Flooding Vulnerability Lessons Learned in Assessing the Effects of Flooding Caused by the Canterbury Earthquake Sequence

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ABSTRACT: *The Canterbury Earthquake Sequence (2010 – 2011) caused significant damage and loss of life in Christchurch, New Zealand. The Earthquake Commission (EQC) is New Zealand's public insurer for natural disaster damage. EQC determined that a new, claimable form of land damage had resulted due to the Increased Flooding Vulnerability (IFV) caused by the subsidence of the land changing the flood risk to residential properties. Tonkin & Taylor Ltd (T+T) on behalf of EQC had by early 2016 completed engineering assessments of over 11,000 residential properties in Canterbury. The purpose of the assessments was to understand and quantify the effects on residential properties of IFV caused by the Canterbury Earthquake Sequence. The completion of these assessments has involved over 75,000 man-hours and is the culmination of 5 years of data collection, policy and methodology development, legal and peer review. This paper examines some of the engineering challenges and how they were dealt with. It also considers what lessons could be learned if the process was to be repeated.*

KEYWORDS: *Flooding, Earthquakes, Flood modelling, Insurance, Canterbury Earthquake Sequence*

SITE LOCATION: Geo-Database

INTRODUCTION

Land in Canterbury has changed forever. This is both a direct and indirect result of the Canterbury Earthquake Sequence (CES) that primarily occurred between September 2010 and December 2011. Aftershocks, of which there have been thousands, including a magnitude 5.7 shake on Valentine's Day, 14 February 2016 are ongoing some 7 years later. The direct changes to the land are those (along with many others) caused by subsidence of the land due to the effects of liquefaction and subsidence, significant rockfall and cliff collapse and also tectonic changes, uplift in the north of Christchurch City and uplift on Banks Peninsula. The indirect changes include siltation of the city's rivers and channels due to increased sediment from the liquefaction ejecta washing into those channels and rivers.

The change in land has changed the flood vulnerability for thousands of residential 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 significant assistance from Tonkin + Taylor (T+T) has undertaken an assessment of Increased Flood Vulnerability (IFV) to fulfill their obligations under the Earthquake Commission Act 1993 (the Act). IFV is defined in legal terms as 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 and quantify properties with IFV land damage by providing an assessment of the increase in flood vulnerability due to physical change on the residential land. Once the engineering

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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 resulted in any decrease in amenity and value to the property. This paper is limited to describing the engineering assessment and the issues that confronted the T+T and EQC team in this mammoth task.

THE ROLE OF THE EARTHQUAKE COMMISSION IN NEW ZEALAND

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 (New Zealand Government, 1993). This form of land insurance is understood to be unique to New Zealand and therefore whilst some of the lessons described in this paper may only be applicable to New Zealand, the issues associated with flooding, earthquakes and the effects on the public are almost universal. 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 CES, with a substantial number of these claims involving land damage.

CANTERBURY EARTHQUAKE SEQUENCE

Major Earthquakes

The Canterbury area has been affected by a large number of seismic events following a major earthquake on 4 September 2010 (as seen in Figure 1). Prior to the Valentine's Day 2015 earthquake, there had been 16 events which have caused dwelling foundation damage resulting in lodgment 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

