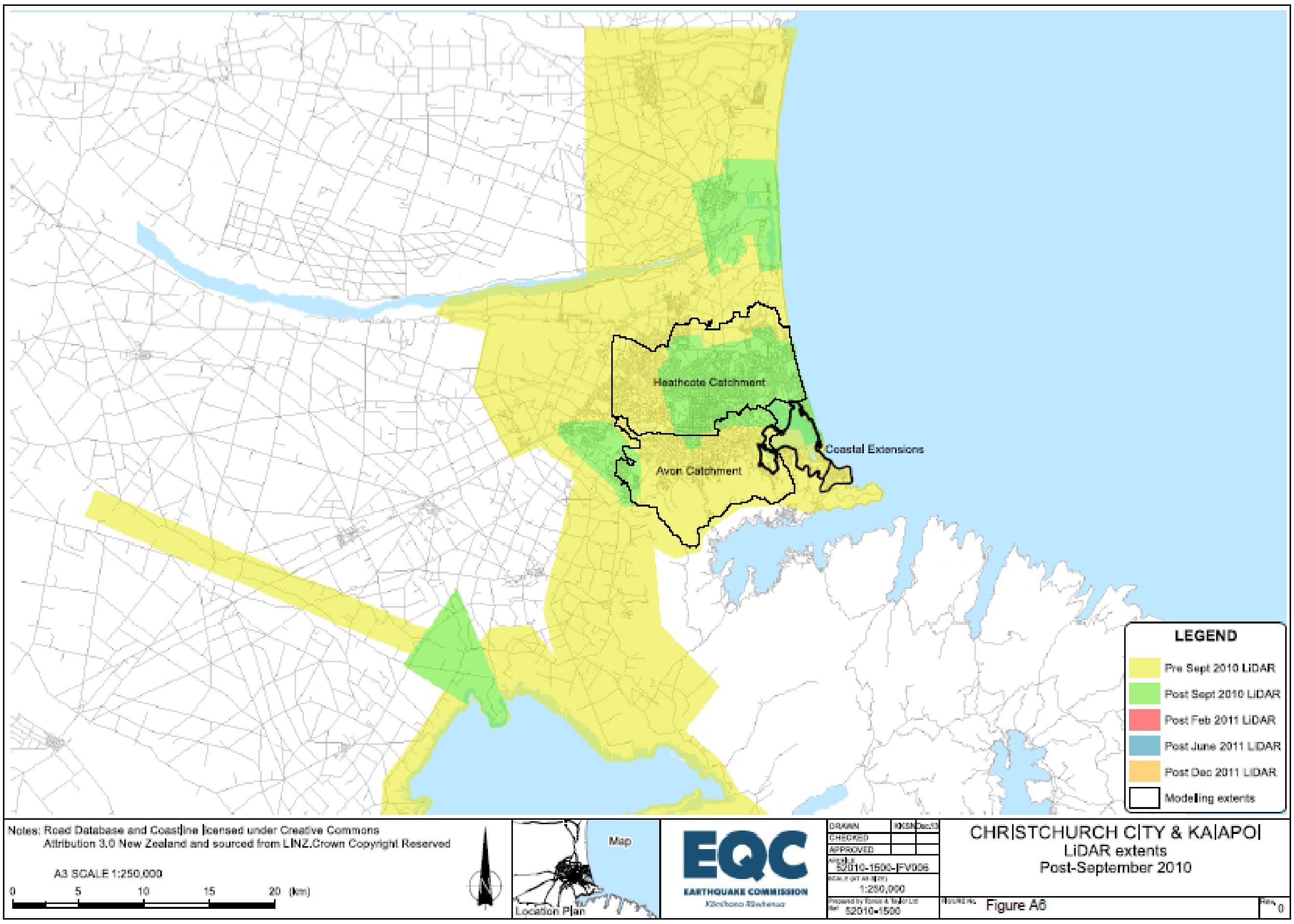

Figure 3: Pre September 2010 and post September 2010 LiDAR extent

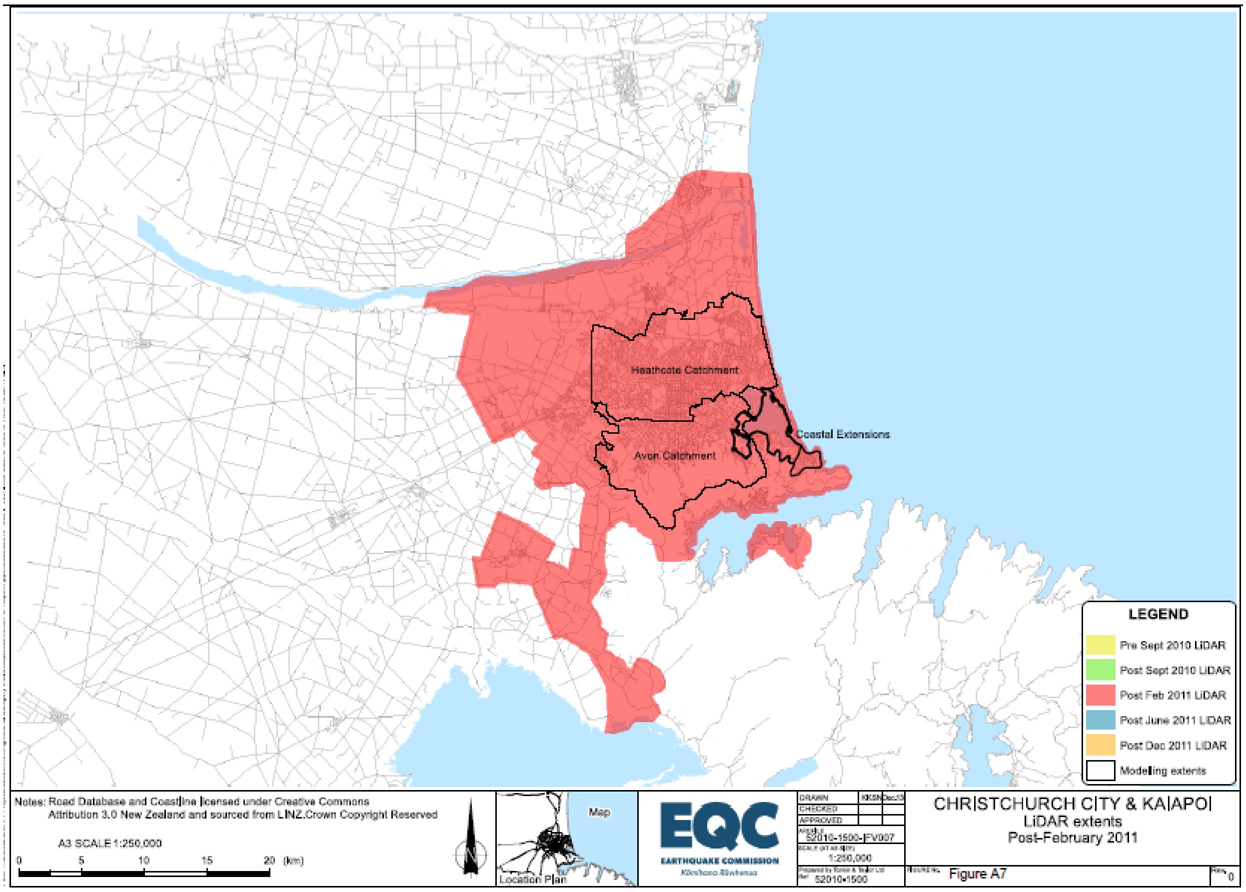

Figure 4: Post February 2010 LiDAR extent

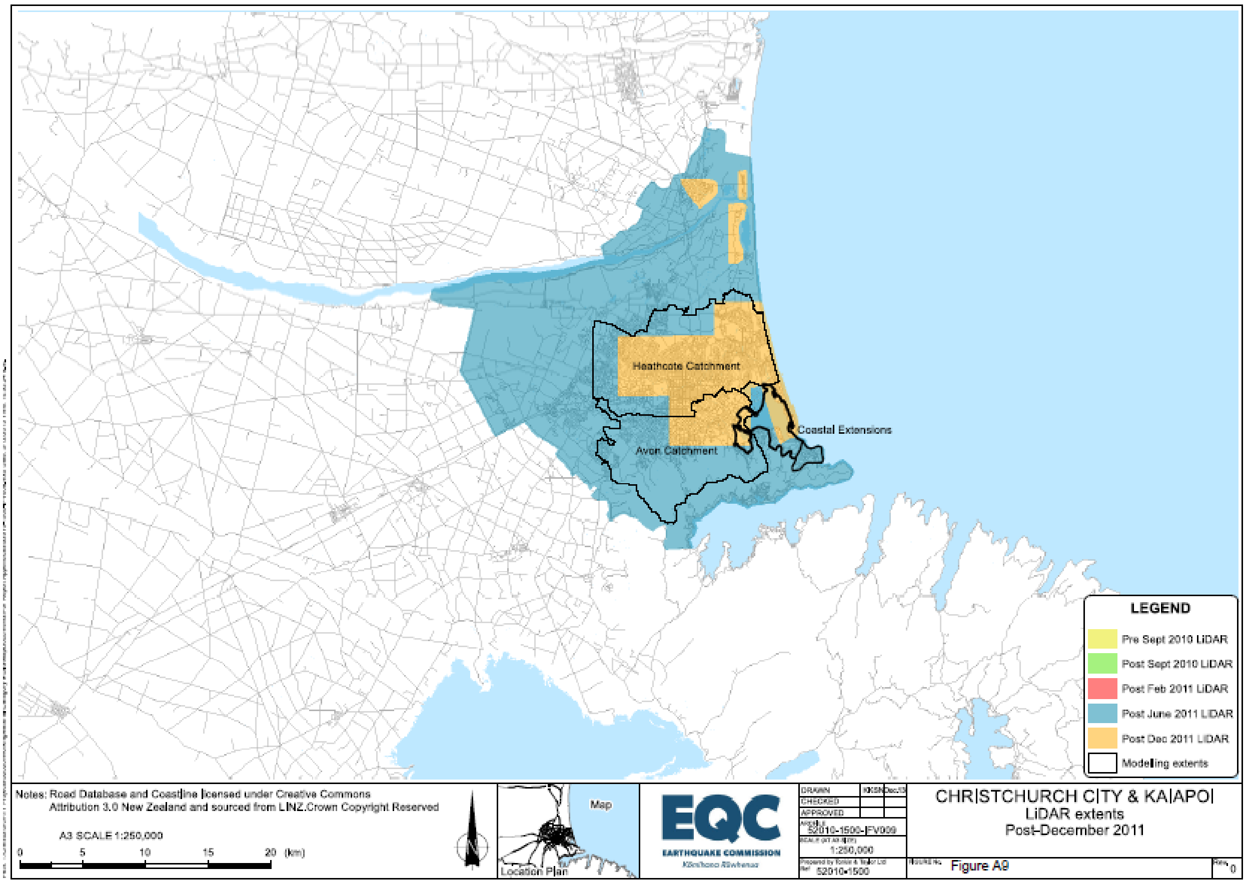

Figure 5: Post December 2011 LiDAR extent

8.2 4 AND 5 MARCH 2014 FLOOD EVENT

During 4 and 5 March 2014 Christchurch experienced a rainfall event that caused extensive flooding across the city. The event highlighted flooding issues, some of which did not exist prior to the earthquakes or have been worsened by the earthquake sequence.

T&T have carried out a preliminary analysis of the rainfall frequency from the recent event in Christchurch. This information will be used to validate the IFV assessment.

The analysis compares recorded rainfall during the 4 and 5 March at approximately 18 gauges across the city. We have then compared this