INCREASED FLOODING VULNERABILITY THE METHODOLOGY AND FLOOD MODELS TO ASSESS 120,000 PROPERTIES IN CHRISTCHURCH

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ABSTRACT

An overland flow model of the whole of Christchurch was developed by Tonkin & Taylor (T&T) on behalf of the Earthquake Commission (EQC) in TUFLOW 2D software. The model results are applied to the assessment of Increased Flood Vulnerability (IFV) that is defined by EQC as a physical change to residential land as a result of subsidence due to the Canterbury earthquake sequence, which adversely affects the amenity and value that could otherwise be associated with the land by increasing the vulnerability of that land to flooding events. This form of land damage has never been assessed before in the world and the technical (including modelling) response has been unique and unprecedented.

The overland flow model covers the entire urban area of Christchurch City. It can be split into component models covering the individual catchments of the Avon, Heathcote and Styx Rivers if required, but can also be run as a single city-wide model. The city-wide model has benefits in extreme events as cross-catchment flows, which occur in Christchurch due to the flat terrain, can be represented. This model is currently being used to assess and identify (out of all 120,000 properties in Christchurch) approximately 13,500 potential IFV properties that will then have a site specific engineering assessment to confirm their status.

This paper describes the model build of the Christchurch overland model, its sensitivity testing, calibration using the 4 and 5 March 2014 flood event and also its application in assessing IFV. This paper also describes the additional work currently in progress to construct a model to assess IFV for Kaiapoi and adjoining residential areas north of the Waimakariri River.

KEYWORDS

Flood, Model, Overland, Christchurch, Kaiapoi, Earthquake

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 20 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

1.1 GENERAL

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.

EQC received a Declaratory Judgment from the High Court to confirm its IFV settlement approach so customers can be confident their settlements are soundly based. This settlement approach is summarized in the Increased Flooding Vulnerability Policy Statement (EQC, 2014).

The earthquake sequence in Canterbury affected flooding patterns in the catchments of the Avon, Heathcote and Styx Rivers. In addition parts of the Kaiapoi area and adjoining residential areas north of the Waimakariri River were also badly damaged as a result of the September 2010 earthquake and have increased flood vulnerability.

This paper is a follow up to Fisher et al (2014) where the physical processes and engineering methodology for the assessment of IFV was described. This paper describes in more detail the development of the overland flood model, the results of the identification of IFV in Christchurch, and a brief summary of the subsequent flood model built by T&T to assess IFV in Kaiapoi.

1.2 LAND DAMAGE DUE TO THE CANTERBURY EARTHQUAKE SEQUENCE

Canterbury experienced four major earthquakes (Magnitude 5.9 to 7.1) during 2010 and 2011. The four major earthquakes occurred on:

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

These major earthquake events and the associated aftershocks are known as the Canterbury Earthquake Sequence. The earthquakes caused significant changes to the land in some locations due to a combination of tectonic and liquefaction effects. Examples of the observed liquefaction-induced land damage due to Canterbury Earthquake Sequence are shown in Figure 1. Mapping of liquefaction and lateral spreading observations was undertaken after each of the major earthquakes and an example of the maps from the February 2011 earthquake is shown in Figure 2.

Figure 1 Observed liquefaction-induced land damage and dwelling foundation damage due to Christchurch earthquakes (from van Ballegooy et al 2014)