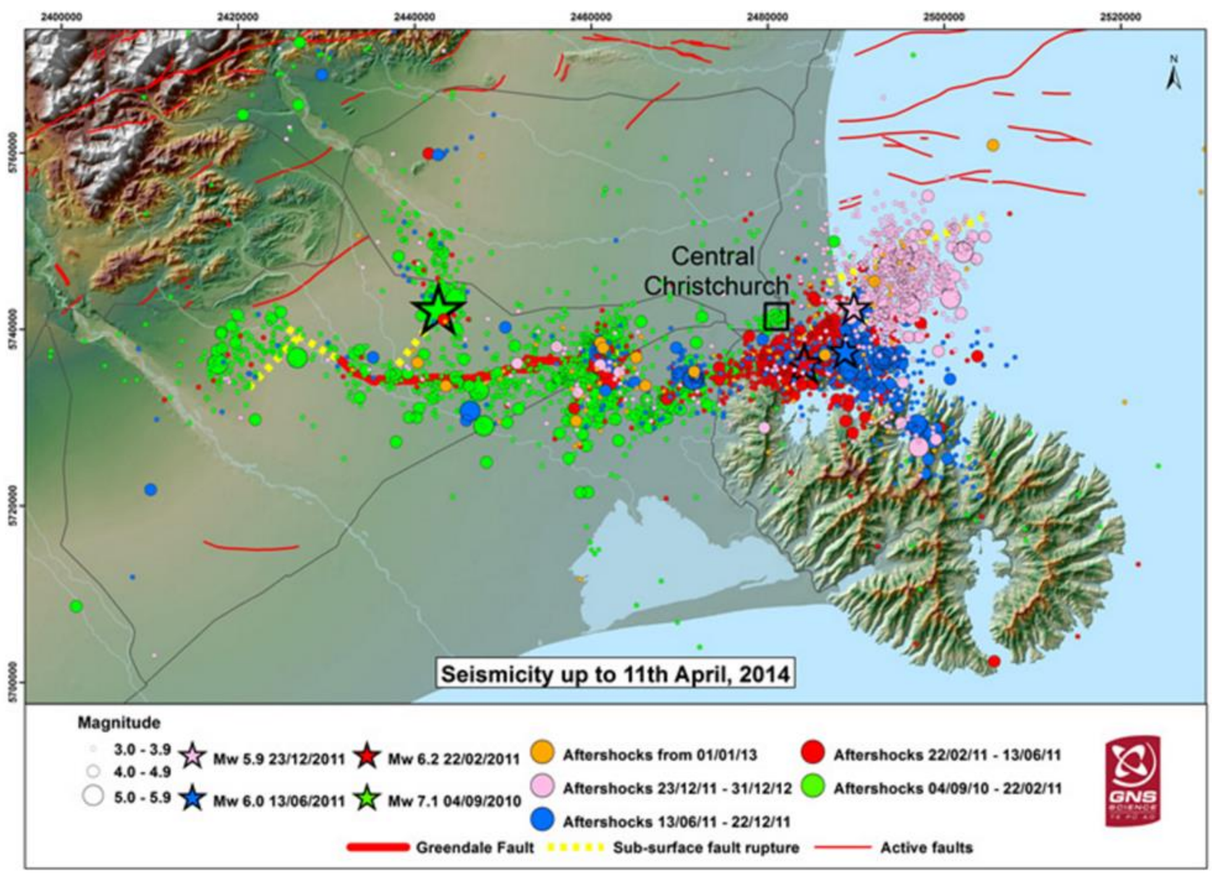

Figure 1. Canterbury Earthquake Sequence Recent Aftershocks (GNS, 2016)

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. Compensation for customers affected by IFV was well progressed at the time of writing this paper, and the payments for ILV are planned in the coming months.

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.

LAND SUBSIDENCE

The land in Christchurch has settled as a result of the CES. 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 2. Areas shown in pink are where the greatest subsidence has occurred with yellow being approximately 0.3 m to 0.5 m subsidence. Areas shown shaded green are where the ground has been tectonically uplifted.