rainfall with the HIRDS database (https://www.niwa.co.nz/software/hirds). HIRDS is a database managed by NIWA that estimates rainfall frequency for any geographic locations in NZ. Figures 6 and 7 show contours of AEP for the rainfall recorded on 4 and 5 March. These plots show the following general trends:

1. In general for short durations the rainfall frequency was high (i.e. more common rainfall event with less intense rainfall);

2. For longer durations (≥ 12 hour) the rainfall had a lower frequency (i.e. was more severe with more intense rainfall);

3. The rainfall frequency varied significantly across the city. In eastern areas the rainfall event was of lower frequency (more severe) than in the west; and

4. In the Flockton Basin region the rainfall frequency was roughly between a 10% and a 3.33% AEP for durations of 6 to 48 hours. The Average Recurrence Interval (ARI) of the rainfall was therefore between 10 and 30 years.

5. T&T also compared the peak river flows recorded by ECan (ECan 2014) in the Avon River at the Gloucester Street gauge (Christchurch CBD). This recorded flow suggests that the flood flows in the Avon at Gloucester Street had a frequency of 2% - 5% AEP (equivalent to 20 to 50 year ARI) (Figure 8). The horizontal red line in Figure 8 shows an estimated peak flow of 28 cumecs in the river. This line can be projected vertically down to where it intersects the trendlines to shows the predicted recurrence interval. The observed flood flow and its frequency may change when the rating curve for the flow gauge is re-evaluated using this last flood. We understand from discussions with CCC and NIWA that the recorded flows at this gauge may have been affected by scaffolding in the river downstream of the Gloucester Street Bridge.