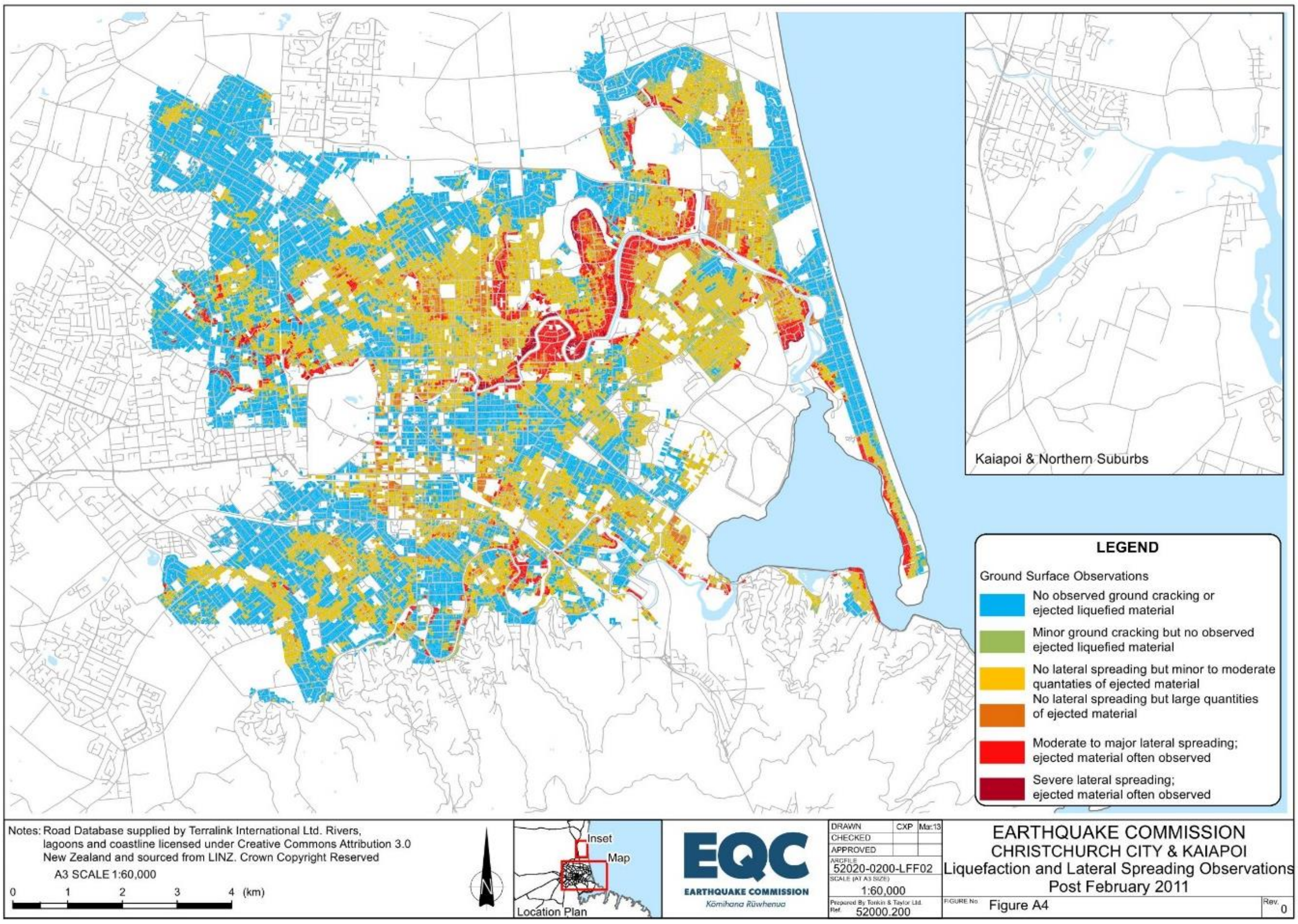

Figure 2 Mapping of liquefaction and lateral spreading observations following the February 2011 earthquake. Note: This map does not show observed land damage in Kaiapoi and Northern suburbs. Liquefaction and lateral spreading did in fact occur in this area during the February 2011 earthquake, however it was observed that it was no more severe in respect of its extent than during the September 2010 earthquake. Therefore no detailed mapping was carried out.

By comparing the ground elevation measured in the LiDAR surveys undertaken before the Canterbury Earthquake Sequence to the surveys undertaken after each of the main earthquakes, the difference between the ground level surveys can be calculated. Figure 3 presents this map of "LiDAR difference" from before the September 2010 earthquake to after the June or December 2011 earthquakes (survey coverage depends on location across the region). This map is used to infer ground subsidence. This shows ground subsidence of more than 0.5 m in some areas around waterways (mostly red zone areas) where lateral spreading has resulted in subsidence. T&T (April 2014) describes the uncertainty associated with the data used to create this map.

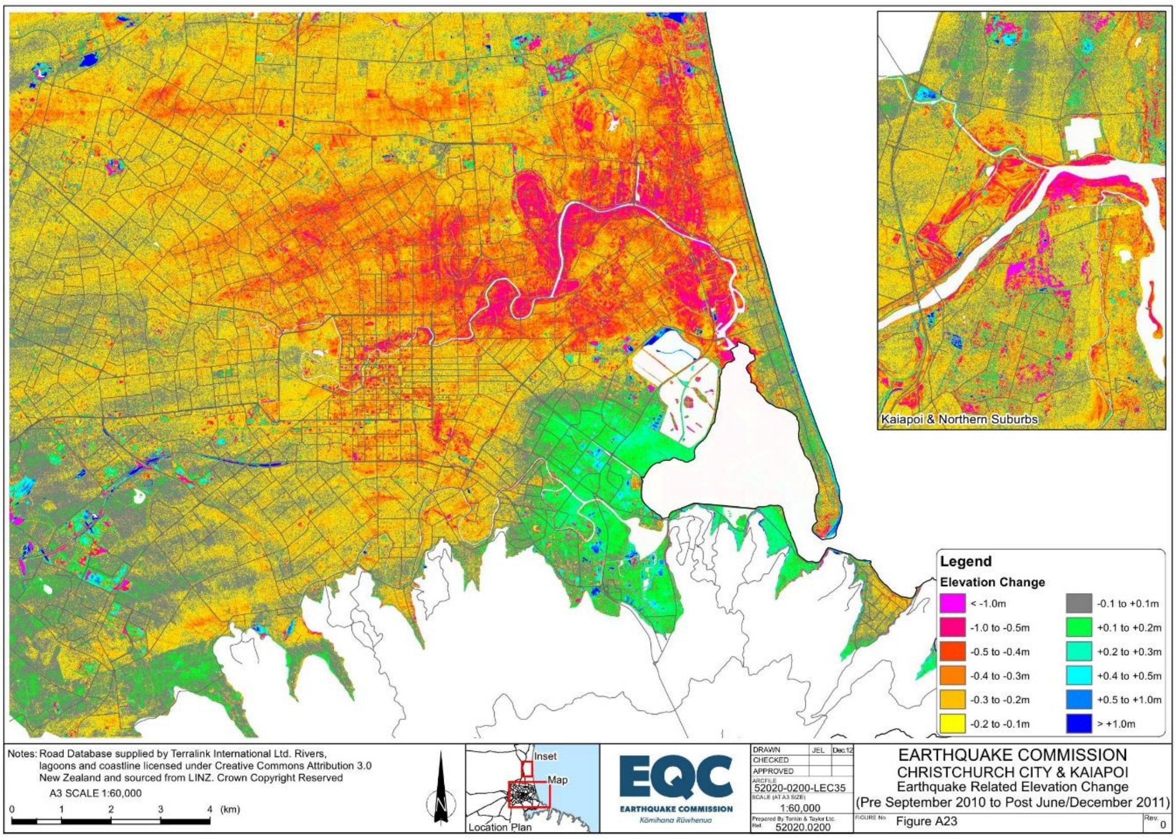

Figure 3 Map showing elevation difference between initial LiDAR surveys undertaken in 2003 to 2008 and final surveys in 2011 to 2012

2 OVERLAND MODEL BUILD FOR CHRISTCHURCH

2.1 MODELLING CRITERIA

IFV is assessed by models that use the following criteria:

- For a storm with a 1% Annual Exceedance Probability (AEP);
- Without temporary stop banks that were constructed along the Avon River after the earthquakes;
- Without an assumption for the effects of future climate change; and
- For existing development.