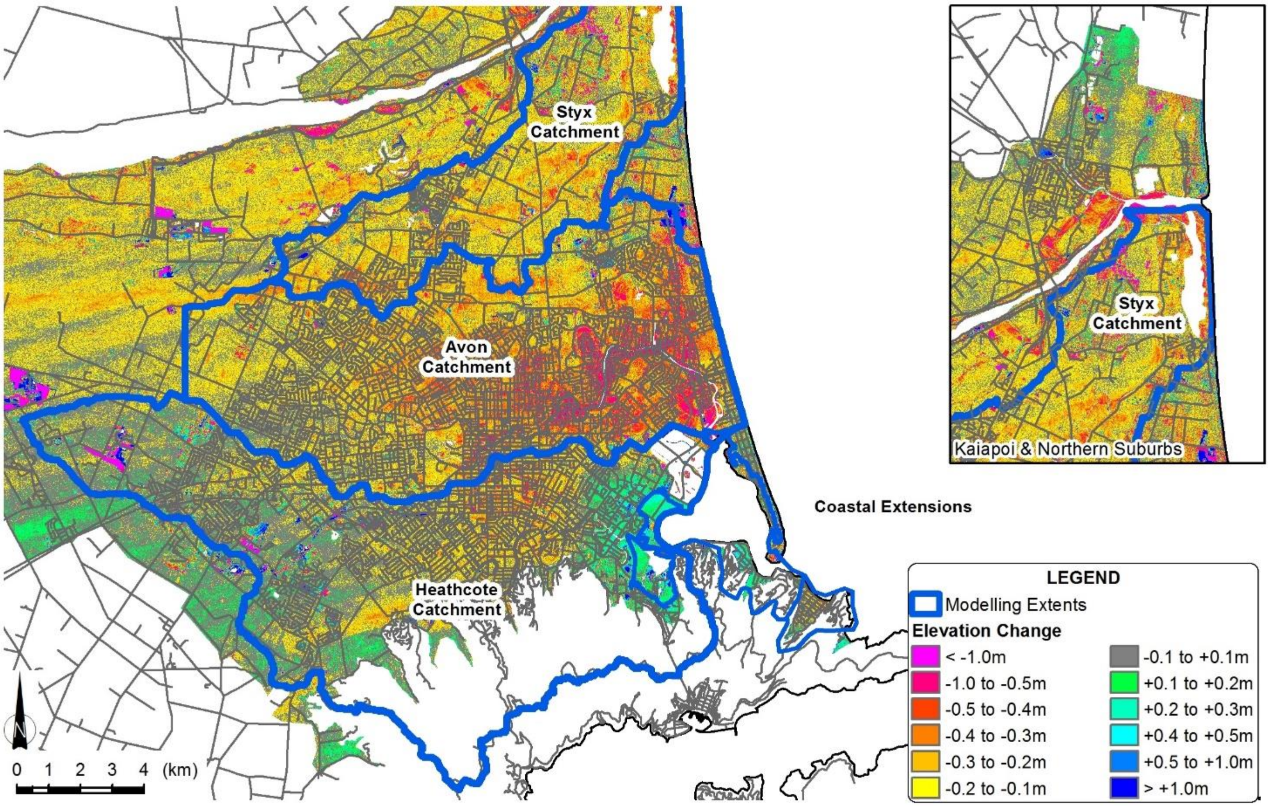

Figure 2. Cumulative earthquake subsidence Pre September 2010 to Post December 2011.

What Was Learned from the Subsidence and the Data Used to Collect It?

Land Damage Mapping Lessons

Figure 2 showed that the majority of the subsidence followed the Avon River, with the most severe subsidence occurring generally east of the city CBD. This was evident to the residents of Christchurch of course, but also was evident from the extensive land damage mapping that was undertaken. Some 65,000 residential properties were visited and the land damage on them recorded by a team of approximately 400 engineers, geologists and scientists managed by T+T over a two year period (T+T, August 2014). This information has been used extensively not just for the assessment of IFV, but also for other forms of land damage and is also available for use by academics and professionals on the Canterbury Geotechnical Database.

One of the key lessons learned from the CES is the value of rapid land mapping via site visits, analysis of aerial photographs, satellite data, land-based topographical survey, LiDAR and customer or residents reports. This information collected and analyzed by T+T enabled us to either verify flood models or challenge anomalies in either the land damage mapping of the flood models, or indeed customer reports.

LiDAR Survey Lessons

Other key lessons found in using LiDAR derived measured subsidence was that the pre-earthquake LiDAR, while extremely useful, was never intended for city wide overland flood modelling. The LiDAR on detailed analysis was found to create two issues:

1. Pre-CES ‘undulations’ in the ground profile, that when compared with the post CES ground profile had smoothed out. The undulations themselves, were not real, but instead the result of LiDAR inaccuracies. This created a picture either local but regular subsidence or apparent uplift in any difference map. This usually coincided with buildings and vegetation where the ground surface was interpolated from adjacent bare earth LiDAR returns; and

2. “Banding” of large swathes across Christchurch observed in the LiDAR surveys (Figure 3). This banding was believed to be caused by various issues related to the flight paths and sweeps of the laser when the aerial surveys were undertaken.

