STYX RIVER EARTHQUAKE EFFECTS

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ABSTRACT

The urban development of Brooklands in the lower Styx River Catchment is at risk of flooding and is predicted to be significantly impacted by sea level rise. The recent Canterbury earthquakes have further exacerbated the flood hazard in Brooklands. This paper highlights the natural and regulatory changes due to the earthquakes.

The earthquakes had a major impact on the Styx River Catchment, including: land deformation, changing river and floodplain profiles and damaged built infrastructure. These impacts have an effect on the nature of the flood hazard in Brooklands. This paper presents the earthquake physical effects and the assessment of change in flood hazard. It also discusses and the range of outputs required to make engineering decisions on the future of Brooklands, within the context of a changing regulatory environment where decision makers have required detailed analyses of this complex system to be undertaken rapidly.

KEYWORDS

Flood, Flooding, Earthquake, Land Damage, Brooklands, Styx River

PRESENTER PROFILE

Graham Harrington has a Masters degree in Soil and Water Engineering from the University of Canterbury. Much of his career has been in the Ministry of Agriculture but for the last six years has worked with the Christchurch City Council and is currently a Senior Surface Water Planner. These responsibilities include technical oversight of Stormwater Management Plans and the provision of information for setting floor levels in relation to the Building Act and the Flood Management Areas in the City Plan. The earthquakes have significantly changed the topography in Christchurch so he is now managing a number of river re-modelling projects which are required for setting new building levels and assisting EQC and CERA with earthquake recovery information.

Tom Parsons is a hydraulic engineer with nine years experience in hydraulic modelling, hydraulic design and analysis. Tom has worked within the fields of stormwater, wastewater and waterways on a range of projects, from conceptual stages to detailed design of new infrastructure and through to construction management. His waterways experience in New Zealand has covered a broad range of environments from steep natural rivers to highly modified urban watercourses and structures. He has worked on the Styx River Catchment Study since joining GHD in 2009 with the most recent investigations being focused on the effects of the Canterbury Earthquakes.

1 INTRODUCTION

The Styx River is near the northern boundary of Christchurch City and drains the suburbs of Belfast and Northlands and passes Spencerville and finally Brooklands before discharging through tide-gates into Brooklands Lagoon. Brooklands Lagoon is connected to the Waimakariri River close to where it discharges into Pegasus Bay. The Waimakariri River and the Lagoon are both tidal in this area. The lower reach of the Styx River – alongside Spencerville and Brooklands village, is a wide, low-lying floodplain which has been very successfully protected from the tide by the tide-gates and is now productive farmland. The location of the catchment is shown in Figure 1, below.

Prior to the earthquake events, investigations were in progress towards a Stormwater Management Plan (SMP) for the catchment. The aim of this was to describe how stormwater would be managed as the catchment develops over the next 35 or so years. The Belfast area was considered as one of the two main development areas for Christchurch – the other one being in the South West of Christchurch. This Stormwater Management Plan was also to serve as the basis for a Catchment Discharge Consent from Environment Canterbury to ensure that stormwater management would proceed in an integrated manner along with the developments and landscape of the area.

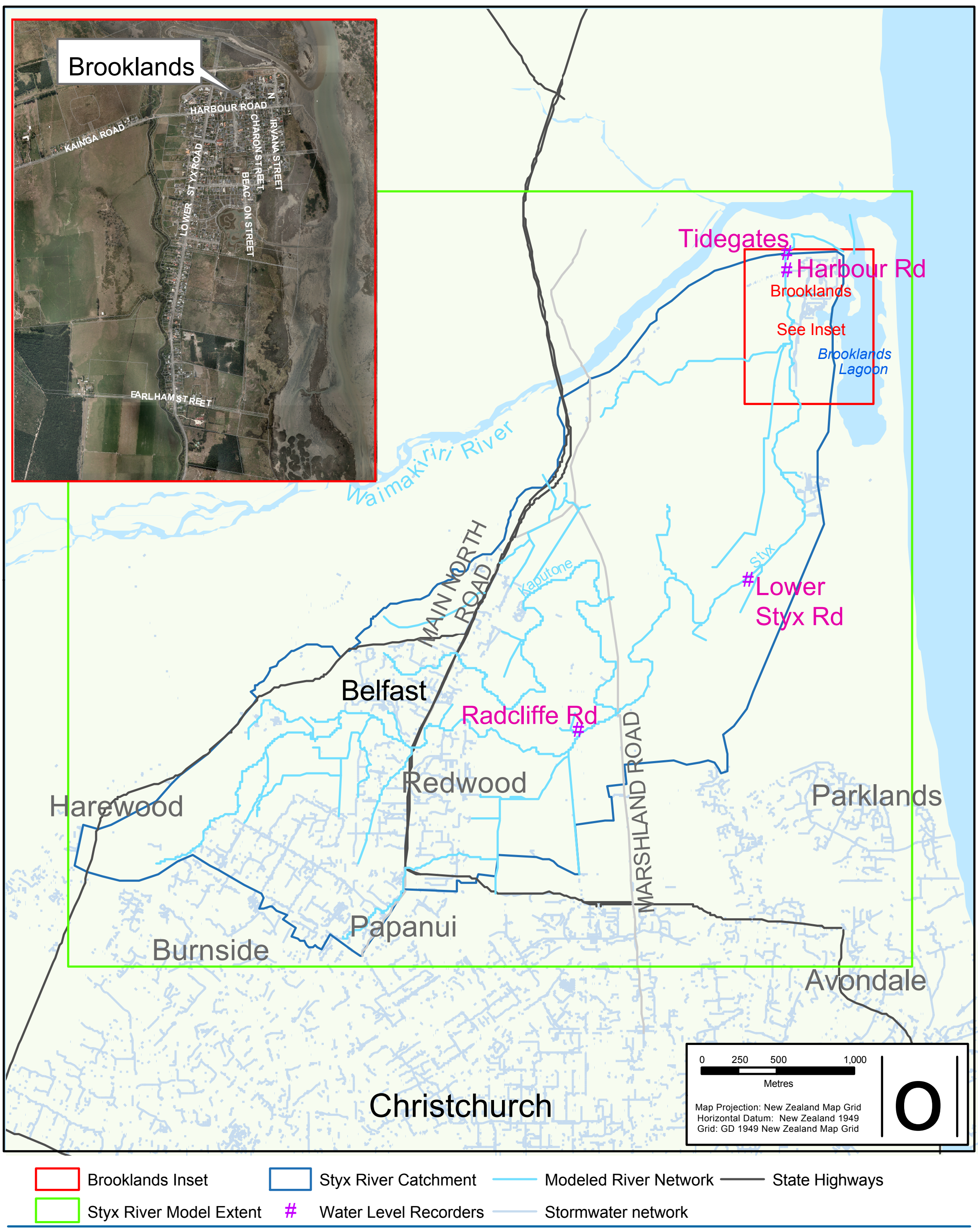
Earlier planning work (Variation 48 to the Christchurch City Plan) had classified the Styx lower floodplain as a "Flood Ponding Area" – recognizing its importance as a detention basin and placing limits on development and filling in the area. Brooklands and Spencerville were classified as "Flood Management Areas" recognizing their vulnerability to flooding and in particular to sea level rise. This classification generally means that higher floor levels will be required as a part of a building consent than would otherwise be the case for a normal building consent under the Building Act.