The models therefore describe the flooding as it would have occurred at the time of the earthquakes. Scenarios were run for the terrain (based on LiDAR) for pre and post each of the four major earthquakes. The change to the flooding between pre and post-earthquake scenario pairs is used for the assessment of change in flooding as a result of the earthquake(s).

2.2 ENGINEERING ASSESSMENT OF IFV

The modelled flood depths are initially assessed for potential IFV using an automated data assessment with thresholds as follows:

1. Has the exacerbated flood depth of the insured land increased by 0.2m or more as a result of the Canterbury earthquake sequence?
2. Has the exacerbated flood depth of the insured land increased by 0.1m or more as a result of a single Canterbury earthquake?

3. Has the insured land suffered observable land damage as a result of the Canterbury earthquake sequence?

These thresholds have been developed to provide a robust initial assessment for most properties. However, exceptions to satisfying all the thresholds in the initial assessment are made in the following cases:

- Event exception: where the insured land meets Thresholds 1 and 3, but not 2;
- Land damage exception: where the insured land meets Thresholds 1 and 2, but not 3;
- Uplift exception: where the insured land is in a specified area where the land has lifted, but it has been shown that the different levels of subsidence within the area have increased the flood vulnerability.

Where the thresholds and the exceptions set out above have been applied and the insured land has been assessed as potentially IFV, our engineers carry out a site-specific assessment of each property. The site-specific assessment is done by a team made up of an assessor, a checker and a reviewer.

In conjunction with the site-specific assessments, an area-wide review (the final engineering review) is carried out. The purpose of this review is to see whether there are any properties that have been inappropriately assessed. As a result, some properties previously assessed will be assessed again for consistency with neighbouring properties and areas. Properties identified in the area-wide review as requiring assessment where they have not previously been identified/assessed, will undergo a site-specific assessment.

In the area-wide review, the engineers will take into account the vulnerability of properties to more frequent flood events. We note that while the 1% AEP flood event is the primary event that is assessed, the 2% AEP and 10% AEP flood events are considered here, and properties that qualify for these events are also included.

The explanation and justification for the thresholds are detailed in the IFV Policy Statement (EQC, September 2014) and T&T (April 2014) which are not the subject of this paper.

2.3 MODEL SELECTION

T&T selected the TUFLOW GPU engine, largely because of the significant reduction in run-times over that using a classic CPU. The faster run-times have made sensitivity testing more feasible within the project timeframe. The sensitivity testing was undertaken to improve confidence in model results. The TUFLOW GPU engine also allows smaller grid sizes to be viable for a large city size model domain. Smaller grid sizes are desirable because they provide better (finer) resolution, which provides more accurate modelling of flowpaths. This is important for the use of the model results by EQC, who require the models to resolve flooding changes on a property by property basis (T&T 2014 Volume 3). A 5m x 5m grid size was used as it provided reasonable resolution of roads, which was tested as part of the sensitivity assessments.

The TUFLOW model is well respected in Australasia, where it is used as a tool for identifying flood hazard and for planning flood mitigation works. The TUFLOW GPU engine is also accepted by the UK Environment Agency for flood modelling as a result of a 2D hydraulic modelling benchmarking exercise (Environment Agency 2013).

2.4 MODEL COVERAGE

The Avon catchment is depicted in pink, the Heathcote catchment in green and the Styx catchment in orange in Figure 4. The main channels have been added into the model as breaklines from the existing MIKE Flood model are shown in blue. Additional significant channels and culverts based on CCC GIS, which have been modelled as channels are shown in red. Pipes which have been modelled as simulated pipes are depicted in purple. Temporary stopbanks along the Avon are shown in yellow.