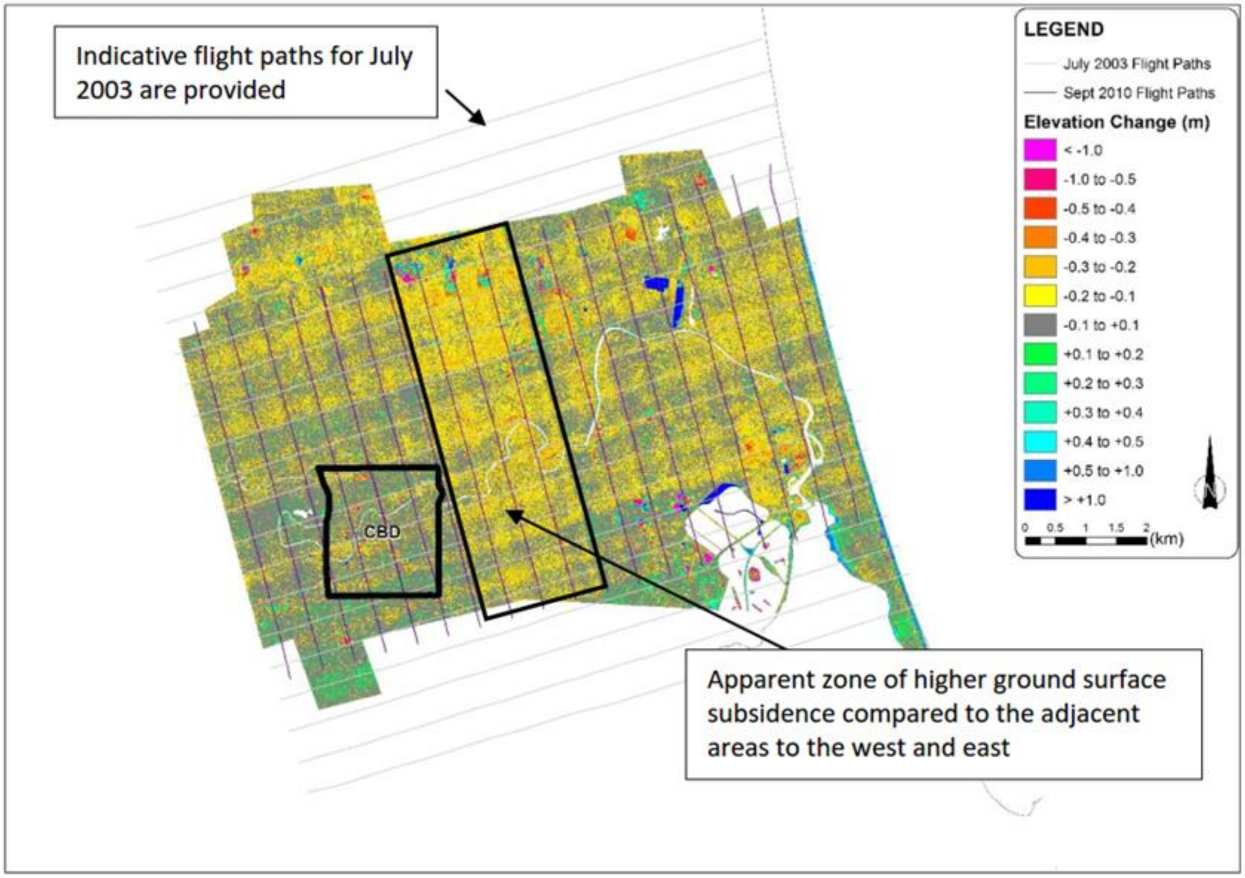

Figure 3. Banding related to LiDAR flight paths, T+T (2015).

Both of the issues described above led to significant work throughout the IFV development and assessment process to determine the effect of flood models using the LiDAR derived Digital Elevation Models (DEM) and was the subject of both peer review and also challenge in the New Zealand High Court.

The key lessons learned here were to:

1. Consider how LiDAR will be used in scoping any specification before the survey is flown (in this case the Christchurch City Council did not know that an earthquake would occur and that this data would be relied upon in this way)
2. Understand survey data available, its accuracy and limitations
3. Consider alternative methods and data and any issues that may limit their use
4. Educate the general public about what LiDAR is, how it is used, who obtained it, and its limitations.

CHRISTCHURCH RIVER CATCHMENTS

We have provided a brief description of the three main rivers within and directly affecting the residents of Christchurch. The river catchments are shown in Figure 4. At the end of this section we provide our observations of the lessons learned from the geography of Christchurch.

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.

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.

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.

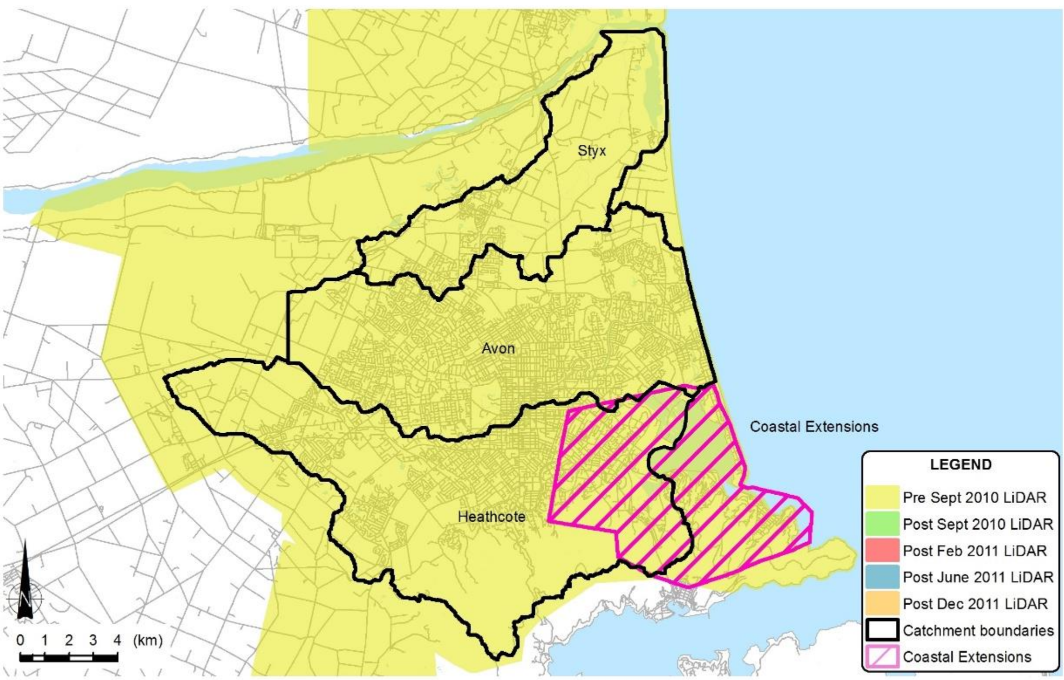

Figure 4. Overland flow model catchment boundaries including the coastal extensions compared with pre-CES LiDAR extent.