To inform the earlier SMP investigations CCC commissioned GHD in 2008 to develop a 1D/2D linked hydrologic/hydraulic model of the of the Styx River and its surrounding catchment. A model was developed using the DHI MIKE product suite including MIKEFLOOD, MIKE11, MIKE21 and MIKEURBAN.

The Brooklands and Spencerville villages were severely impacted by the Magnitude 7.1 Earthquake on 4th of September 2010. They were again affected to a lesser extent by the Magnitude 6.3 Earthquake on 22nd of February 2011 and the $10{,}000^{+}$ subsequent aftershocks. Land levels appear to have settled by between 150mm and 300mm which has increased the risk of flooding from both the Styx River and also from the tide – where the prospect of sea level rise makes this area quite vulnerable.

Once new aerial laser survey (LiDAR) information was available – following each of the major earthquake events – the hydraulic model was used for the assessment of earthquake effects on the developed areas and thus contributed, along with geotechnical assessments, to the decision to "red zone" Brooklands village following the earthquakes. This is a process where the Government has offered to buy the properties within such a zone.

The earthquakes therefore significantly changed the regulatory environment and increased the major stakeholder interest in the computer model and the type of investigations which were requested. The Earthquake Commission (EQC) were interested in investigations which would indicate what was the change in flooding risk – which they would need to reverse or compensate or mitigate in some suitable way. The Christchurch Earthquake Recovery Authority (CERA) needed information to decide whether it was economically feasible to repair damage and reconstruct the development area in accordance with the present building codes and flood protection standards. This meant that there were typically pre- and post-earthquake model runs of each scenario after each major earthquake event for which new LiDAR topographic information was flown. The return intervals most commonly used were; 0.5% AEP – for consideration of City Plan "Flood Management Area" requirements and; 2% AEP – for consideration of Building Act requirements. There were also assessments with and without the Ministry for the Environment (MfE) guideline allowance for 0.5m projected sea level rise – so we could assess the immediate risk situation and the future risk situation.



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Data source: CCC: Parcel Layer 2011, Roads Layer 2011, Stormwater Network 2011, Aerial Imagery Feb 2011. GHD: Styx River Model Extent, Styx River Catchment, Modeled River Network. Created by Gpayne2. Edited by Amarburg.

Figure 1: Catchment Location Map

2 OBSERVED EARTHQUAKE EFFECTS

2.1 LAND DEFORMATION

2.1.1 RIVER SHAPE

The lower Styx River has a shallow grade and is subject to the growth of weed during the summer which needs to be routinely removed or "harvested" to keep the low flow river levels from inundating the flood berm. Typically the removal of these weeds is undertaken once per year and would lower the average water surface level by 500mm to 600mm.

The lower Styx River cross sections had been surveyed in 2009 as a part of the earlier investigations so the changes as a result of the earthquakes – as distinct from any ongoing sedimentation and/or erosion – are fairly evident. The changes in cross section 17, near Spencerville, are shown in Figure 2. These changes are typical of the earthquake effects which occurred in the lower Styx River from the point it emerges onto the floodplain. Such changes were not so evident in the upper reaches of the river, probably due to variability in soil conditions and greater depths to groundwater.

Typically, what happened was that, along with a general settlement of the land, there was cracking and lateral spread of the ground towards the centre of the riverbed – as can be seen in Photograph 1. The other main effect is bed heaving as a result of the squeezing by the banks moving inwards – and perhaps from the pressurized liquefied soil beneath. There may have also been some infill by liquefied sand or silt erupting into the bed and also being transported from upstream. It is evident in photograph 2 however, that in this diversion channel close to Brooklands village, the actual bed of the channel has heaved because of the normal bed litter being visible – and there is none of the typically grey liquefaction silt on the surface.