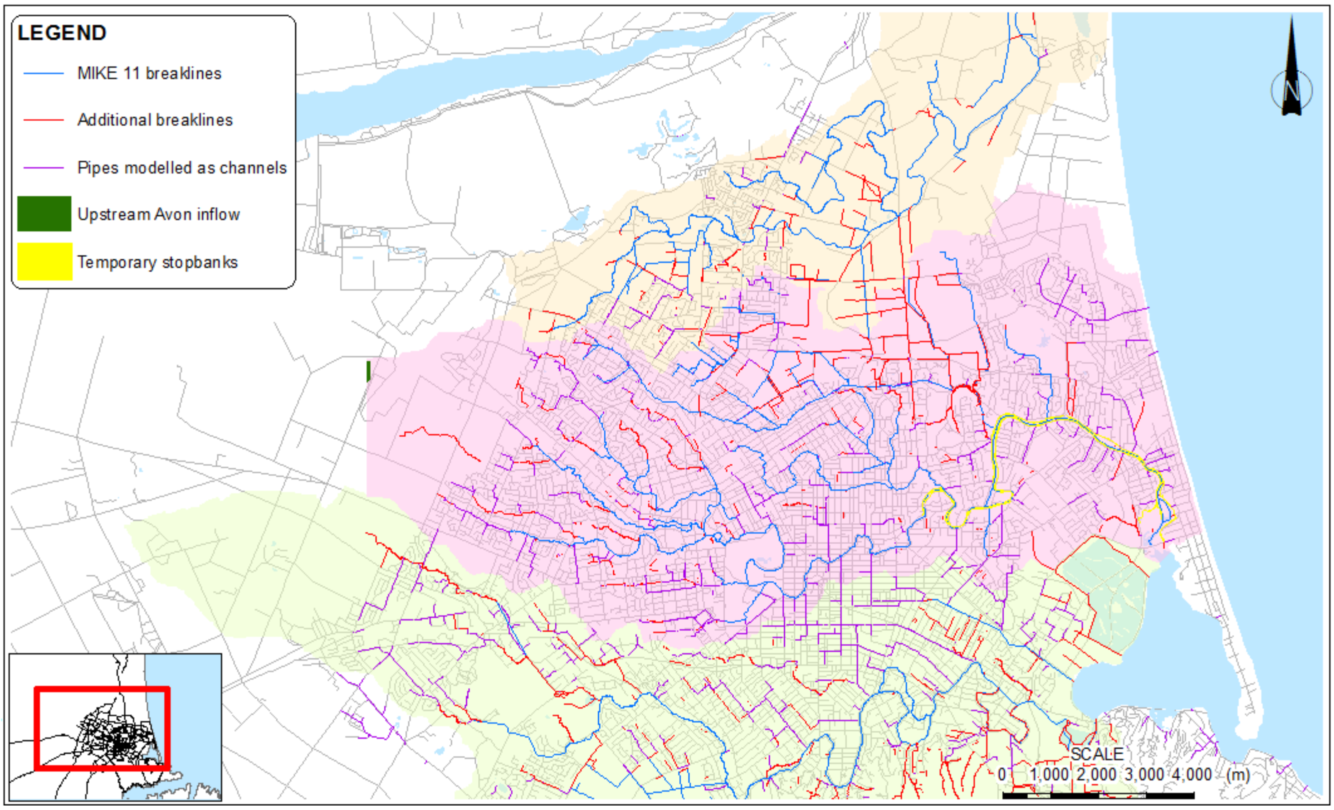

Figure 4 Avon catchment (T&T 2014 Volume 3)

2.5 MODEL DEVELOPMENT AND SENSITIVITY TESTING

The process for developing the overland flow model is illustrated in Figure 5 showing base model development, sensitivity testing and calibration.

The Avon River catchment was selected for sensitivity testing as it was considered to be representative of Christchurch catchments and enabled more sensitivity assessments to be undertaken with shorter run times. An exception to this was that the rainfall duration sensitivities that were conducted using the city-wide model, given that each of the three major catchments are known to respond differently to rainfall of differing durations. The conclusions reached from the sensitivity testing was applied to final model runs that used the single city-wide model.

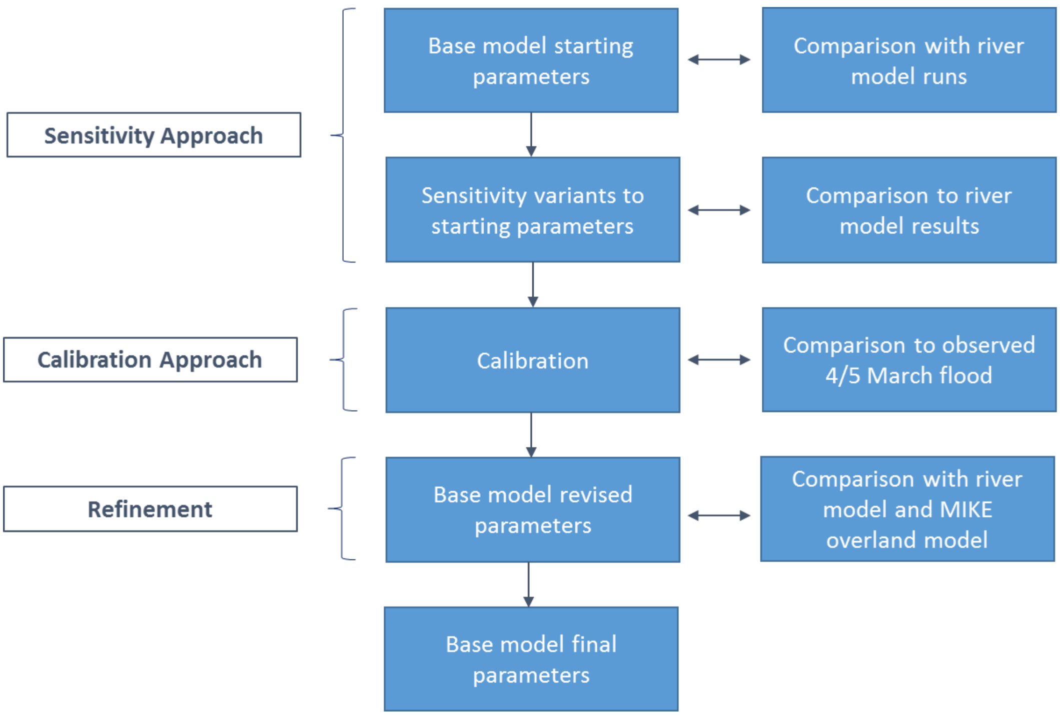

Figure 5 TUFLOW model build and testing process (T&T 2014 Volume 3)

Sensitivity testing was carried out over a range of parameters and model architecture elements, including the rainfall distribution (variation of temporal profile applied for constant rainfall depth for each duration and frequency), surface roughness, surface soil infiltration rates, antecedent groundwater level, representation of roads in the hydraulic model, allowance for piped networks and variation in channel invert level.