Lessons Learned on the Geography of the City

The descriptions above have been derived from flood model build reports by GHD (2012). Whilst the descriptions are believed to be accurate and concise, what is missing from these are an in-depth knowledge of each and every sub-catchment, and the history of those sub-catchments both pre-historic and historic. The authors know from experience on IFV that considerable time must be spent with locals including residents, local engineers (councils), other consultants, reviewing old newspaper articles and official archive maps and of course walking the river, channels and catchments to get a true sense of how the natural and man-made drainage systems work, what has happened and why.

A flood model can easily be built, but it must be convincing. The hardest aspect is not to convince another engineer, whether that is a peer reviewer or a colleague, but to convince the public, who are ultimately the people who are affected by the results. Verification and calibration to actual flood events are a useful demonstration that the model is appropriate and for identifying areas where additional work should be undertaken. A brief description of the calibration of the flood models used for IFV is provided in a subsequent section of this paper.

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

The CES 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 2. Flood vulnerability has also changed due to 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.

1. 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.
2. 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.
3. 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.
4. 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.

What Did We Learn from the Flood Modelling Undertaken for IFV?

1. The majority of areas and properties affected by IFV were already within the 1% annual exceedance probability (AEP) floodplain, however many residents were not aware that their property had been in the floodplain since before the CES.
2. In general terms the worst affected areas had been ‘red zoned’ (where residential redevelopment is generally not cost effective on an individual basis, T+T Volume 1 (2014)) Therefore the residential properties to be assessed, whilst damaged, usually affected only a portion of the property.
3. The increase for many properties was on the margins of the accuracy of the LiDAR used to derive the DEMs
4. The general public usually assumed that if their property has subsidence (which much of the city had, that therefore there must have been a corresponding increase in flooding. In fact for most of the city this was not the case. This is because where the land has dropped uniformly, then the water flood level had also dropped by a similar amount. This does not mean that there has not been an increase, only that the increase in flood depth is usually less than the subsidence that has occurred. This effect is illustrated in Figure 5. All areas shown shaded in Figure 5 are where there has been a calculated increase in flooding caused by the CES. As expected this is primarily concentrated along the main rivers, however large number of properties in the suburbs of Linwood, Phillipstown and Woolston have also undergone an increase in Flood Vulnerability.

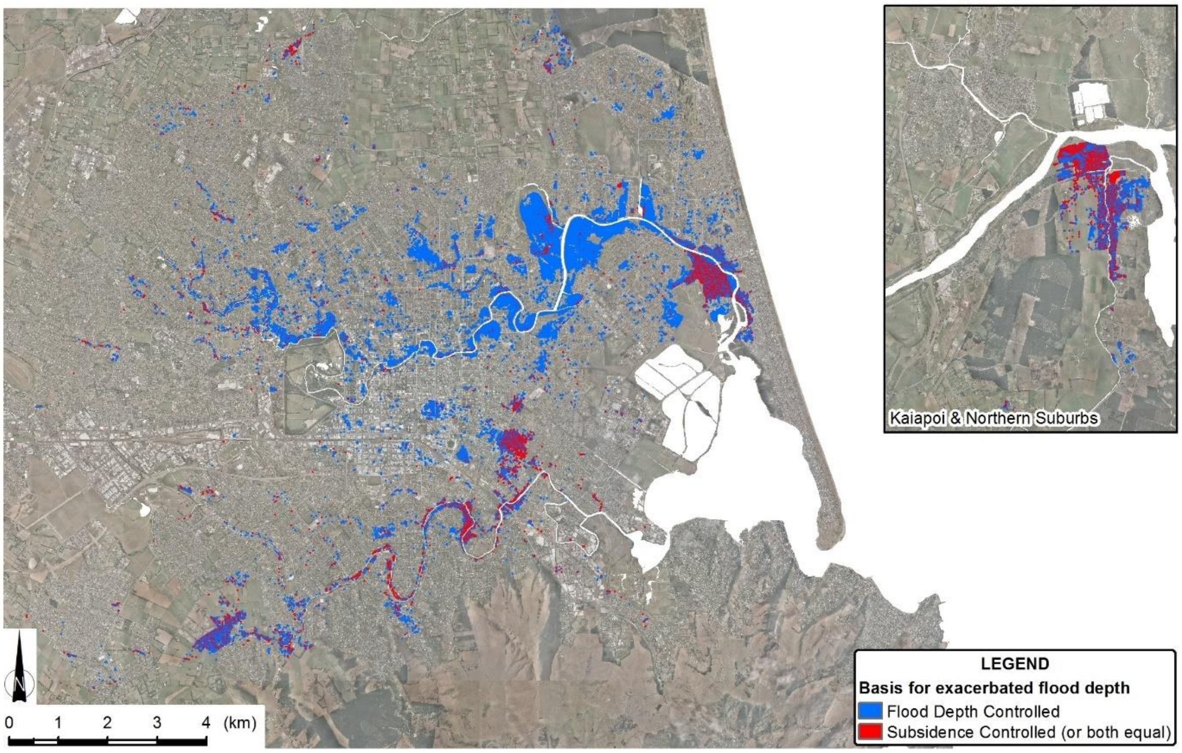

Figure 5. Map showing (shaded blue) areas where the earthquake induced subsidence is greater than the resulting increase in flood depth. Area (shown shaded red) is where the flood depth has increased more than the subsidence that has occurred.