Photograph 1: Lower Styx Bank Slumping

Photograph 2: Lower Styx Diversion Channel bed heave

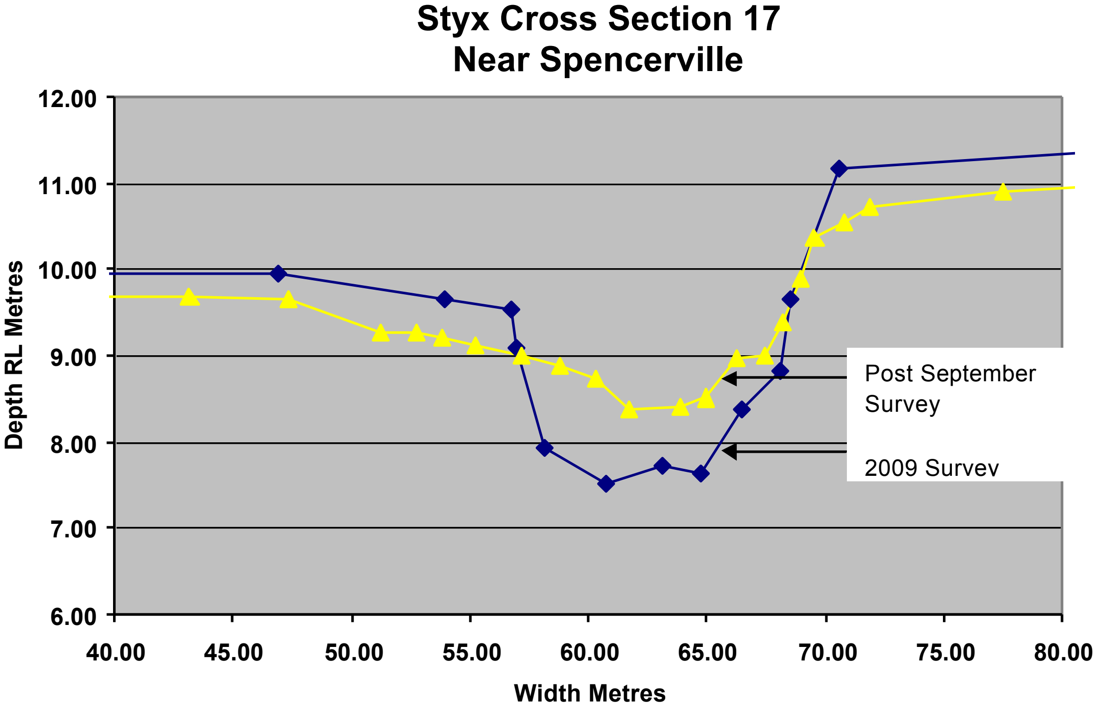

Figure 2: Typical Change in Cross-Section in the Lower Styx

2.1.2 FLOOD PLAIN TOPOGRAPHY

Four aerial laser (LiDAR) surveys have been undertaken - October 2010. January 2011, May 2011 and August/September 2011 - with the August/September flight covering the entire catchment. This complete data set has been used in the analysis of change in land level presented in this paper. Subsequent earthquakes, most notably December 2011, may have further exacerbated the observed effects but the inspection of the intervening LiDAR survey data sets showed that the September 2010 Earthquake had the greatest impact.

The effect of the general land damage on the flood plain was typically to drop the flood plain level relative to the sea by approximately 150 mm – 300 mm. The cause for this drop can be generally attributed to liquefaction and settlement. The change in level between LiDAR surveys before the September 2010[1] and after the June 2011 earthquakes is presented in Figure 3.

Areas where the greatest drop in land level can be seen are along the terrace adjacent to the flood berm on the true left bank of the river and along the banks of the Styx River. Some of this change may be attributed to bank failure as described above.

The most notable change in level shown in Figure 3 is along the base of Brooklands lagoon. This change is more likely due to the water level in the lagoon at the time of flying the LiDAR than earthquake effects. As LiDAR survey cannot penetrate the water surface the level of the tide may have influenced the results.

There are other areas within Brooklands where the land level has increased. This can be attributed to building platforms being raised for new development in order to meet the requirements of the Flood Management Area - after the 2003 survey and prior to September 2010 earthquake.

The effects of this drop on flood level are discussed in more detail later in this paper but more generally the drop in flood plain, and more critically settlement beneath the sand dunes (reducing their level relative to the sea), significantly increases the risk of tidal flooding in large events due to over-topping from Brooklands Lagoon. In conjunction with the effects of the river the drop in flood plain level has decreased the flow rate at which first flooding occurs.

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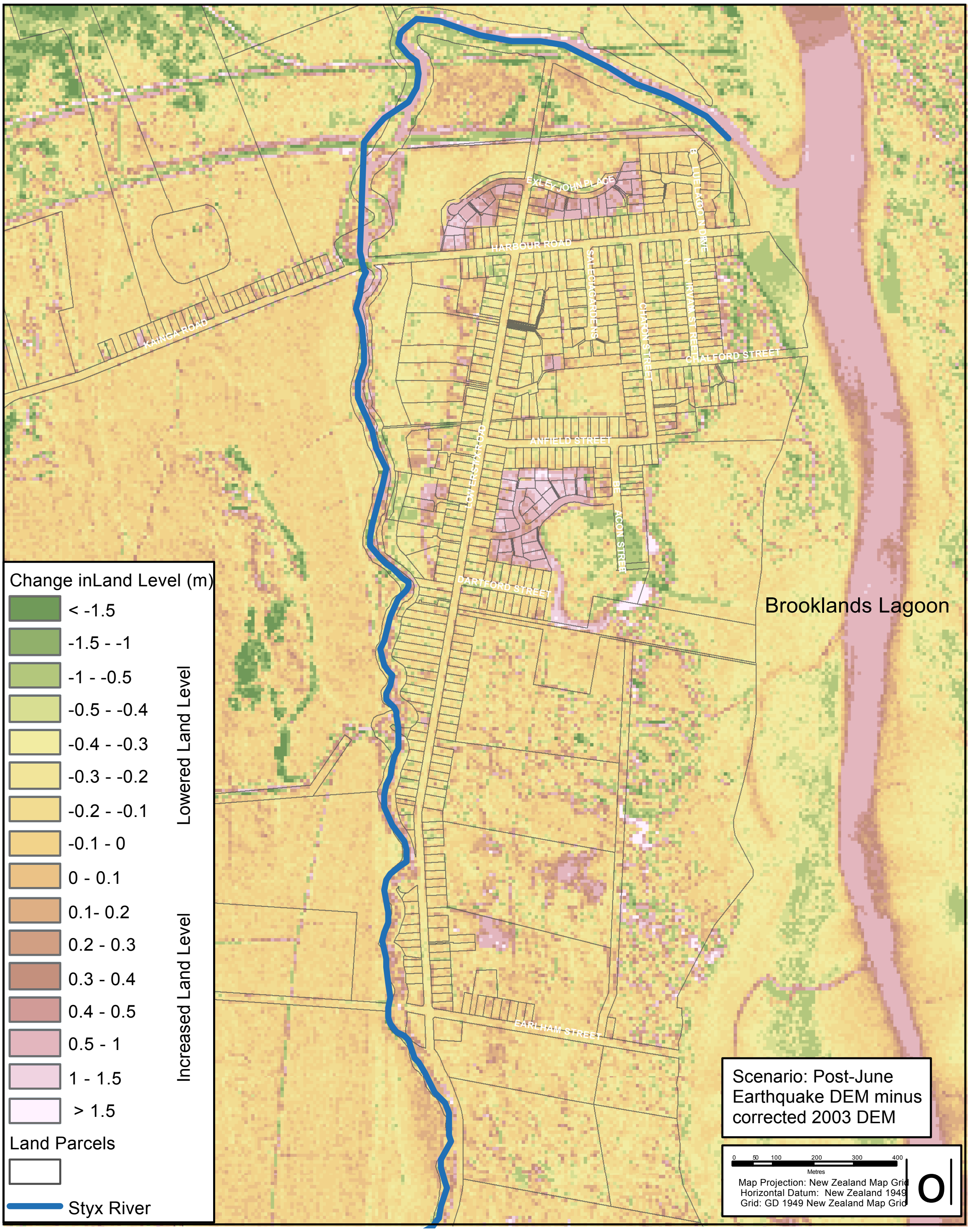
[1] The LiDAR data used in this comparison is the corrected 2003 data. The cause and affect of the correction is discussed elsewhere in this paper.