The models that have been developed exhibited relatively low sensitivity to many of the parameters for which sensitivity testing was carried out. The greatest sensitivity was exhibited for the primary pipe network capacity, which was tested by removing rainfall to represent the primary pipe network draining with a 20% AEP level of service. This sensitivity test revealed that if this pipe network does globally function to this level of service at all times, then substantially less flooding than predicted by the models would occur. Upon closer consideration this assumption was found to be flawed, mainly due to the very flat topography in Christchurch. Once tailwater levels have risen during a flood event, available hydraulic grade is minimal and it was found that pipe networks convey less and less flow as flood levels rise, to the point where submerged pipes may convey very little flow at all near to the peak of significant floods (due to a lack of available hydraulic grade). This conclusion is supported by observations of flooding.

The results were also shown to be sensitive to the infiltration rates applied. There was a large difference in model results between simulations with no infiltration and simulations with some allowance for infiltration. Accounting for soil infiltration has been the practice adopted by Christchurch City Council (CCC), and is the practice for CCC river flood models, which have been calibrated. The finding of the sensitivity analysis was that allowance for soil infiltration should be made.

Relatively low sensitivity was displayed in model results to the other parameters examined. Of particular interest was the low sensitivity in resultant peak flood levels and peak flood discharge to adopted rainfall profile, when comparisons between the CCC rainfall distributions and the nested rainfall hyetograph was made. Low sensitivity in results was also observed when the rainfall duration was increased.

The sensitivity testing has enabled a thorough understanding of the results sensitivity to model architecture and input parameters. The models can now be used with greater confidence for the IFV assessments.

2.6 MODEL CALIBRATION

Subsequent to the model building process, a flood event occurred in Christchurch that was appropriate for model calibration. The rainfall event of 4 and 5 March 2014 has been hindcast using the TUFLOW model. The rainfall input to the model was varied spatially as collected in 18 rain gauges across the city, and modelled flood extents were compared with observed flood extents. This comparison revealed a need for inclusion of more of the piped drainage network in the model than had been previously included. This was addressed with simulated pipes in subsequent iterations of the model. After the inclusion of simulated pipes in the TUFLOW model, there was a good fit between observed and modelled flood extents in areas where sufficient observations had been collated.

Finally, the model was compared to both earlier MIKE overland flow models and MIKE river models. This comparison necessitated an amendment to the chosen tidal boundary. The earlier model adopted a static 10% AEP tidal boundary, whereas as a result of the comparison a dynamic tidal boundary timed to coincide with peak intensity rainfall for each of the three rivers was adopted for the base model final parameters. After the downstream tidal boundary was adjusted the different models produced comparable results in the tidally affected areas.

Figure 6 shows a comparison of the modelled flow at the Gloucester Street gauge (Avon River) with the gauged flow from the 4 and 5 March 2014 flood event. Rainfall is also shown on this plot. It is considered that the peak observed flow at Gloucester Street gauge may be underestimated due to out-of-bank flow. It was also proven from the model that the Gloucester Street gauge underestimates the observed flows for the falling limb of the hydrograph.

Figure 7 shows the spatial distribution of flooding comparing the calibrated model with observed flood extents. The modelled flood depths and extents matched the actual flooding well where it was observed (and recorded). We considered the model to sufficiently represent the observed flood, which gave further confidence to the application of the model for the for the IFV assessments.