6. The flooding event of 4 and 5 March is currently (at the time of writing) being used to validate the overland flow models to ensure that realistic results are produced. Preliminary findings of the validation show general agreement between the observed and modelled results.

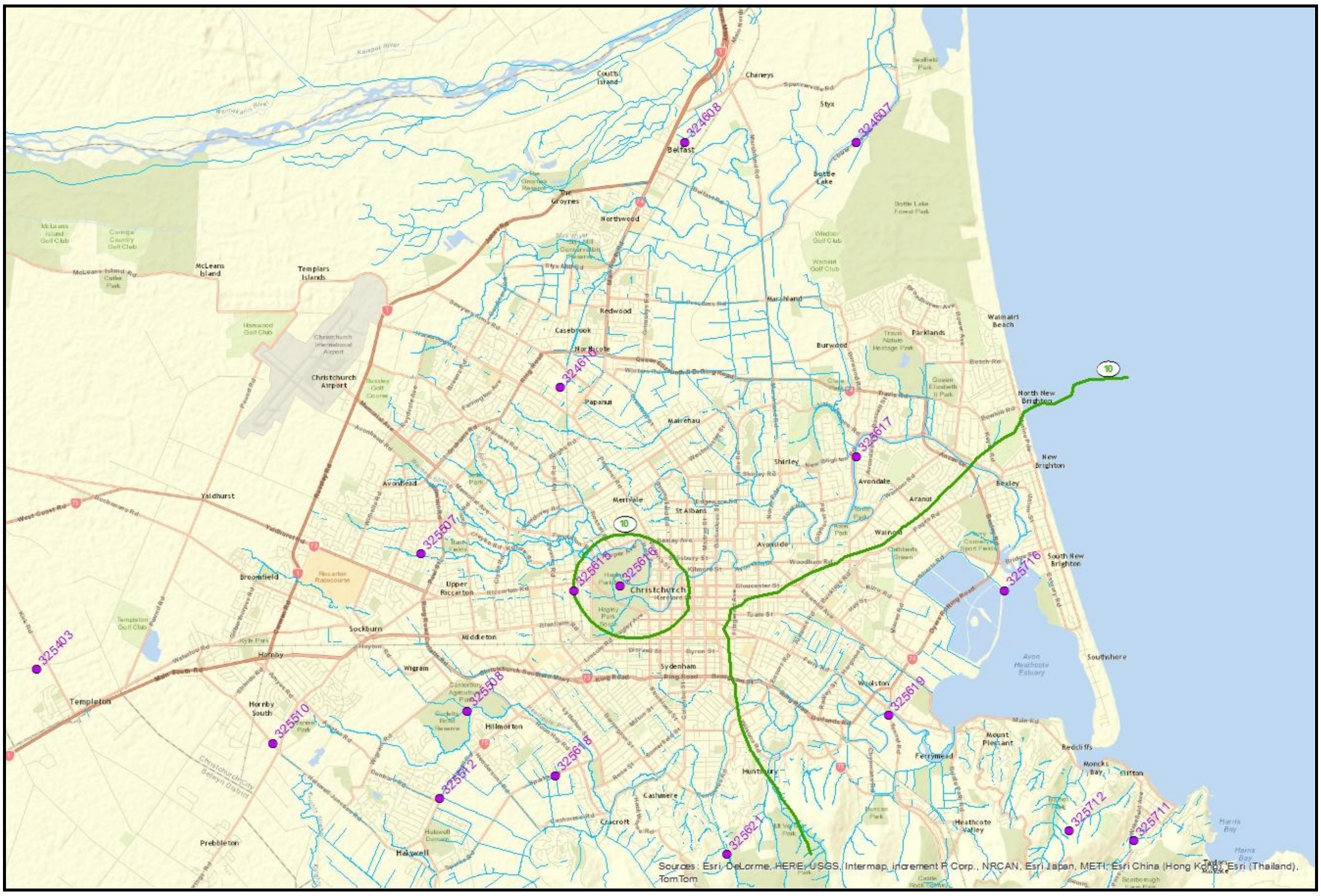

Figure 6: Annual exceedance probability 6 hr duration for 4/5 March 2014 rainfall event