FLOOD MODELS USED IN DETERMINING IFV

Description of Flood Models Used

T+T reviewed existing information and available models before proceeding with the following choices for flood modelling. Following peer review by EQC's International Peer Review Panel (Benn et al. 2014), it was decided that a bespoke citywide model (the Overland flow model) would be developed to address issues including grid sizes and sensitivity testing. In summary, a description of the flood models used for the assessment of IFV is as follows:

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.

Unique Modelling Issues and Effects of the 4 and 5 March 2014 Flood Event

Recent advances in technology enabled the Overland model to be developed using a GPU processor. The GPU processor allowed much faster run times than the existing River flood models and instead of taking between 5-10 days for a single run to be completed, using GPU a run could be completed in around 12-24 hours. As such, multiple sensitivity runs were undertaken before finalizing the model for its IFV use. A more traditional CPU model would have taken significantly longer to develop given the slower run times when compared with a GPU model.

Using TUFLOW GPU a single model of the whole of Christchurch City was built, tested, verified and peer reviewed ready for implementation in a period of around four months.

4 and 5 March Flood Event

The usefulness of the increase processing speed became apparent following the 4 and 5 March 2014 flood event. At the time of the flood event occurring (which T+T hindcast as between a 20 and 50 year Average Recurrence Interval (ARI) river flood event as measured in the Avon at the Gloucester Street gauge), the IFV model was in the final stages of completion. However, the model had not (because there was no data available) been verified or calibrated to actual flooding. The event provided an opportunity to undertake this. Again, the value of rapid mapping proved extremely useful. Teams involving T+T, EQC, NIWA and CCC independently mapped flood extents. CCC also collated flood reports from residents. This mapping together with river and rain gauge data was used to calibrate the model. We consider (and the International Peer Review Panel agreed) that the resulting Overland flow model was appropriate for the use of IFV. A comparison of the calibrated model and the observed mapping for the Avon catchment is shown in Figure 6. A similar comparison is shown for a badly affected area known as the Flockton Basin in Figure 7.

Of interest is that until the March 2014 flood event, it appeared that the effects of any flooding caused by the CES were largely unknown by the general public, albeit some local areas had experienced regular flooding. Whilst EQC and T+T had been working (at that time) for approximately 2 years on developing policy and methodology for IFV this only generally became of interest to the mainstream media as a reaction to the March 2014 flood event. A downside of the flood occurring post CES was that because there had been few significant floods for 15 to 30 (depending on location) or more years, many residents incorrectly assumed that the flooding that they observed was all attributable to the CES. In fact, T+T's analysis for IFV showed that, whilst there had been an increase, in many cases it was only a fraction of the total post-CES 1% AEP flood depth. This has been a key public education issue that EQC and T+T have had to address as part of the process.