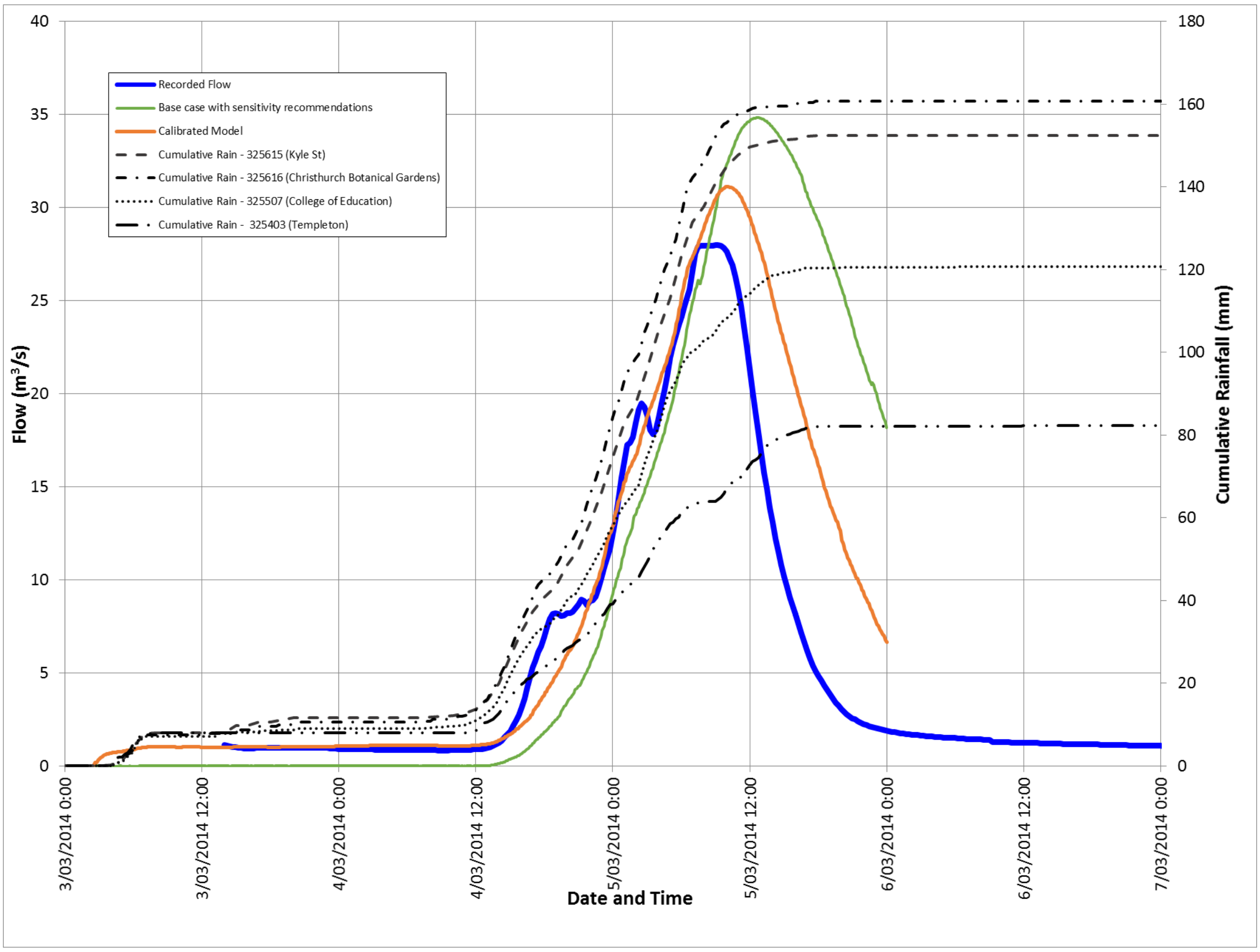

Figure 6 Flow time series Gloucester gauge for the 4 and 5 March 2014 calibration event

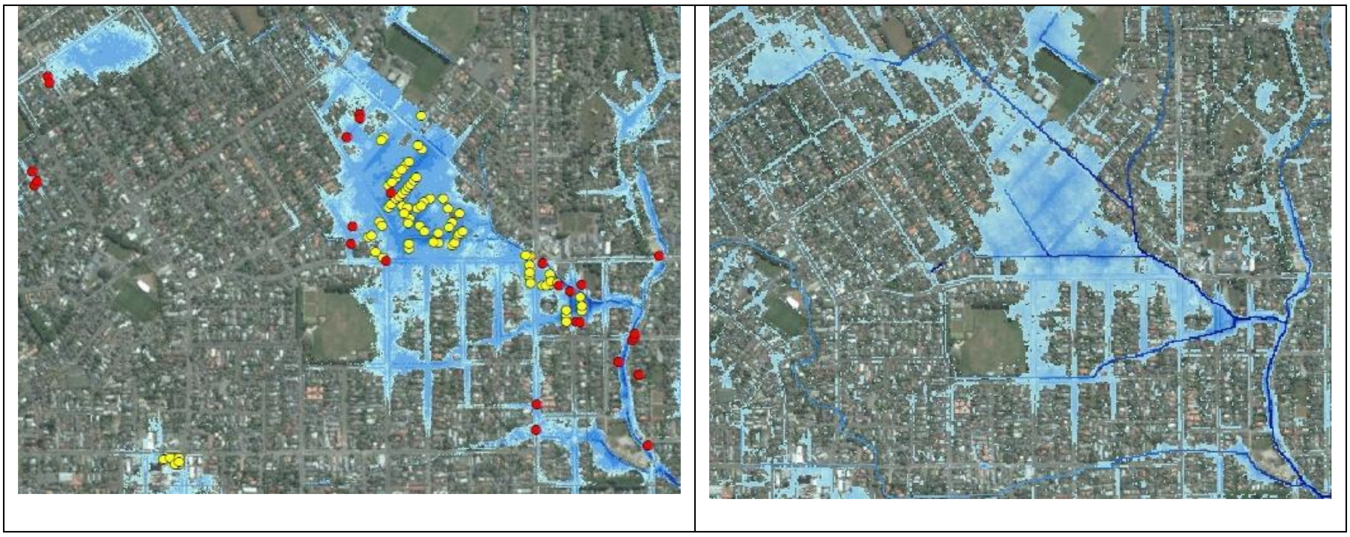

Figure 7 Calibration run of maximum depths (right is modelled) compared to a combined T&T, CCC and NIWA observed flooding map (left is observed) for the 4 and 5 March 2014 event – Flockton Basin.

3 KEY FINDINGS OF FLOOD MODELLING

3.1 COMPARISON OF PRE AND POST EARTHQUAKE FLOOD EXTENT

A notable finding of the study is that regionally across Christchurch the flood extents are largely unchanged (Figure 8). There have as expected been local increases in flood extents e.g. in Avondale where there was significant subsidence, Linwood and Bexley.