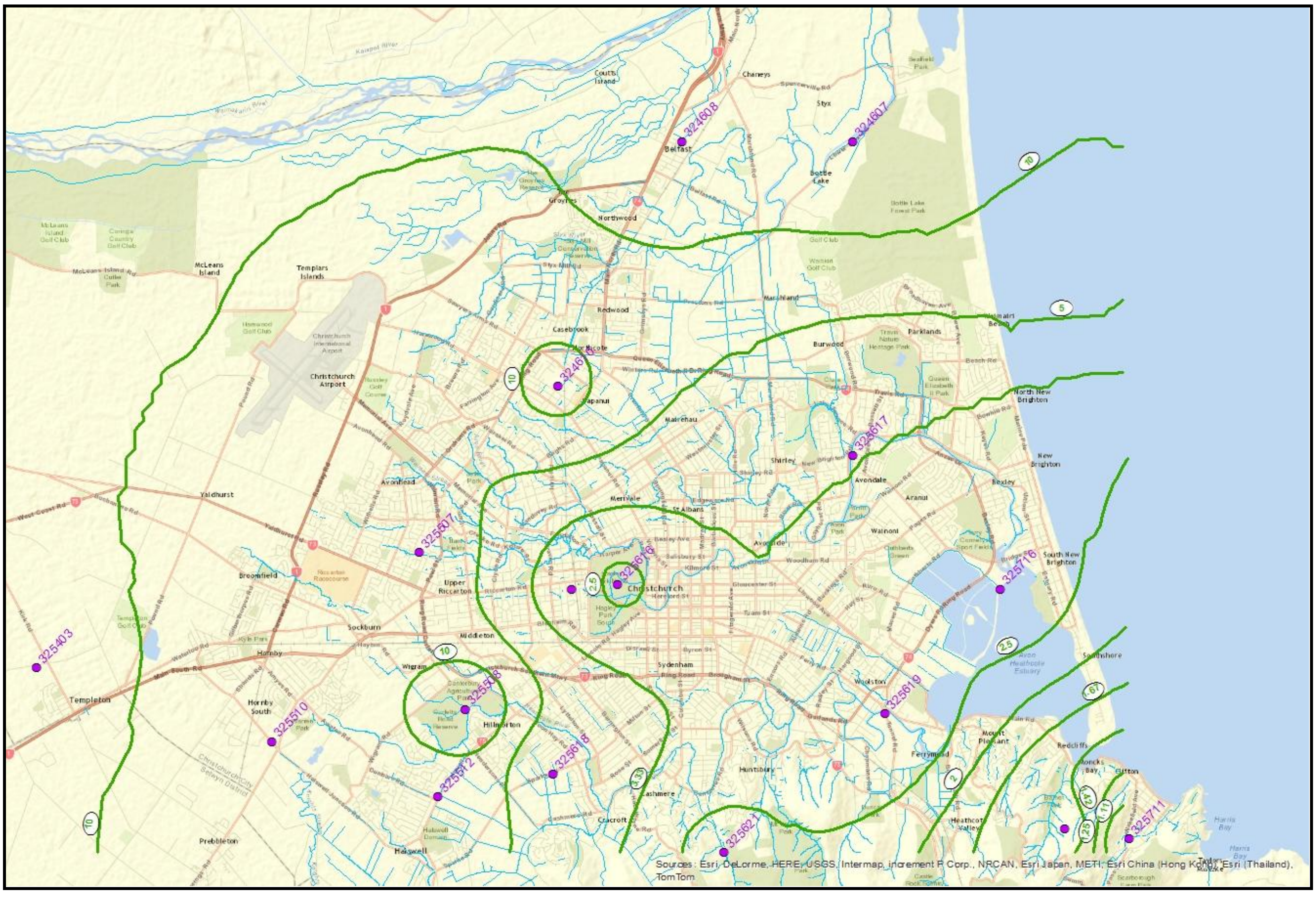

Figure 7: Annual exceedance probability 24 hr duration for 4/5 March 2014 rainfall event