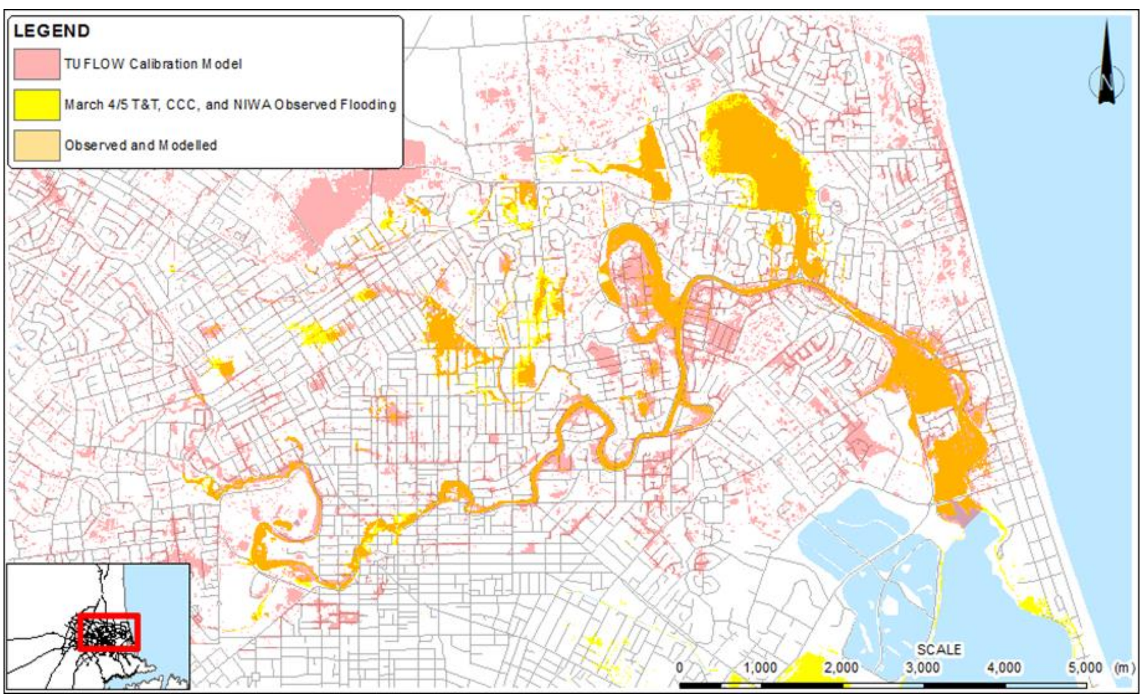

Figure 6. Calibration run of maximum depths compared to a combined T&T, CCC and NIWA observed flooding map for the 4 and 5 March 2014 event.

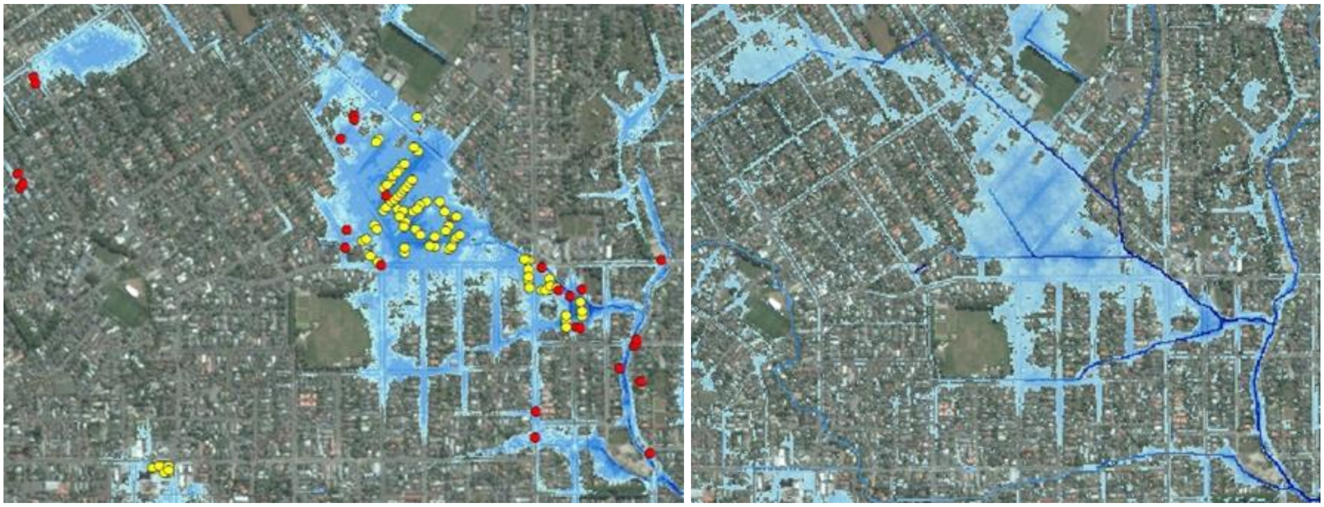

Figure 7. Calibration run of maximum depths (right) compared to a combined T&T, CCC and NIWA observed flooding map (left) for the 4 and 5 March 2014 event – Flockton Basin.

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 CES 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 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.

RESULTS AND SITE SPECIFIC ASSESSMENTS

Approximately 18,000 properties were identified as having potential IFV across Canterbury (including in Sumner and Kaiapoi). Whilst a large number of these properties either had no valid insurance claim lodged with EQC or were located in the Red Zone, over 11,000 properties still required site specific assessments to determine their engineering IFV status. Figure 8 shows the engineering IFV status of the properties at May 2016 with approximately 6,000 properties being confirmed as having IFV from an engineering perspective.