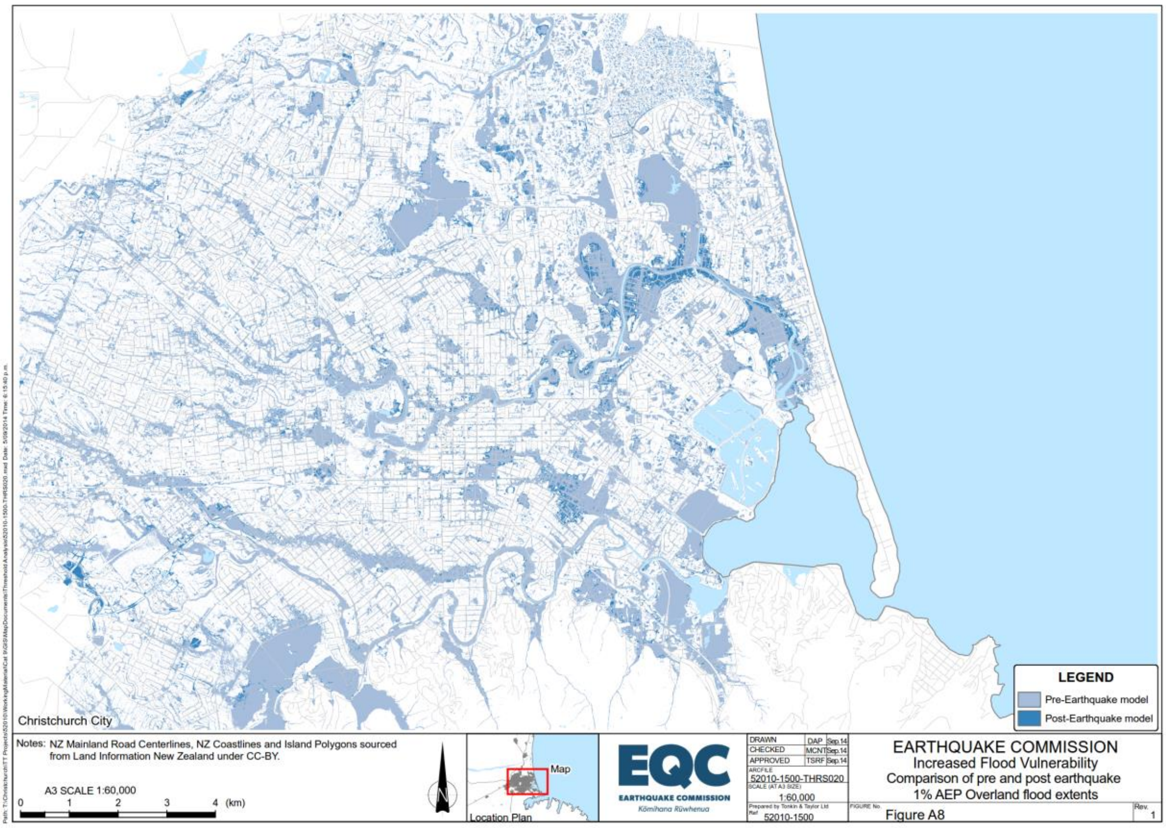

Figure 8 Comparison of pre-earthquake flood extents (light blue) vs post-earthquake flood extents (dark blue)

3.1.1 IDENTFICATION OF POTENTIAL IFV PROPERTIES AND EXCEPTIONS

Table 1 provides a summary of the potential IFV properties (and exceptions) in Christchurch. This shows that approximately a third of potential IFV properties are located in the residential red zone, which are predominantly located adjacent to the Avon River or the Avon-Heathcote Estuary. The three technical categories (TC1, TC2 and TC3) are land zonings defined by MBIE and the residential red zone is as defined by CERA.

Figure 9 shows the spatial distribution of potential IFV properties and exceptions. This shows that the highest density of potential IFV properties is located along the Lower Avon where significant subsidence has occurred. The area around Linwood and Phillipstown also has significant density of IFV properties, but is caused predominantly by overland flooding rather than fluvial flooding.

Table 1 Estimate of potential IFV properties (including exceptions) in Christchurch (Simpson 2014)

Technical Category	**Potential IFV**	**Exceptions**		**Total**
		Event	**Land Damage**	
TC1	39	6	0	45
TC2	2,501	335	987	3,823
TC3	4,757	405	97	5,259
Subtotal	**7,297**	**746**	**1,084**	**9,127**
Red Zone	4,207	104	36	4,347
Total	**11,504**	**850**	**1,120**	**13,474**