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Data source: CCC: Parcel Layer 2011, Roads Layer 2011. GHD: Change in Height (dem1103_diff). Created by amarburg.

Figure 3: Change in land level between 2003 and August 2011

2.2 BUILT INFRASTRUCTURE

2.2.1 SUBSURFACE ASSETS

The effect of the general land damage on the subsurface assets is typically to dislodge and break underground pipes and for them to fill with liquefied silt. One of the most dramatic effects in Brooklands was the eruption of the manholes by about 300mm above the road level as shown in photograph 3. It was initially thought that this was due to floatation on the liquefied subsoil; however, level surveys indicate that it is more to do with the settlement of the ground around the manholes.

Silt was also commonly ejected from around the footings of power poles as in photograph 4 – which tended to de-stabilise the poles.

There is little underground stormwater infrastructure in Brooklands Village except for plastic field drains beneath the roadside swales and some piping which leads this water to the Styx river.

Photograph 3: Brooklands Sewer Manholes

Photograph 4: Silt ejected around power poles

2.3 HYDRAULIC EFFECTS

The immediate effect of the earthquake on the river was to rapidly increase recorded water levels as shown at the Radcliffe Rd gauge in Figure 4. This level recording site is in the mid reach of the Styx River, beyond the tidal backwater effects caused by impoundment behind the tide-gates. This gauge does show the general summer trend to higher water levels as the weed growth in the lower reaches of the river causes a greater resistance to flow. This trend of higher water levels shown in Figure 4 makes a step change at the time of the February earthquake – and this has been interpreted as the time when significant damage to the river took place which decreased the conveyance capacity.

It is also notable in Figure 4 that a minor fresh occurred in the river immediately following the earthquake as the groundwater ejected during the earthquake was drained away through the river channel.

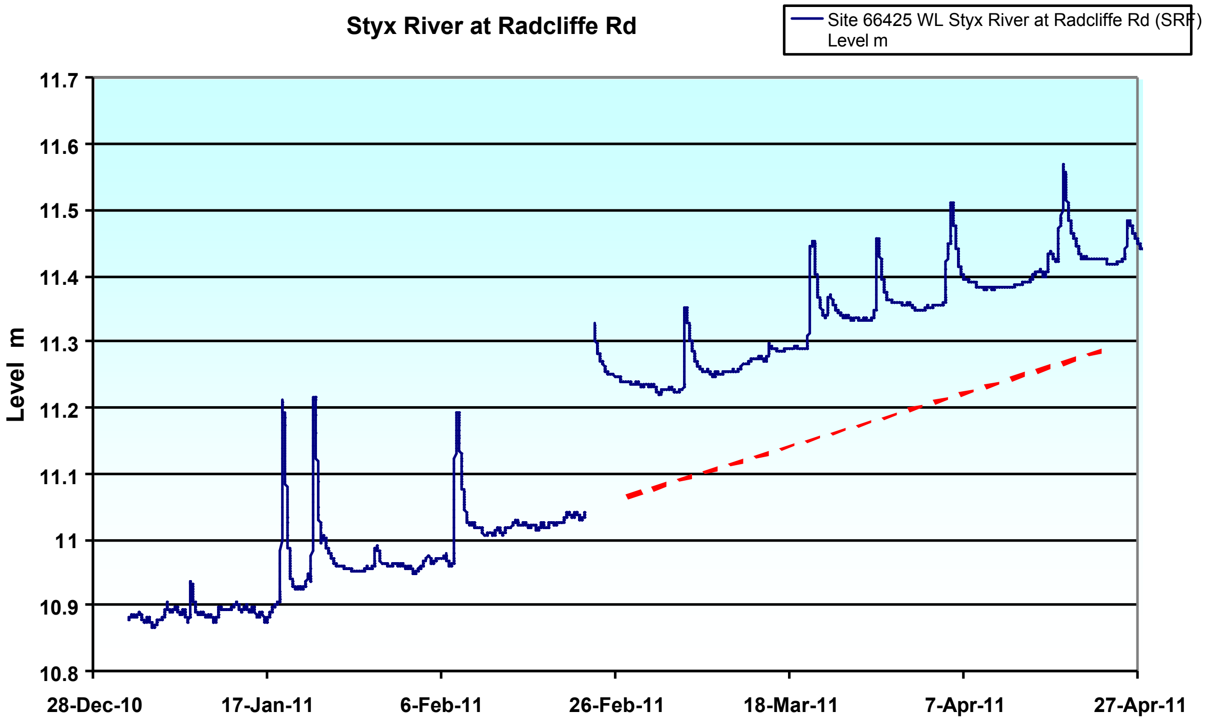

Figure 4: Recorded Water Level at Radcliffe Rd

3 FLOOD HAZARD

CCC identified soon after the September earthquake that the land damage may have significantly altered the flood hazard in the catchment; most notably, in and around Brooklands. This immediately raised a number of questions with regards to:

- The effects of the earthquakes on flood behavior (including flood depth and the ability of the river to pass flood flows);
- The effect of the earthquakes on coastal inundation;
- Potential mitigation measures; and
- The effects of planning restrictions on repair/rebuilding of Brooklands.