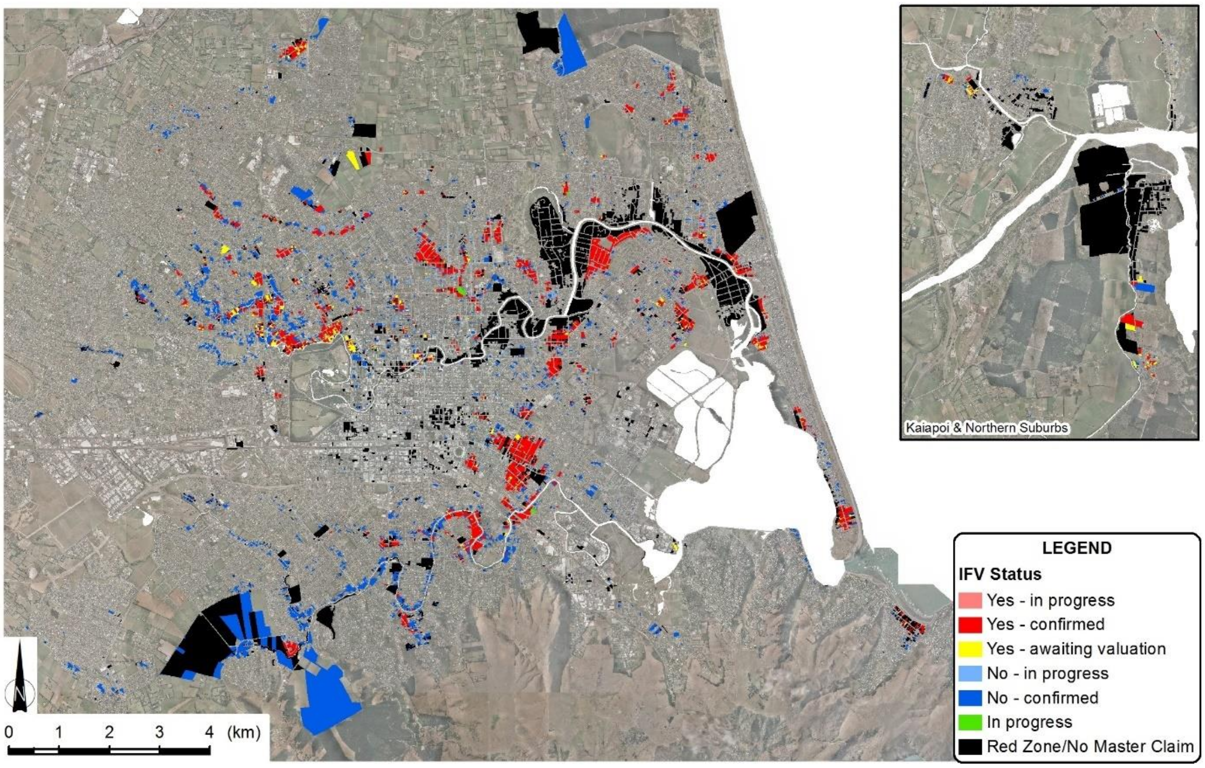

Figure 8. Map showing engineering IFV status of the properties at May 2016.

From late 2014 until early 2016, a team of over 100 professional staff assessed in excess of 11,000 properties such that EQC's customers could be compensated. The professional staff hours for the site-specific assessments was over 75,000 man-hours. Bespoke software with Google earth overlays were developed by T+T to systematically track the multi stage site-specific assessment process. This software also had to be compatible with EQC's own IT system requirements and also provide support to EQC's independent valuers.

Key Lessons Learned from Site Specific Assessments

At the time of commencing site-specific assessments, it was considered that the methodology for assessments was confirmed. In fact, given the variations in flood data, property data and types and IT system requirements, it quickly became apparent that a significant amount of work was required to adapt and develop policies and procedures for different situations. The complexity of the adaptation needed to take account of legal, practical, IT, programme and customer communication and relation requirements.

Close and regular communication with various stakeholders and a flexible attitude was required to enable changes to be made where necessary. The resources required to implement changes were typically very high, often requiring 20-30 professional staff to be involved.

CONCLUSIONS

The Canterbury Earthquake Sequence (CES) caused massive irreversible changes to the land in Canterbury. T+T worked closely with EQC to collect data on what had occurred, collect existing information and methods to assess Increased Flooding Vulnerability (IFV) caused by the CES. The assessment used land subsidence information for the Christchurch City catchments, as well as other changes to rivers and drainage in order to determine where flood depths increased as a result of the CES.

Many lessons were learned at different stages of the assessment. During the land damage mapping, rapidly mapping damage using a variety of sources allowed us to quickly verify or challenge results. We learned about banding and other data collection artifacts, which can occur during LiDAR. Whilst assessments could not have been used without LiDAR survey, it also required careful consideration of flood increases to understand whether they were real increases, or errors caused by LiDAR inaccuracy.

During flood modelling, the considerable time spent with local residents, engineers, and consultants, as well as using historical data and existing flood models and walking the river and catchments to get a sense of the drainage systems proved invaluable. Calibration and verification using real flood events was necessary to provide confidence that the model results were anchored in reality.

Many people in Christchurch were not aware that they were situated in a floodplain, which existed long before the CES. At the same time, subsidence does not always correspond to an increase in flooding due to water levels dropping by a similar amount as the ground. Therefore, the increase in flooding vulnerability caused directly by the CES was much less than many residents expected.

The resources required to undertake site-specific assessments for potential IFV properties were huge. 75,000 man-hours was required over a period of approximately 12-18 months to assess over 11,000 properties on a site-specific basis. This effort was necessary to achieve the expected level of quality for such a significant event.

Finally, while the methodology for assessing IFV was thought to be confirmed when site-specific assessments had started, variations in data meant that a significant quantity of work was required to adapt and develop methodologies for unforeseen situations. Close and regular communication with stakeholders, as well as flexibility and a willingness to adapt the approach to assessing properties was required to enable changes to be made and ultimately allow effective assessment of IFV in Christchurch.

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