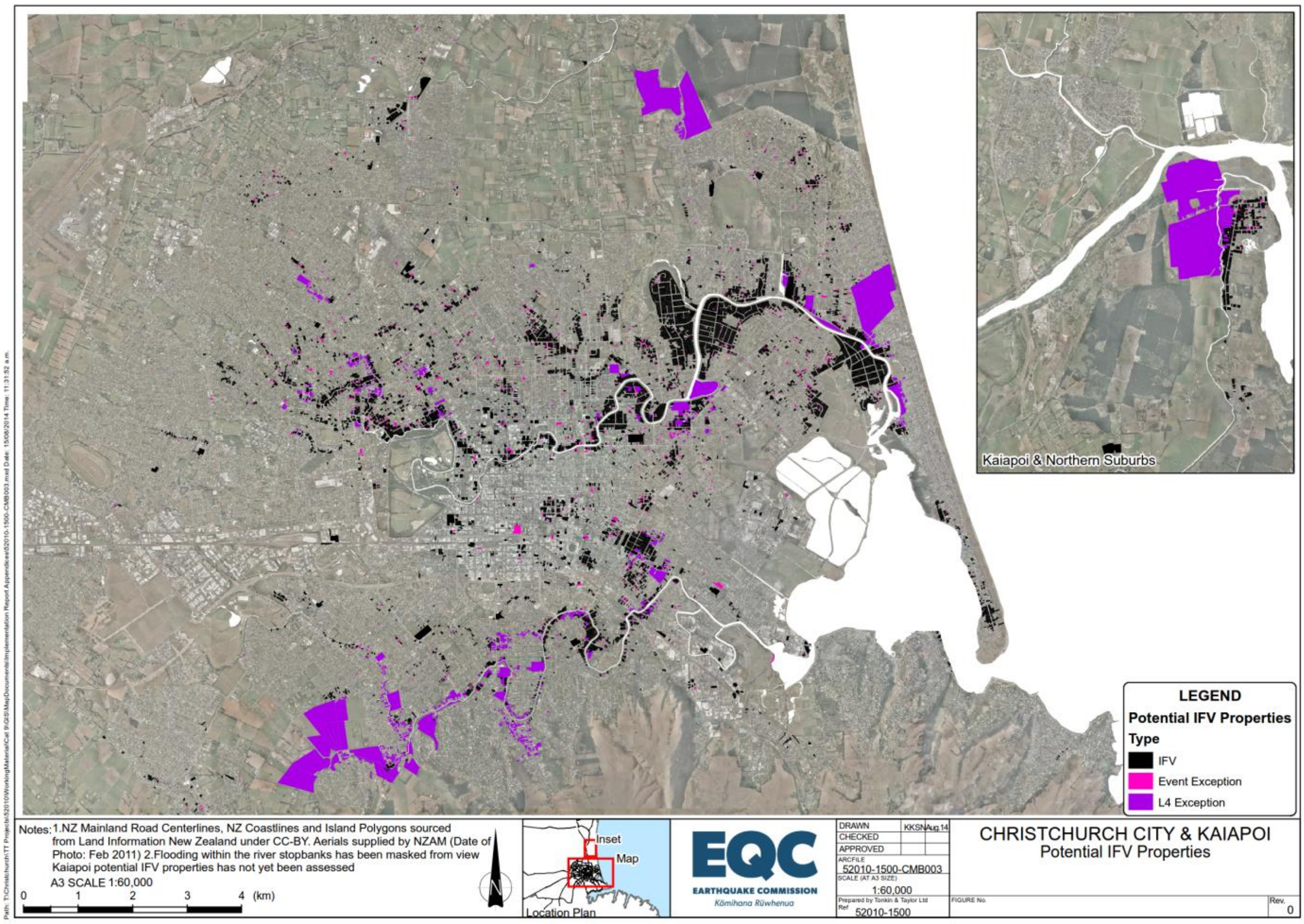

Figure 9 Identification of potential IFV properties (and exceptions) in Christchurch (Simpson 2014)

4 ASSESSMENT OF IFV FOR KAIAPOI

A flood model has been developed by T&T at EQC's request to identify potential IFV properties in the Kaiapoi, Kairaki and The Pines Beach areas area. These areas were badly damaged during the September 2010 earthquake with a significant number of residential properties being red zoned as a result.

Kaiapoi itself is located adjacent to, and straddles, the Kaiapoi River. The upstream surface drainage system is extensive and complex. A significant flood event was experienced in Kaiapoi in June 2014 which caused some surface and house flooding.

A new TUFLOW GPU model was necessary because there was no other model in existence that was suited to the task. Waimakariri District Council had built a model which covered the extent of the assessment area, but run-times were excessive which rendered it unsuited to IFV assessment. Model-specific sensitivity testing was undertaken to complement sensitivity testing completed for the Christchurch overland flow model.

The modelled flooding has been verified using flood reports collected by WDC for the June 2014 flood event (which had an ARI between 3 and 15 years).

Extensive flooding is predicted for Kaiapoi in response to a 1% AEP rainfall event. The changes in land level due to earthquakes have caused changes in floodable extents and depths.

Properties are currently being assessed in accordance with EQC's policy to determine whether they have IFV.

5 CONCLUSIONS

As a result of the earthquake sequence in Canterbury, the topography of the land has undergone significant changes. T&T on behalf of EQC has undertaken a city wide assessment for residential properties that have been affected have experienced an increase in flooding caused by the Canterbury earthquake sequence.

The issue required complex legal, policy and bespoke engineering analysis to define what damage had occurred as a result of the earthquakes and to provide a robust methodology to ensure a consistent assessment across Christchurch. An assessment of this type as far as the authors are aware is a world first. Extensive documentation has bene provided to support the methodology and assessment adopted including international peer review. A Declaratory Judgement was sought (and subsequently received) by EQC to determine the legality of the approach.

To assess IFV in a reasonable timeframe T&T constructed an overland flood model using TUFLOW GPU. This model was the first city wide scale flood model developed for Christchurch. The model underwent significant sensitivity testing to establish its usefulness. Following the flood event of 4 and 5 March 2014 the model was verified and calibrated using available flood data including river flow gauges, observed and survey flood extents. A subsequent overland flow model has been developed for the area between the Ashley and Waimakariri Rivers to assess IFV in the areas of Kaiapoi, Kairaki and The Pines Beach.

The IFV methodology and flood modelling has undergone international peer review by a panel of three experts experienced in hydraulics, flood hazard mapping and management.

Approximately 13,500 properties have been identified as having potential IFV in Christchurch. Approximately a third of these are located in the residential red zone.

These properties are currently undergoing site specific assessments to establish whether they meet EQC's definition of IFV.

ACKNOWLEDGEMENTS

We thank Christchurch City Council for CCC's continued support and supply and use of data for this workstream.

We also the International Peer Review Panel for their helpful and timely review of the IFV assessment methodology and overland model.

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

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