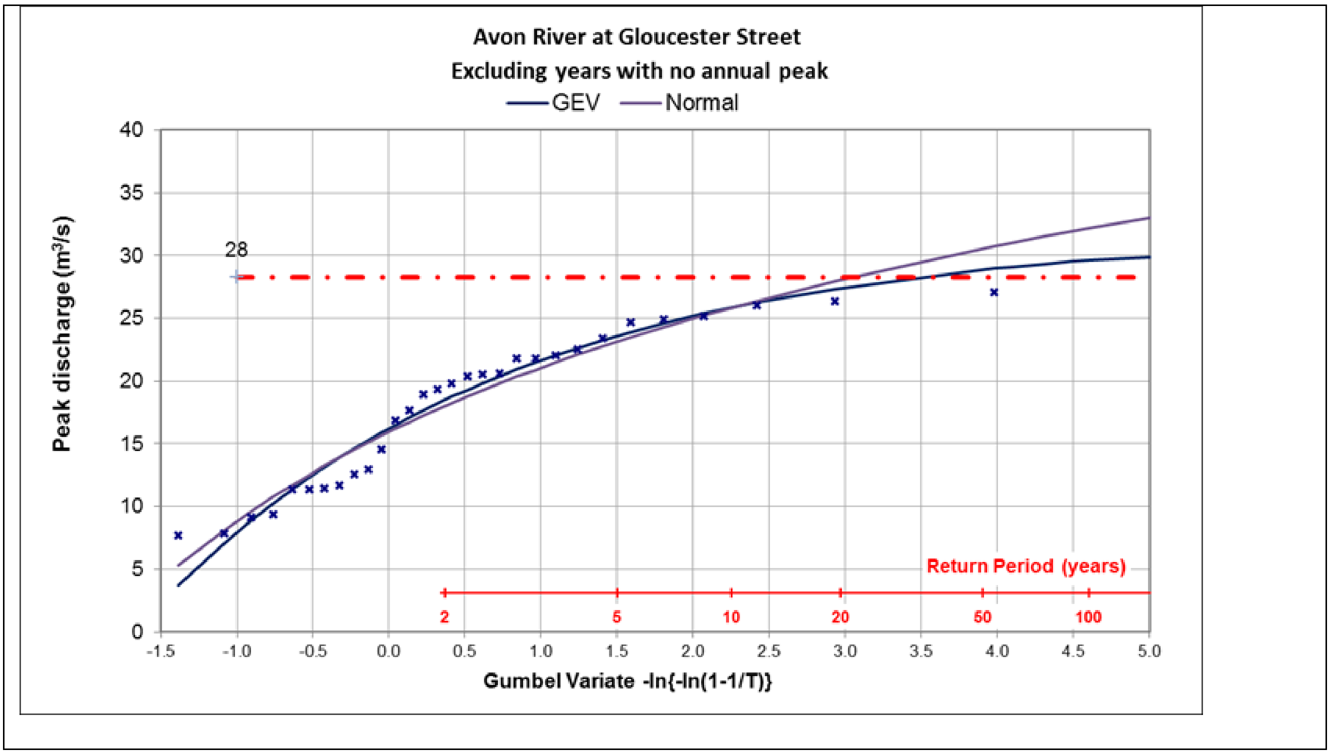

Figure 8: Frequency analysis of recorded discharge in Avon at Gloucester Street and peak flow of 28 m^3/s for 4/5 March 2014

9 CONCLUSIONS

The process of developing a comprehensive framework, policy, methodology and modelling ensures that a fair, reasonable and consistent approach is achieved. This enables EQC's customers to be appropriately compensated for their loss. The identification of potential properties is programmed for completion at the start of May 2014 and will be followed by on engineering onsite assessments and valuation assessments.

Whilst the modelling and identification is not yet complete, preliminary modelling suggests that there may be significant numbers of residential properties at greater risk of flooding due to earthquake subsidence. It is important to note that a key finding is that many of these properties were also at risk of flooding pre-earthquake, but the severity (depth and/or extent) has increased. EQC is only able to compensate customers for the increase of vulnerability (not any pre-earthquake effects of flooding).

The IFV land damage identification has involved engagement with multiple agencies including Christchurch City Council and NIWA. This engagement has helped ensure that the most appropriate and accurate data has been used in developing IFV.

ACKNOWLEDGEMENTS

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We especially thank Olivia Sullivan of EQC for her direction in developing this work and for reviewing this paper.

REFERENCES

EQC 2014 http://www.eqc.govt.nz/canterbury-earthquakes/land-claims/types-of-damage-on-flat-land

ECan 2014 http://ecan.govt.nz/services/online-services/monitoring/river-flows/Pages/River-flow-north.aspx

GHD (31 August 2012), Stormwater Modelling Consolidation – Avon River Model Status Report.

Goring, D (2011) Bridge Street & Ferrymead 2011 tide Derek Goring Avon Heathcote estuary Mulgor.xls.

NIWA https://www.niwa.co.nz/software/hirds