Investigations into these issues have been undertaken using the hydraulic model of the system developed to inform the Styx River SMP and they were well underway prior to the February 2011 earthquake. The subsequent earthquakes required reconsideration of the flood behavior of the catchment.

3.1 PRE-QUAKE FLOODING BEHAVIOUR

3.1.1 FLUVIAL FLOODING

The behaviour of flooding of the Styx River depends on location within the catchment. Flooding in the upper catchment (above Main North Road) is driven by peak river flow and river capacity (i.e. the shape and size of the main channel).

The mid catchment is flatter than the upper catchment and is influenced by both river capacity and available flood plain storage. The river berms are much wider and overtopping of the main channel is likely in modest rainfall events.

In the lower reaches (below Marshlands Road) flooding is influenced by the tide, the tide gates and the volume of flood water. Flooding about Brooklands is more dominated by storage in the flood plain upstream of the tide gates rather than channel capacity. When the tide gates are closed flood water ponds behind the flood gates eliminating the influence of channel capacity. As a result the flood extent and depth is driven by flood volume (i.e. the total depth of rainfall) and the shape of the flood plain.

3.1.2 COASTAL FLOODING

Overtopping of the sand dunes behind Brooklands Lagoon in extreme tide events (allowing for storm surge and barometric effects) has been identified as a potential flooding scenario. The inundation of Brooklands could result and the risk of this flooding will significantly increase with sea level rise. However, there are significant restrictions to tidal flooding due to the limited period during which the tide level is predicted to overtop the trough in the sand dunes. The level of flooding in the Styx River due to overtopping of the sand dunes is constrained by the available conveyance and the friction of the ground surface.

3.2 ASSESSMENT METHODOLOGY

3.2.1 PRE-QUAKE

The hydraulic model used the best data available at the time to predict the behaviour of the river and flood inundation throughout the catchment for a range of events. The model hydrology (MOUSE model B) and hydraulics were calibrated to match the August 2008 flood event (with an average recurrence interval of approximately 10 years) using the original 2003 ground surface data.

The model was used to predict flooding resulting from rainfall[2] and sea level[3] up to a 0.5% AEP event. The flood levels resulting from the 0.5% AEP events are required for setting building floor levels as required in the city plan Flood Management Areas. The model has also been used to establish the 2% AEP flood level required to set building platform heights in accordance with the building code.

3.2.2 RE-CALIBRATION

At the time of writing this paper and since the first earthquake in September there have been four LiDAR surveys undertaken to measure the change in ground surface as a result of the earthquakes in Brooklands and the wider Styx River Catchment. The most recent and comprehensive of these flights was undertaken after the earthquake on the 13th of June 2011. The post-June LiDAR data has been independently verified using traditional surveying techniques. Other cross checks were undertaken to verify the accuracy of the 'post-quake' survey data with comparisons made between the LiDAR data and the river cross-section survey and the LINZ benchmark database.

A comparison of the post-quake data sets and the original pre-quake LiDAR data set collected in 2003 highlighted significant change in the land surface (in the region of 300 mm in Brooklands) and underlying inaccuracy in the original data set (in the order of 200 – 250 mm). An error in the geoidal correction in the original 2003 LiDAR was identified as the source of the underlying inaccuracy. The affect of the correction varied with distance from the Central City. The Styx River catchment was worst affected with the survey data being below the actual topography.

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[2] The CCC Waterways, Wetlands and Drainage Guide provides design rainfall data for the catchment including a 16% increase in intensity for climate change.

[3] The design sea level is derived from historical tide level recorders and inherently includes non astronomical effects such as storm surge. An allowance for 500 mm sea level rise was included in the SMP.

The earlier predictions of flooding using the model were affected by the error in the survey data and the model required re-calibration to allow true comparisons of earthquake effects. The error had the following effects:

- The flood plain was modelled closer to the bed level of the river with the uncorrected surface model (reducing the capacity of the channel before first flooding and increasing the amount of storage available for a given flood level);
- For the recorded August 2008 flood greater runoff volume was required to replicate the flood level with the uncorrected surface model;
- This extrapolated in the design storms to give greater runoff volumes and flood depths; and
- Even though depths were greater; flood levels were lower.

The hydraulic model was re-calibrated to the August 2008 storm event using the corrected 2003 LiDAR data. The effect of the re-calibration was to:

- Better replicate the August 2008 event flows and water levels;
- Reduce the required run-off volume to replicate the August 2008 event;
- Reduce the extrapolated run-off volume in the design storm events;
- Reduce design storm flood plain inundation depths; and
- Reduce design storm flood plain inundation levels.

3.2.3 POST-QUAKE

The ground surface model created from the revised August/September LiDAR data was used in conjunction with river cross section data collected after the September 2010 earthquake to test for changes in flood inundation extent and depth. The simple process of updating the model ground surface level grid and river cross-section was complicated by the uncertainties with survey data accuracy. Once confidence was gained in the surveys undertaken after the earthquakes it was a quick task to update the model.

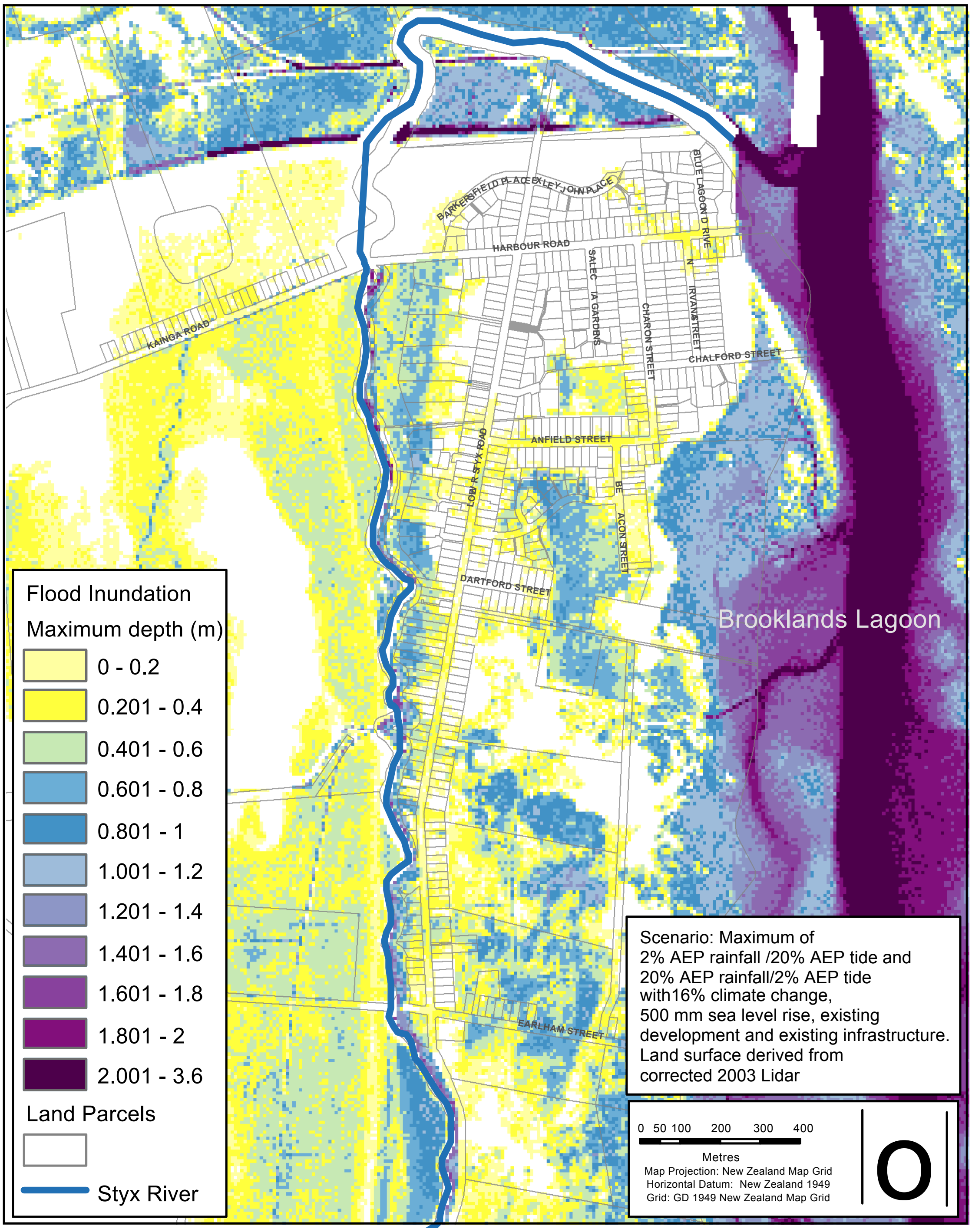
There is a mismatch in timing of the data collection between the river cross sections and the wider topographic survey but, as described above, the observations were that the September Earthquake had a significantly greater affect on the river and flood berm than the combined effects of subsequent earthquakes.

With the inclusion of the post earthquake geometry in the model it was possible to calculate the impact of the earthquakes on flood extent and depth. Flood velocities were of less concern given the nature of the flooding in the Brooklands area with ponding depths behind the flood gates being of primary concern.

3.3 FLOOD INUNDATION PREDICTIONS

3.3.1 PRE-QUAKE INUNDATION

Changes in the land surface required the hydrological model to be re-calibrated. This affected the absolute level of flood predictions and flood depth predictions. The inundation extent in the Brooklands area produced by the greater of the 2% AEP design rainfall and sea level event with the re-calibrated model is presented below in Figure 5.



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Data source: CCC: Parcel Layer 2011, Roads Layer 2011. GHD:max flood depth (max of EQ_Q5_50T_500SLR_ED_2003_Re-Cal_v17 MAX DEPTH0.asc and EQ_Q50_5T_500SLR_ED_2003_Re-Cal_v16 MAX DEPTH0.asc). Map colors based on www.ColorBrewer.org, by Cynthia A. Brewer, Penn State. Created by amarburg.

Figure 5: Pre-Quake Inundation Depth

The tidal inundation predictions show a significant hydraulic grade between Brooklands Lagoon and the Styx River due to the limited period during which the tide level was above the trough in the sand dunes. The effects of the limited conveyance of the overland flow paths is to somewhat protect Brooklands against the impact of tidal flooding; noting that the surface model does not allow for morphological affects which may occur during overtopping of the sand dunes. Ignoring of potential erosion of the sand dunes was considered an acceptable approximation given the nature of the vegetation of the dunes.

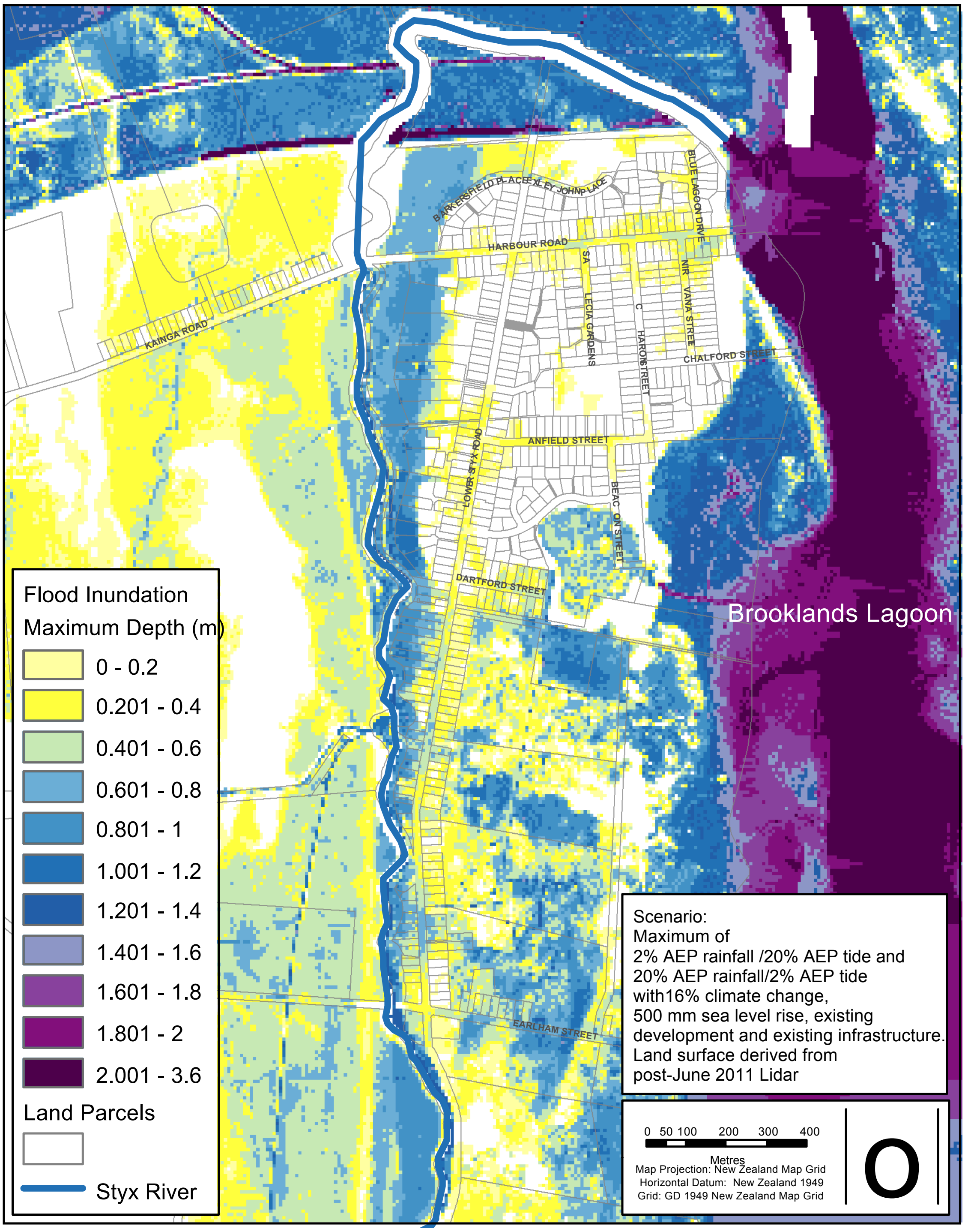
3.3.2 POST-QUAKE

The mechanisms for flooding within the catchment have not changed with the earthquake; however there has been a subtle change in the dominance of the types of flooding at Brooklands with the coastal inundation scenarios becoming increasingly more dominant. With the lowering of the land surface upstream of the tide gates there is now more flood plain storage for a given flood level but there is an increased risk of flooding from the coastal events.

The effect of the general land damage on the flood plain is typically to:

- Drop the flood plain level relative to the river and the sea;
- Drop the flood level in the fluvial flooding scenario;
- Slightly increase flood depth from overtopping of the river banks; and
- Increase coastal flooding extent and depth in large events due to over topping from Brooklands Lagoon.

Overall it has been found that the potential for flooding of Brooklands from both the Styx River and the tide has increased due to the land damage. Figure 6 presents the results from the re-calibrated model for the 2% AEP event with the 'post-Quake' geometry. Figure 7 presents a difference in predicted flood level between the results presented in Figures 5 ('pre-Quake') and 6 ('post-quake').



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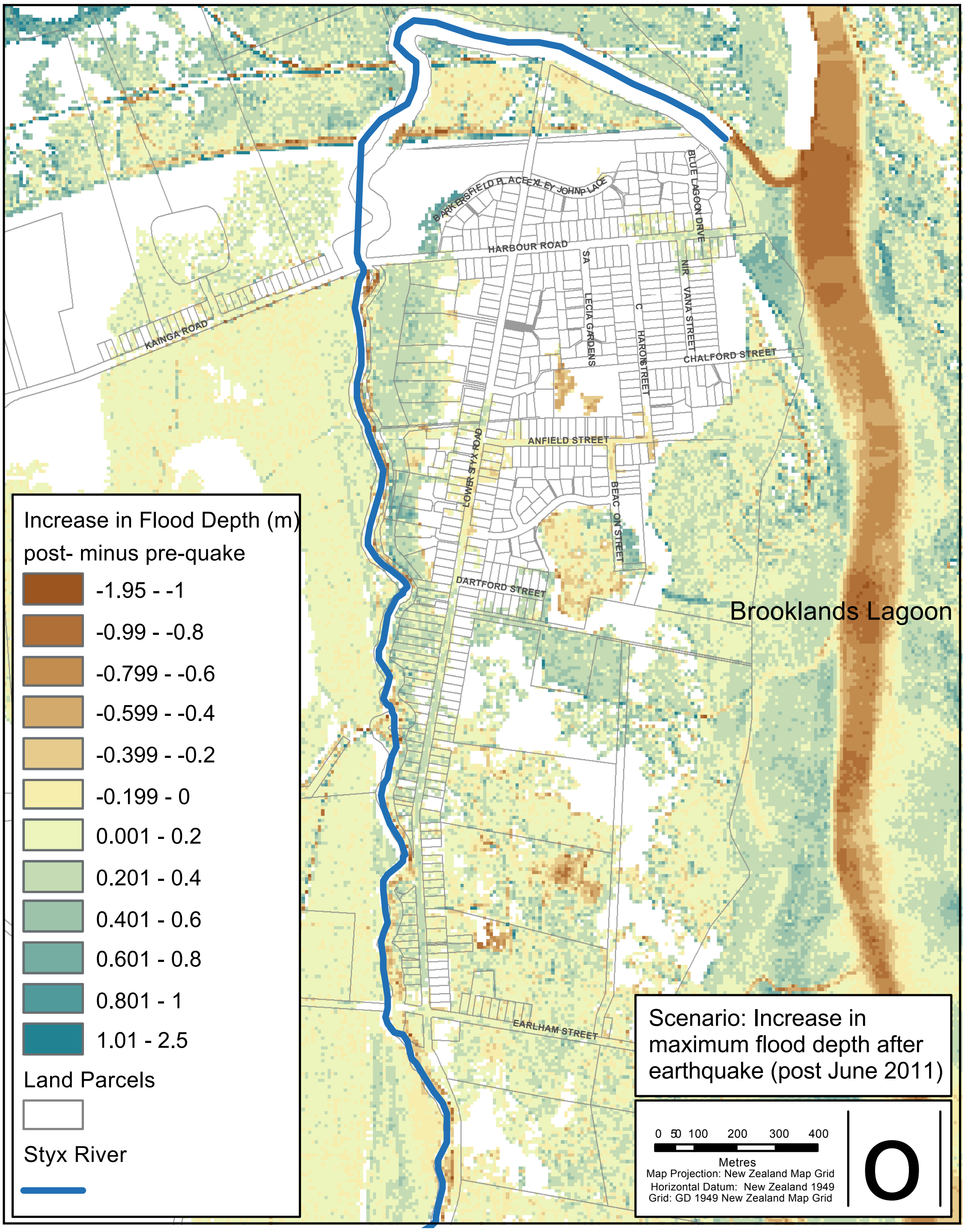
Data source: CCC: Parcel Layer 2011, Roads Layer 2011. GHD:max flood depth (max of EQ_Q50_5T_500SLR_ED_June2011_Re-Cal_v18 MAX DEPTH0.asc and EQ_Q5_50T_500SLR_ED_June2011_Re-Cal_v19 MAX DEPTH0.asc). Map colors based on www.ColorBrewer.org, by Cynthia A. Brewer, Penn State. Created by amarburg.

Figure 6: Post-Quake Inundation Depth



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Data source: CCC: Parcel Layer 2011, Roads Layer 2011. GHD: increase in flood depth (postqmaxd - oldcal03maxd). Created by amarburg.

Figure 7: Change in Inundation Depth Resulting from the Earthquake in a 2% AEP Rainfall Event

It can be seen in Figure 7 that the most dramatic changes in predicted inundation depth occur in the main channel of the Brooklands Lagoon. This is probably due to the level of the tide in the lagoon during the collection of the LiDAR data. This affects the modeled ground surface thus reducing predicted inundation depth.

More critically, it can be seen that there is a general increase in predicted flood depth across the flood plain in the order of 200 mm – 300 mm. The flood level increased in the tidal inundation scenario by approximately 20 mm with a similar drop in the fluvial flooding scenario. The number of flooded properties (rather than flooded houses) has increased as a result of the earthquakes from a total of 360 to a total of 418 as provided in Table 1. The measure of 'flooding' is any predicted floodwater touching the property.

Table 1: Earthquake Effects on Predicted Flooded Properties

	Not Flooded	Flooded
Pre-Quake	204	360
Post-Quake	146*	418^

*Of the 146 post-quake non flooded properties 62 were predicted to flood prior to the earthquakes but this change is mostly due to filling of land during development.

^ Of the 418 post-quake flooded properties 120 are properties which were not predicted to flood prior to the earthquakes.

3.4 OUTPUTS REQUIRED

A range of outputs were required from the model to inform various stakeholders and authorities. The main interest was focused on change in flood depth in Brooklands and Spencerville for a range of scenarios. Flood inundation depth maps were provided showing testing of different variables, such as: existing and future land use, AEP rainfall and sea level, duration of rainfall, flood mitigation measures, sea level rise and adjustments to rainfall estimates for future predicted climate change estimates.

The results of the modeling were of interest to three authorities: the Christchurch City Council (CCC), the Canterbury Earthquake Recovery Authority (CERA) and the Earthquake Commission (EQC). Each had different criteria for analysing the effects of the earthquakes and were interested in different impacts. For example, CCC planning regulations are focused on future flooding including climate change (to set building floor levels), whereas EQC are interested in present day impacts on flood depth. CERA have an interest in long term viability of the community and were interested in sea level rise and flood mitigation options. CCC officers took particular care to prioritise the various agencies interests so that wider decision making was facilitated as best possible.

One area of investigation was communal flood protection measures, including stop banking. Testing of stop bank scenarios was undertaken using the model through modifications to the representation of the ground surface and 'blocking out' of protected areas. This allowed the estimation of stop bank crest levels from the flood plain model results.

It must be noted however, that the flooding effects are not the only consideration in relation to post-earthquake zoning decisions. Geotechnical considerations including land stabilization needs and building foundation requirements – as well as infrastructure costs - would also have been part of these decisions.

4 CONCLUSIONS

The analysis of earthquake impacts and possible mitigation measures using this model has made a very helpful contribution to understanding earthquake impacts and the decision-making which has been necessary following the earthquake. It has enabled the quantification of changes and helped others to confidently assess the financial impacts of flooding and rebuilding within the bounds of the changing regulatory environment. The mapping in particular enables non-specialist parties to appreciate the situation and form their own opinions – or ask appropriate questions. The authors have formed this view based on the level of interest that was shown in the model and its results and the questions that were asked during the course of this project.

The additional work on the model and in particular the correction of the earlier LiDAR means that we are now more confident of the model results and for this and any future investigations which may need to be done in this catchment

ACKNOWLEDGEMENTS

The authors would like to acknowledge those affected by the earthquakes; directly or indirectly. The earthquakes have created hardship in many communities, including Brooklands. The investigations undertake to assess change in flooding has indirectly impacted the residents of Brooklands and many others in the community through the change in land zoning.

The efforts of engineers and regulators should also be recognized, with many putting sustained efforts at work and for their community whilst being in difficult personal situations. All efforts were made to give residents of earthquake affected properties and authorities precise and accurate information as quickly as possible so that they were able to make difficult decisions in a timely manner.